SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Conference Proceedings **CMRE-CP-2024-001**

Climate Change and Security Workshop Proceedings

Sandro Carniel, Aniello Russo, Fabio Lissi (*eds*.)

March 2024

About CMRE

The Centre for Maritime Research and Experimentation (CMRE) is a world-class NATO scientific research and experimentation facility located in La Spezia, Italy.

The CMRE was established by the North Atlantic Council on 1 July 2012 as part of the NATO Science & Technology Organization. The CMRE and its predecessors have served NATO for over 50 years as the SACLANT Anti-Submarine Warfare Centre, SACLANT Undersea Research Centre, NATO Undersea Research Centre (NURC) and now as part of the Science & Technology Organization.

CMRE conducts state-of-the-art scientific research and experimentation ranging from concept development to prototype demonstration in an operational environment and has produced leaders in ocean science, modelling and simulation, acoustics and other disciplines, as well as producing critical results and understanding that have been built into the operational concepts of NATO and the nations.

CMRE conducts hands-on scientific and engineering research for the direct benefit of its NATO Customers. It operates two research vessels that enable science and technology solutions to be explored and exploited at sea. The largest of these vessels, the NRV Alliance, is a global class vessel that is acoustically extremely quiet.

CMRE is a leading example of enabling nations to work more effectively and efficiently together by prioritizing national needs, focusing on research and technology challenges, both in and out of the maritime environment, through the collective Power of its world-class scientists, engineers, and specialized laboratories in collaboration with the many partners in and out of the scientific domain.

CMRE-CP-2024-001

Climate Change and Security
Workshop Proceedings

Edited by

Sandro Carniel
Aniello Russo
Fabio Lissi

This document, which describes work performed under the Project Climate Change and Security Analysis (CCSA) of the STO-CMRE Programme of Work, has been approved by the Director.

Intentionally blank page

Programme Chairs

Dr Sandro Carniel (NATO STO-CMRE)
Mr Aniello Russo (NATO STO-CMRE)

Local Organizing Committee

Dr Elena Camossi (NATO STO-CMRE)
Mr Fabio Lissi (NATO STO-CMRE)
Ms Ilaria Saudella (NATO STO-CMRE)

NATO HQ Organizing Committee

Mr Alvaro Martin-Blanco (NATO STO-OCS)
Mr Daniel Bayliss (NATO STO-OCS)

Supporting Organizations

NATO OTAN
Centre for Maritime Research & Experimentation
La Spezia | Italy
S&T organization

NATO OTAN
Office of the Chief Scientist
Headquarters | Brussels - Belgium
S&T organization

Intentionally blank page

CMRE-CP-2024-001

Climate Change and Security Workshop Proceedings

Sandro Carniel, Aniello Russo, Fabio Lissi

Executive Summary: NATO 2022 Strategic Concept (SC) describes Climate Change (CC) as a "defining challenge of our time, with a profound impact on Allied security. […] a crisis and a threat multiplier". It further states, "CC also affects the way our armed forces operate. Our infrastructure, assets and bases are vulnerable to its effects. Our forces need to operate in more extreme climate conditions and our militaries are more frequently called upon to assist in disaster relief." Finally, the SC concludes, "NATO should become the leading international organisation when it comes to understanding and adapting to the impact of CC on security. The Alliance will lead efforts to assess the impact of CC on defence and security and address those challenges. We will contribute to combatting CC by reducing greenhouse gas emissions, improving energy efficiency, investing in the transition to clean energy sources and leveraging green technologies, while ensuring military effectiveness and a credible deterrence and defence posture."

Already at the 2021 NATO Summit in Brussels, NATO leaders agreed to an ambitious Climate Change and Security Action Plan (CCSAP) with the goal of improving NATO's understanding of CC as well as of its implications on security and defence. Since then, NATO has prepared every year the Climate Change and Security Impact Assessment (CCSIA), briefing Allies on the most recent research conducted on the impact of CC on several Allied capabilities and enablers, as well as strategic posture. Finally, in 2022, the Alliance has also approved the establishment of a new Climate Change and Security Centre of Excellence (CCASCOE) with Canada as the host Nation.

Within the NATO Science and Technology Organization (STO), the Office of the Chief Scientist (OCS) tasked the Centre for Maritime Research and Experimentation (CMRE) to develop a new project dedicated to the investigation of the interaction between CC and security (CC&S) from a scientific perspective, and focussed (but not limited to) on the Maritime Domain, aligned with the NATO Warfighting Capstone Concept (NWCC). CMRE, based in La Spezia, Italy, has thus started CC&S research activities in 2023, following the CCSAP guidelines along four main pillars: awareness, adaptation, mitigation, and outreach. A critical part of this effort was to bridge the gap between the vast ranges of practitioners involved and to merge different expertise into a single forum.

The following workshop proceedings are the result of the *Climate Change and Security Workshop* held in Lerici, Italy, from the 3rd to the 5th of October 2023. The Workshop, sponsored by OCS and organized by CMRE, was the starting point to create a CC&S community of scientists, armed forces, political decision makers, and industry leaders, to maximise NATO outreach in this field. The collected contributions encompass a wide range of disciplines, dealing with this epochal phenomenon not only in terms of the understanding of its physical foundations, but also of its direct and indirect consequences on NATO's strategic environment, personnel, infrastructure, platforms and assets, and ability to conduct Multi-Domain Operations (MDO).

Contacts and further information about the event and contributors are available at: https://www.climatechangesecurity.org/

Intentionally blank page

Climate Change and Security Workshop Proceedings

Sandro Carniel, Aniello Russo, Fabio Lissi

Abstract: Building on NATO Climate Change and Security Action Plan (CCSAP) and NATO 2030 initiative, NATO Science and Technology Organization (STO) is committed to deepen research on the climate-induced security challenges and to find innovative solutions. Within the Climate Change and Security (CC&S) Programme commissioned by the Office of the Chief Scientist (OCS), the Centre for Maritime Research and Experimentation (CMRE) hosted a dynamic and multidisciplinary workshop on the critical intersection between CC&S, uniting an array of distinguished experts. The Climate Change and Security Workshop was held in Lerici, Italy 3 – 5 October 2023, at Villa Marigola.

The event was attended by 112 participants and featured 5 keynote speakers and 39 presenters. This gathering facilitated in-depth discussions on the multifaceted climate-induced security challenges and innovative solutions within the maritime domain. Spearheaded by CMRE, in collaboration with OCS, the workshop collected contributions spanning from scientific, political, and military areas of expertise, in accordance with the four pillars of the NATO CCSAP: awareness, adaptation, mitigation, and outreach. The workshop strengthened CMRE's network of partners in the CC&S field and effectively outlined the new CMRE Climate Change and Security Analysis (CCSA) Project.

During the three days, 5 keynotes, 21 papers presentation, 24 poster pitches, and 2 panels were offered to the audience. This document collects the 17 papers accepted for publication.

Keywords: Climate Change, Security, Maritime Domain, Workshop

Intentionally blank page

Contents

Preface

NATO 2022 Strategic Concept (SC) describes Climate Change (CC) as a "defining challenge of our time, with a profound impact on Allied security. […] a crisis and threat multiplier". Already at the 2021 NATO Summit in Brussels, NATO leaders agreed to an ambitious Climate Change and Security Action Plan (CCSAP) with the aim of improving NATO's understanding of CC as well as of its implications on security and defence. Within the NATO Science and Technology Organization (STO), the Office of the Chief Scientist (OCS) tasked the Centre for Maritime Research and Experimentation (CMRE) to develop a new project dedicated to the investigation of the interaction between CC and security (CC&S) from a scientific perspective, and focussed on the Maritime Domain. CMRE, based in La Spezia, Italy, has thus started CC&S research activities in 2023, following the CCSAP guidelines along four main pillars: awareness, adaptation, mitigation, and outreach. A critical part of this effort was to bridge the gap between the vast ranges of practitioners involved and to merge different expertise into a single forum.

The scientific evidence regarding the impacts of CC has become progressively more solid, supported by strong facts and undisputed peer-reviewed publications. Global Warming affects the whole climate system, and oceans are no exception, although they are still our best allies contrasting the main effects of CC, retaining over 90% of the energy increase suffered after in the last 150 years. More than this, CC has become a powerful threat multiplier, and its associated physical effect proved to have direct consequences also on the military, economic and social dimensions. For example, environmental factors can affect energy supplies to both civilian populations and military operations, making energy security a major topic of concern, but also have a direct impact on military platforms and enablers performances. In this context, NATO is aiming to become the leading international organisation when it comes to understanding and adapting to the impact of CC on security.

To understand the importance of oceans for the global economy and societies in general, we have to look at the share of human activities taking place at, or depending upon, the seas. The Centre for International Maritime Security suggested a 66-70-80-90-99 rule, highlighting that 66% of global wealth comes from or near the sea; 70% of the globe is oceanic; 80% of its population is coastal; 90% of goods arrive by sea; and 99% of international digital traffic goes by submarine cables. It should not come as surprise, then, than NATO is dedicating considerable effort at boosting its maritime capabilities and at understanding the impact of CC on them. To support this effort, CMRE developed a new programme sponsored by OCS and named Climate Change and Security Analysis (CCSA), investigating the CC&S nexus and the vast range of spill-over effects produced both in the physical and social domains.

In the framework of outreach activities of CCSA, in October 3-5 2023, CMRE organized the *Climate Change & Security Workshop* in Lerici, Italy. The event was designed to meet the needs of different CC&S Subject Matter Expert (SME) communities to fully address the CC&S nexus. At the same time, the workshop leveraged CMRE's expertise in the maritime domain and had a strong focus on the impacts of CC on the oceans. The conference was intended as multi and interdisciplinary by vocation, and saw a diverse and multifaceted participation of earth and natural scientists (coming from physic, maths, chemist, geology), together with social scientists (from economics and international politics), but also military practitioners, industry stakeholders and political decision-makers. The core idea was to bridge scientific research with the needs of operators, and to enhance the strategic understanding of CC&S.

Keynotes and presenters at the workshop offered an upsurge of tailored scientific activities, many of which consolidated at CMRE with the help of the Nations, and offered an overview on new aims and challenges for NATO. The Proceedings offered hereafter address very well the three overall Workshop objectives:

- Bring together three different typology of experts: scientific, socio-political, and military/operational from across all services;
- Identify additional research gaps, methods, and tools with the help of SMEs;
- Share the foundations to forge new higher educational paths and new curricula in CC&S.

This collection presents cutting-edge scientific research results, as well as experimental solutions to military and strategic challenges, both in terms of adaptation to climatic effects and mitigation of the environmental footprint of military platforms. Those include but do not limit to: new tools to better analyse CC signals; advanced methods to tame uncertainties; Arctic competition scenarios; future CC impacts on naval sensors and maritime situational awareness; governance instruments; solutions for infrastructure protections; and, educational efforts, that should reflect new education curricula capable of grouping subjects rather than separating them in single disciplines. These Proceedings are therefore reflecting the multi, inter and transdisciplinary essence of the CC&S Workshop, integrating in a holistic way different scientific components with social science aspects well aligned with the NATO Multi-Domain Operations (MDO) concept. As such, they aim to represent the starting point to which different communities will look back at as a reference of a new common path they need to walk along together.

The support provided by John Redmayne, Julia Nurzynska, and Paolo Franchi for the preparation of the Workshop Proceedings is gratefully acknowledged.

CLIMATE
CHANGE &
SECURITY
03-05 OCTOBER 2023
LERICI, ITALY

Workshop Proceedings

Are we approaching at tipping point of the Atlantic Ocean circulation?

Stefan RAHMSTORF[a,1]
[a] *Potsdam Institute for Climate Impact Research (PIK), University of Potsdam, Germany*
ORCiD ID: Stefan RAHMSTORF https://orcid.org/0000-0001-6786-7723

Abstract. The Atlantic Meridional Overturning Circulation (AMOC) is a large-scale overturning motion of the entire Atlantic, from the Southern Ocean to the High North. It moves around 15 million cubic meters of water per second (i.e. 15 Sverdrup), passing through the Gulf Stream as part of its much longer journey. Since the AMOC moves the bulk of the heat into the Northern Atlantic, with its warm northward surface flow and cold and deep southward return flow, it is highly relevant for climate. Several new studies suggest that it may already be approaching a “tipping point” this century, possibly even in the next few decades, leading to a completely new climatic state. The AMOC has repeatedly shown major instabilities in recent Earth history and it has weakened over the past hundred years, being now likely weaker than any time in the past millennium. Several groups of paleo-climatologists have used a variety of methods to reconstruct the AMOC over longer time spans, and it is clear that the long-term weakening trend is anthropogenic, confirmed also by climate models as a response to global warming. In addition, there appear to be decadal oscillations particularly after the mid-20th century. The AMOC “tipping point”, first described by Stommel in a highly simple model that captures a fundamental feedback, was later confirmed by sophisticated 3-dimensional ocean circulation models, as well as fully fledged coupled climate models. The big uncertainty, however, is how far the present climate is from this tipping point. Models greatly differ in this regard, as this appears to be sensitively dependent on the finer details of the density distribution of the Atlantic waters, but increasingly the evidence points to the risk being greater than 10% already during this century. This paper will present evidence that unequivocally supports unprecedented, urgent and ambitious climate action to tackle the risks of this and other climate system “tipping points”.

Keywords. AMOC, tipping points, climate change

1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) has been in the news lately, with new studies suggesting that it may already be approaching a tipping point this century, possibly even in the next few decades. This paper presents a summary of recent findings about this risk.

---

[1] Stefan Rahmstorf, rahmstorf@ozean-klima.de.

1.1. The AMOC is a big deal for climate

The AMOC is a large-scale overturning motion of the entire Atlantic, from the Southern Ocean to the High North. It moves around 15 million cubic metres of water per second (i.e. 15 Sverdrup). The AMOC water passes through the Gulf Stream along a part of its much longer journey, but contributes only a small part of the Gulf Stream's total flow of around 90 Sverdrup. The AMOC is driven by density differences and is a deep-reaching vertical overturning of the Atlantic; the Gulf Stream is a near-surface current near the US Atlantic coast and mostly driven by winds. However, the AMOC moves the bulk of the heat into the northern Atlantic so is highly relevant for climate, because the southward return flow is very cold and deep; heat transport is the flow multiplied by the temperature difference between northward and southward flow. The wind-driven part of the Gulf Stream contributes much less to the net northward heat transport, because that water returns to the south at the surface in the eastern Atlantic at a temperature not much colder than the northward flow, so it leaves little heat behind in the north. So for climate impact, the AMOC, and not the Gulf Stream, is the biggest deal.

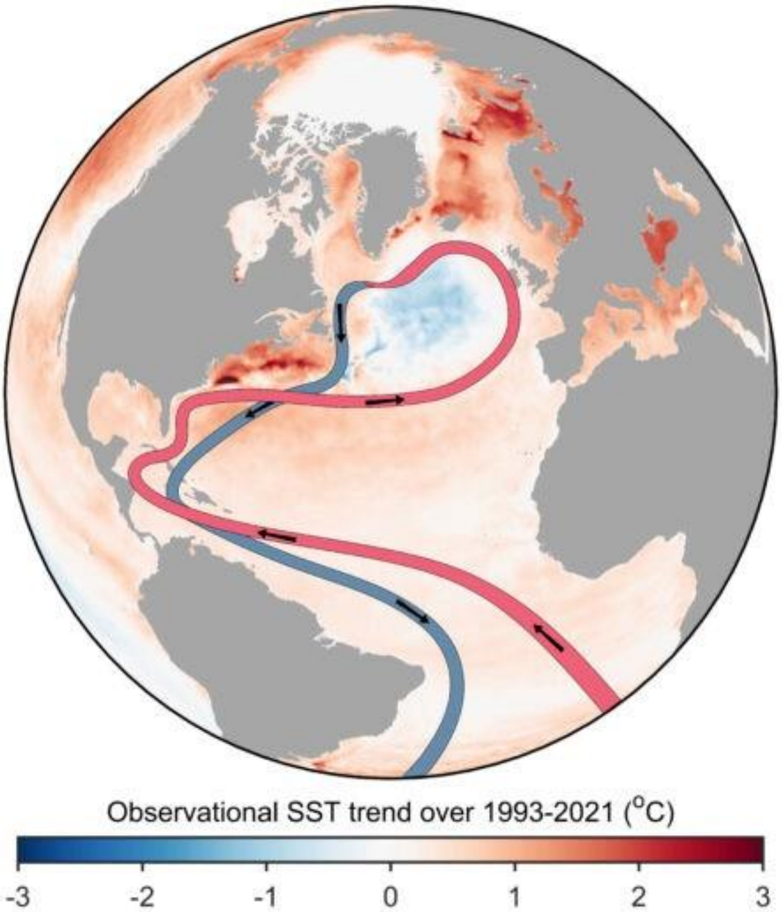


Figure 1: A very rough schematic of the AMOC: warm northward flow near the surface, deep-water formation, deep southward return flow in 2000 – 3000 metres depth. In the background the observed sea-surface temperature (SST) trend since 1993 from the Copernicus satellite service, showing the 'cold blob' in the northern Atlantic west of the British Isles discussed below. Graph by Ruijian Gou.

2. AMOC evolution

The AMOC has repeatedly shown major instabilities in recent Earth history, for example during the Last Ice Age, prompting concerns about its stability under future global warming, see e.g. Broecker 1987, who warned about “unpleasant surprises in the greenhouse” [1]. Major abrupt past climate changes are linked to AMOC instabilities, including Dansgaard-Oeschger-Events and Heinrich Events [2].

2.1. The AMOC has weakened over the past hundred years

We do not have direct measurements over such a long time (only since 2004 from the RAPID project), but only various indirect indications. We have used the time evolution of the “cold blob” shown in **Figure 1**, using sea-surface temperature (SST) observations since 1870, to reconstruct the AMOC in Caesar et al. 2018 [3]. In that article, we also discuss a “fingerprint” of an AMOC slowdown which also includes excessive warming along the North American coast, also seen in **Figure 1**. The correlation of this fingerprint with the AMOC in historic runs with CMIP6 models has recently been shown by [4], see **Figure 2**.

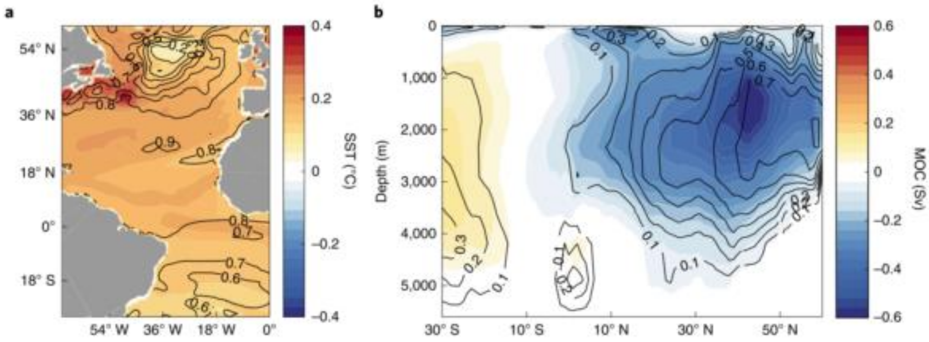


Figure 2: Correlation of SST variations (left) with AMOC variations (right) in historic runs with CMIP6 models, from Latif et al. 2022.

Others have used changes in the Florida Current since 1909 [5], or changes in South Atlantic salinity [6], to reconstruct past AMOC changes.

2.2. The AMOC is now weaker than at any time in the past millennium

Several groups of paleo-climatologists have used a variety of methods to reconstruct the AMOC over longer time spans. We compiled the AMOC reconstructions we could find in [7], see **Figure 3**. The proxy data reconstructions compare quite well with other methods (in situ measurements by the RAPID array; a combination of empirical model with historical hydrographic data; or based on satellite altimetry and cable measurements) as far as they overlap for the recent variability since 1950, as is shown in [8].

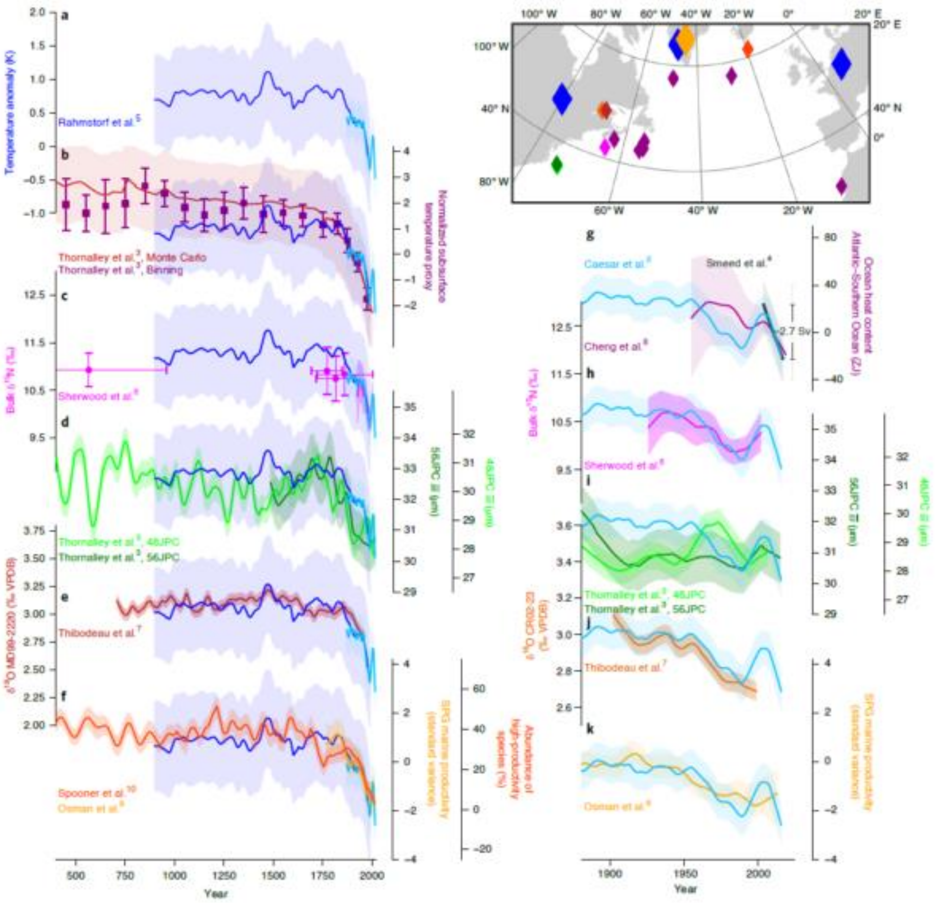


Figure 3: A compilation of nine different proxy series for the AMOC evolution. Data locations are shown in the inset map, from Caesar et al. 2021.

2.3. The long-term weakening trend is anthropogenic

These changes are basically what climate models predict as a response to global warming, although I would argue that the climate models underestimate the weakening trend. A recent study [9] has combined observations and models to isolate the role of different drivers and concludes for the “cold blob” region: “consistent with the observations, an anthropogenic cooling is diagnosed by the method over the last decades (1951–2021) compared to the preindustrial period.”

In addition, there appear to be decadal oscillations particularly after the mid-20th Century. Such oscillations may be natural variability, or an oscillatory response to modern warming, given there is a delayed negative feedback in the system (weak AMOC makes the “cold blob” region cool down, which increases the water density and hence strengthens the AMOC). Increasing oscillation amplitude may also be an early warning sign of the AMOC losing stability.

Very short-term SST variability (seasonal, inter-annual) in the cold blob region is likely just dominated by the weather, i.e. surface heating and cooling, and not indicative of changes in ocean currents.

3. AMOC tipping points

3.1. The AMOC has a tipping point, but it is highly uncertain where it is

This tipping point was first described by Stommel 1961 [10] in a highly simple model which captures a fundamental feedback. The region in the Northern Atlantic where the AMOC waters sink is rather salty, because the AMOC brings salty water from the subtropics to this region. If it becomes less salty by an inflow of freshwater (rain or meltwater from melting ice), the water becomes less dense, sinks less, and the AMOC slows down. Thus, it brings less salt to the region, which slows the AMOC further. This is called the "salt advection feedback". Beyond a critical threshold this becomes a self-amplifying "vicious circle" and the AMOC grinds to a halt: the AMOC tipping point.

That this tipping point exists has been confirmed in numerous models since [10], including sophisticated 3-dimensional ocean circulation models as well as fully fledged coupled climate models, see also [11]. The big uncertainty, however, is in how far the present climate is from this tipping point. Model predictions differ greatly in this regard, as this effect appears to be very sensitive to the finer details of the density distribution of the Atlantic waters. This can be considered as sailing a ship into uncharted waters, where you know there are dangerous rocks hidden below the surface, but you do not know exactly where they are.

3.2. Standard climate models have suggested the risk of an AMOC collapse is relatively small during this century.

For example, the IPCC Special Report on the Ocean and Cryosphere concluded: "The AMOC is projected to weaken in the 21st century under all RCPs (very likely), although a collapse is very unlikely (medium confidence). Based on CMIP5 projections, by 2300, an AMOC collapse is about as likely as not for high emissions scenarios and very unlikely for lower ones (medium confidence)".

It has long been my opinion that "very unlikely", meaning less than 10% in the calibrated IPCC uncertainty jargon, is not at all reassuring for a risk we really should rule out with 99.9% probability, given the devastating consequences should an AMOC collapse occur.

3.3. Standard climate models probably underestimate the risk.

Nevertheless, these model results probably underestimate the risk. There are two reasons why: they largely ignore Greenland ice loss and the resulting freshwater input to the northern Atlantic which contributes to weakening the AMOC; and, their AMOC is likely too stable. There is a diagnostic for AMOC stability, namely the overturning freshwater transport, which was introduced in [12] based on Stommel's model [10]. Basically, if the AMOC exports freshwater out of the Atlantic, then an AMOC weakening would lead to a fresher, i.e. less salty, Atlantic, which would weaken the AMOC further. Data suggest that the real AMOC exports freshwater, in most models it imports freshwater. [13] nicely sums up the problem and provides further references. Standard climate models get the observed "cold blob", but only later. **Figure 4** and **Figure 5** present some graphs from the current IPCC report, AR6.

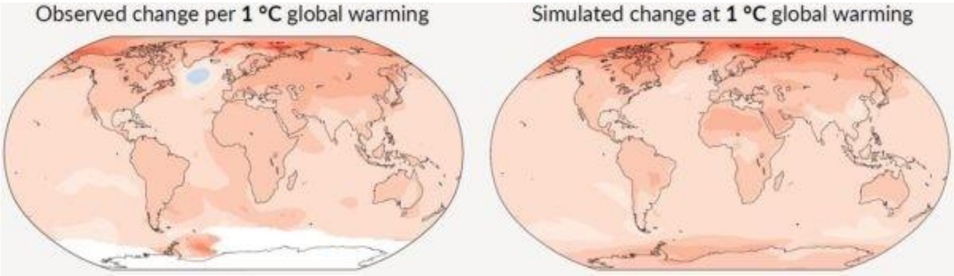
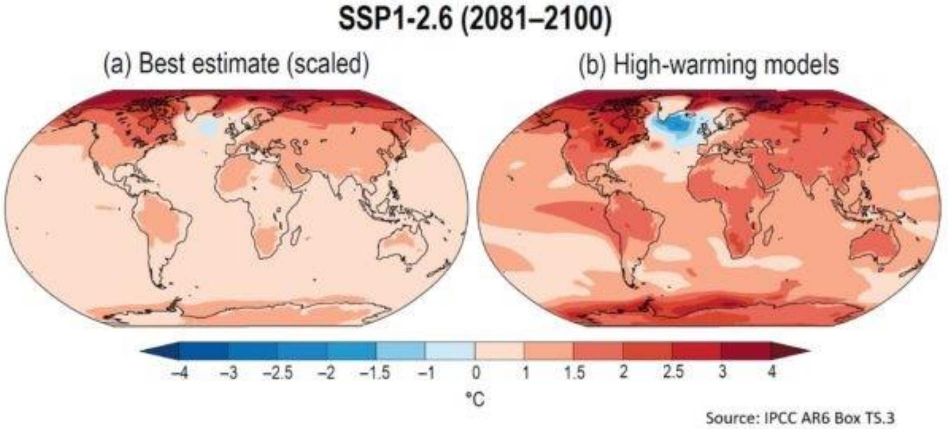


Figure 4: Observed vs simulated historic warming (normalised to 1 °C). At this stage the 'cold blob' is not yet seen in the model average. Source: IPCC AR6.



Source: IPCC AR6 Box TS.3

Figure 5: Simulated warming by the end of this century. Now the 'cold blob' appears in the CMIP6 models.

3.4. There are possible early warning signals

New methods from non-linear dynamics search for warning signals when approaching tipping points in observational data, from cosmology to quantum systems. They use a critical slowing down, increasing variance or increasing autocorrelation in the variability of the system. An example is provided by [14] that used eight different data series and concluded there is "strong evidence that the AMOC is indeed approaching a critical, bifurcation-induced transition."

Another study, this time using 312 paleo-climatic proxy data series going back a millennium [15], reporting a "robust estimate, as it is based on sufficiently long observations, that the Atlantic Multidecadal Variability may now be approaching a tipping point after which the Atlantic current system might undergo a critical transition".

Recently, a third comparable study by Danish colleagues has been published [16], which expects the tipping point already around 2050, with a 95% uncertainty interval for the years 2025 – 2095. Individual studies always have weaknesses and limitations, but when several studies with different data and methods point to a tipping point that is already quite close, I think this risk should be taken very seriously.

4. Conclusions

Timing of a critical AMOC transition is still highly uncertain, but increasing evidence points to the risk being far greater than 10% during this century, and even rather worrying for the next few decades. The conservative IPCC estimate, based on climate models that are too stable and do not consider the full effects of freshwater forcing, is in my view outdated now. I personally agree with the recent Climate Tipping Points report by the OECD, which advised: "Yet, the current scientific evidence unequivocally supports unprecedented, urgent and ambitious climate action to tackle the risks of climate system tipping points".

References

[1] Broecker, W. (1987). Unpleasant surprises in the greenhouse?. *Nature*, *328*, 123-126. https://doi.org/10.1038/328123a0

[2] Rahmstorf, S. (2002). Ocean circulation and climate during the past 120,000 years. *Nature*, *419*, 207-214. https://doi.org/10.1038/nature01090D

[3] Caesar, L. et al. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, *556*, 191-196. https://doi.org/10.1038/s41586-018-0006-5

[4] Latif, M. et al. (2022). Natural variability has dominated Atlantic Meridional Overturning Circulation since 1900. *Nat. Clim. Chang.*, *12*, 455-460. https://doi.org/10.1038/s41558-022-01342-4

[5] Piecuch, C.G. (2020). Likely weakening of the Florida Current during the past century revealed by sea-level observations. *Nat Commun 11*, 3973. https://doi.org/10.1038/s41467-020-17761-w

[6] Zhu, C., & Liu, Z. (2020). Weakening Atlantic overturning circulation causes South Atlantic salinity pile-up. *Nat. Clim. Chang.*, *10*, 998-1003. https://doi.org/10.1038/s41558-020-0897-7

[7] Caesar, L. et al. (2021). Current Atlantic Meridional Overturning Circulation weakest in last millennium. *Nat. Geosci. 14*, 118-120. https://doi.org/10.1038/s41561-021-00699-z

[8] Caesar, L. et al. (2022). Reply to: Atlantic circulation change still uncertain. *Nat. Geosci.*, *15*, 168-170. https://doi.org/10.1038/s41561-022-00897-3

[9] Qasmi, S. (2023). Past and future response of the North Atlantic warming hole to anthropogenic forcing, *Earth Syst. Dynam.*, *14*, 685-695, https://doi.org/10.5194/esd-14-685-2023

[10] Stommel, H. M. (1961). Thermohaline convection with two stable regimes of flow. *Tellus*, *13*(2), 224-230

[11] Rahmstorf, S., et al. (2005). Thermohaline circulation hysteresis: A model Intercomparison. *Geophys. Res. Lett.*, *32*, L23605

[12] Rahmstorf, S. (1996). On the freshwater forcing and transport of the Atlantic thermohaline circulation. *Climate Dynamics*, *12*, 799-811. https://doi.org/10.1007/s003820050144

[13] Liu, W., Liu, Z., & Brady, E. C. (2014). Why is the AMOC Monostable in Coupled General Circulation Models?. *J. Climate*, *27*, 2427-2443. https://doi.org/10.1175/JCLI-D-13-00264.1

[14] Boers, N. (2021). Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nat. Clim. Chang.*, *11*, 680-688. https://doi.org/10.1038/s41558-021-01097-4

[15] Michel, S. L. L. et al. (2022). Early warning signal for a tipping point suggested by a millennial Atlantic Multidecadal Variability reconstruction. *Nat. Commun.*, *13*, 5176. https://doi.org/10.1038/s41467-022-32704-3

[16] Ditlevsen, P., & Ditlevsen, S. (2023). Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nat. Commun.*, *14*, 4254. https://doi.org/10.1038/s41467-023-39810-w

Future changes in wave climate in the Mediterranean and High-North Seas under naval operations' perspective

Andrea LIRA-LOARCA[a], Aniello RUSSO[b], Sandro CARNIEL[b],
Michele BOLLA-PITTALUGA[a,c] and Giovanni BESIO[a,1]
[a] *Dept. of Civil, Chemical and Environmental Engineering. University of Genoa, Italy*
[b] *NATO STO Centre for Maritime Research and Experimentation. La Spezia, Italy*
[c] *Weather Water Sand srl. Genoa, Italy*
ORCiD ID: Andrea LIRA-LOARCA https://orcid.org/0000-0003-2251-6684, Aniello RUSSO https://orcid.org/0000-0003-3651-8146, Sandro CARNIEL https://orcid.org/0000-0001-8317-1603, Giovanni BESIO https://orcid.org/0000-0002-0522-9635

Abstract. While past studies have relied on Global Climate Models (GCM) with low spatial resolution to analyse future wave climate changes, high-resolution Regional Climate Models (RCMs) projections can improve the characterization of wave climate. This is especially important for conducting coastal impact assessments and adaptation studies, as well as examining the potential impact on naval operations. For example, a sea state above three (i.e., significant wave height above 1.25 metres) is likely to reduce the effectiveness of Search and Rescue and other naval operations. This study focuses on analysing the changes in the frequency of occurrence of sea states above three; comparing historical and future periods on a monthly and seasonal scale, in two areas of NATO interest: the Mediterranean Sea and the high-North Seas (including Northeast Atlantic Ocean and Nordic Seas). This works aims to provide useful information to stakeholders in the maritime domain and decision makers who need to anticipate and plan for the impact of climate change on the wave climate in these regions.

Keywords. Climate change, wave projections, extreme waves, naval operations

1. Introduction

Naval operations are impacted by meteorological and oceanographic conditions, with sea state playing a crucial role in operations planning, safety, and efficiency. The integrated wave climate parameter, significant wave height (H_s), is of particular importance in assessing the impact of changing climate patterns on maritime safety, ship stability, and operations planning. General Circulation Models (GCMs) and Regional Climate Models (RCMs) have become invaluable tools for forecasting future climate scenarios. These models offer insights into potential shifts in sea state likelihoods and the implications for naval operations.

The Mediterranean and high-North Seas (including Northeast Atlantic Ocean and Nordic Seas) are regions of significant maritime activity, including diverse spectrum of operations ranging from trade and transport to defence and environmental monitoring. Therefore, an understanding of future sea state changes due to a changing climate is important for strategic anticipation and risk assessment. GCM-RCM projections often exhibit biases due to model parametrization and simplified physics, among others, which can be

---

[1] Corresponding Author: Giovanni Besio, giovanni.besio@unige.it.

addressed with bias-correction techniques.

In this paper, we investigate potential future changes in significant wave height for the Mediterranean and high-North Seas, focusing on wave conditions above sea state three, providing a comprehensive analysis of the shifts in extreme wave events that have significant implications for naval operations. We present a comprehensive analysis of wave projections derived from GCM-RCMs in the Mediterranean and GCMs in the high-North Seas, taking into account the influence of bias correction. By examining potential shifts in wave height distributions, extreme events, and temporal patterns, we aim to provide valuable insights into the evolving wave conditions in the coming decades.

The remainder of this paper is organised as follows: Section 2 describes the data sources and methodologies used for wave data, bias correction and ensemble characterization; Section 3 presents the main results, highlighting notable changes in H_s seasonal and monthly characteristic and finally, Section 4 summarizes our key conclusions and suggests avenues for future research.

2. Data and Methods

2.1. Mediterranean Sea data

This work uses the wind-wave hindcast in the Mediterranean Sea developed by the Meteocean research group[2] of the University of Genoa providing high-resolution wave climate data from 1979 to 2020 with a regular grid of ≈10 km developed with the third-generation wave model Wavewatch III (WW3) [1]. The hindcast has been validated against buoy observations providing data of integrated wave parameters in different locations in the Mediterranean Sea [2, 3].

The wave climate future projections were obtained using the same WW3 configuration as the hindcast, forced by surface wind fields of different Euro-CORDEX [4, 5] models (GCM-RCM combinations) with 6-hour temporal resolution and 0.11° (≈12.5 km) spatial resolution [6, 7, 8, 9, 10]. Wave climate simulations for each model were obtained for the base-period from 1970 until 2005 and for the Representative Concentration Pathway (RCP) 8.5 high-emission scenario extending from 2006 until 2100. The information regarding the GCM-RCM combinations used in this study is presented on Table 1.

Table 1. EURO-CORDEX RCM and driving GCM combinations and notation used.

Institution	RCM	GCM	Notation
SMHI	RCA4	ICHEC-EC-EARTH	RCA4-EC-EARTH
DMI	HIRHAM5	ICHEC-EC-EARTH	HIRHAM5-EC-EARTH
CLMcom-ETH	COSMO-crCLIM-v1-1	ICHEC-EC-EARTH	COSMO-crCLIM1-EC-EARTH

2.1.1. Ensemble characterization

Future changes in wave climate in the Mediterranean Sea were evaluated for a multi-model ensemble of three different GCM-RCM simulations for mid-century (2030 – 2050) and, end-of-century (2080 – 2100) with respect to hindcast (1985 – 2005).

Results are presented with respect to the *ensemble mean*, averaging the values predicted by each model in the ensemble, giving equal weight to each model. In order to assess the robustness and uncertainty of the results across the different GCM-RCMs, this work follows the methodology proposed by the IPCC Fifth Assessment Report [11]. Regions where the models agree on the sign of change and regions with large/significant changes or small changes with respect to internal variability are highlighted. Internal variability is defined as the median across all models of the standard deviation of the annual means in the base period within each model.

---

[2] http://www3.dicca.unige.it/meteocean/hindcast.html.

2.2. High-North Seas data

For the wave hindcast in the high-North Seas, this work used the ERA-5 re-analysis, produced by the Copernicus Climate Change Service (C3S) at the European Centre for Medium-Range Weather Forecasts (ECMWF). It provides hourly estimates of wave integrated parameters on a global regular 0.25° grid, from 1979 to the present day.
For the wave projections, the Norwegian Meteorological Institute and the Arctic Data Centre produced a series of wave climate projections forced with wind field ensembles from six Coupled Model Intercomparison Project (CMIP) 5 models for the high-North Seas covering a period of three decades of the 20th and the 21st centuries and the RCP4.5 and RCP8.5 emission scenarios [12, 13]. In this work, future changes in wave climate for the high-North Seas were evaluated for the EC-EARTH GCM simulation against the hindcast period 1971 – 2000, and end-of-century 2071 – 2100.

2.3. Bias correction of wave projections

GCM and RCM outputs exhibit varying levels of systematic errors or biases when compared with observations or hindcast data — caused by inter alia, simplified physics and discretization, coarse spatial resolution, and internal variability [14, 15] — which can be inherited in downscaling processes i.e., when using wind surface fields to force wave numerical models. To correct such biases, this work used the EQM-Month technique which consists of applying the traditional Empirical Quantile Mapping technique (also known as Distribution Mapping or Probability Mapping) to correct the distribution function of the GCM-RCM projections to agree with the hindcast distribution as,

$$X* = F^{-1}_{hind}\ F_{RCM_{hist}}(X)\ , \qquad (1)$$

where $X*$ is the bias-adjusted value of the raw GCM-RCM variable X, and F_{hind} and $F_{RCM_{hist}}$ are the empirical distribution functions of the hindcast data and GCM-RCM, respectively, during the baseline period. The EQM method is applied to the data grouped by month, therefore obtaining twelve different groups to be corrected, to account for the temporal variability of wave climate [16, 17].

2.4. Sea state three wave climate

The World Meteorological Organization (WMO) has developed a standardized system for describing the state of the sea, known as the WMO Sea State Code. WMO Sea State Three (SS-3) is characterized by waves with heights of up to 1.25 metres with a wave period of around 8 seconds. At this level, the sea is considered to be moderate, with small to moderate waves and some whitecaps or foam streaks visible on the surface.
This study presents:

- Mean value of H_s above SS-3, by season and month.
- Percentage of sea states above SS-3, by season and month.

3. Results

Figure 1 presents the seasonal[3] results of the mean significant wave height (left) and percentage of sea states (right) above SS-3 for the hindcast period 1985 – 2005. The highest values are obtained for winter in the Western Mediterranean with mean H_s up to approximately 2.7 metres and approximately 60% of the sea states being above 1.25 metres. The lowest mean H_s

---

[3] Meteorological seasons have been used: winter December, January, and February; spring March, April, and May; summer June, July, and August; and, fall September, October and November.

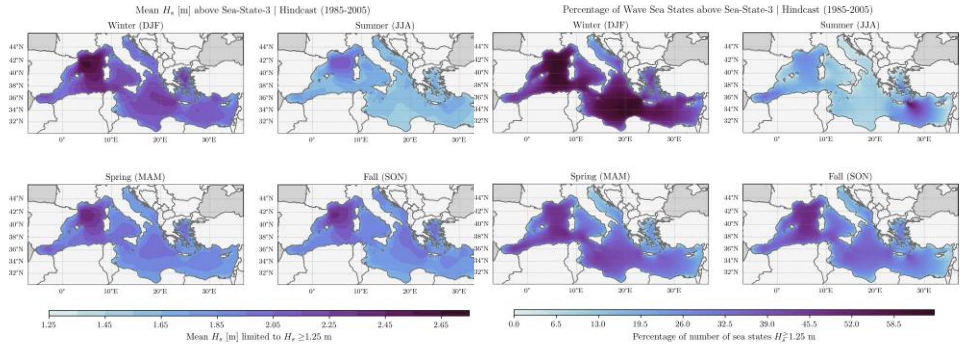


Figure 1. Mean *Hs* values (left) and Percentage of sea states (right) for *Hs* sea states over the SS-3 threshold in the Mediterranean Sea, per season, for the hindcast period 1985 – 2005.

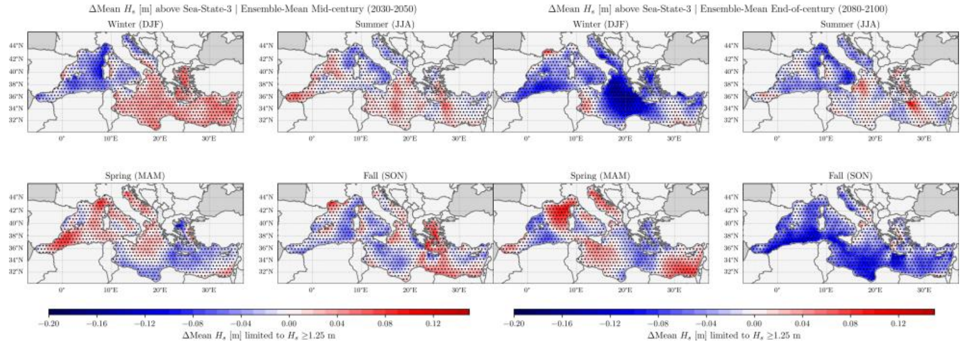


Figure 2. Seasonal difference in the mean values of *Hs* over SS-3 between the hindcast and the ensemble mean for mid-century (left, 2030 – 2050) and end-of-century (right, 2080 – 2100).

values are obtained for summer for the southern part of the basin where about 10% of the sea states are above SS-3.

Figure 2 presents the future changes of $H_s > H_s^{SS-3}$, per season, between the ensemble mean and the hindcast (1985 – 2005), for mid-century (left, 2030 – 2050) and end-of-century (right, 2080 – 2100). The stippling indicates 'large change with model agreement', i.e., the multi-model ensemble mean is large compared with internal variability (greater than two standard deviations) and at least two of the three GCM-RCMs agree on the sign of change. End-of- century conditions present robust decreases of -0.2 metres for the Central Mediterranean during winter and the overall basin during fall, whereas robust increases of 0.13 metres are obtained in the Western Mediterranean, Ligurian Sea and Eastern Mediterranean during spring. The projected changes present a higher spatial variability for mid-century conditions, where a robust increase of approximately 0.08 metres in the Central and Eastern Mediterranean is highlighted.

Figure 3 presents the future changes of the percentage of sea states above SS-3, per season, between the ensemble mean and the hindcast for mid-century (left) and end-of-century. It can be highlighted that the Adriatic Sea presents changes classified as small changes with model agreement, i.e. the ensemble mean of the future projections is small with respect to the internal variability present in GCM-RCMs simulations. With respect to future changes, the Balearic and Ligurian seas present a robust increase of 3 – 6% for spring for both mid- and end-of-century conditions with the highest increases forecast for mid-century. A robust increase is also noticeable for summer and fall in the Aegean Sea for both periods. A robust decrease is observed for fall in the rest of the basin with the largest decreases of up to -12%.

For the high-North Seas, Figure 4 presents the monthly results of the mean values of H_s above SS-3 for the hindcast period 1971 – 2000, and Figure 5 presents the future changes between the EC-EARTH and the hindcast for end-of-century (2071 — 2100). The highest hindcast values are obtained for December-March with values of up to 6.6 metres and

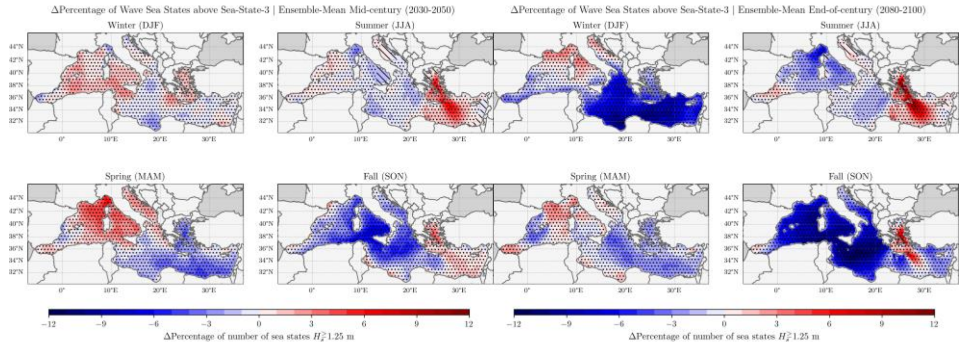


Figure 3. Seasonal difference in the percentage of sea states where the significant wave heights exceeds SS-3 between the multi-model ensemble (ensemble mean) for mid-century (left, 2030 – 2050) and end-of-century (right, 2080 – 2100).

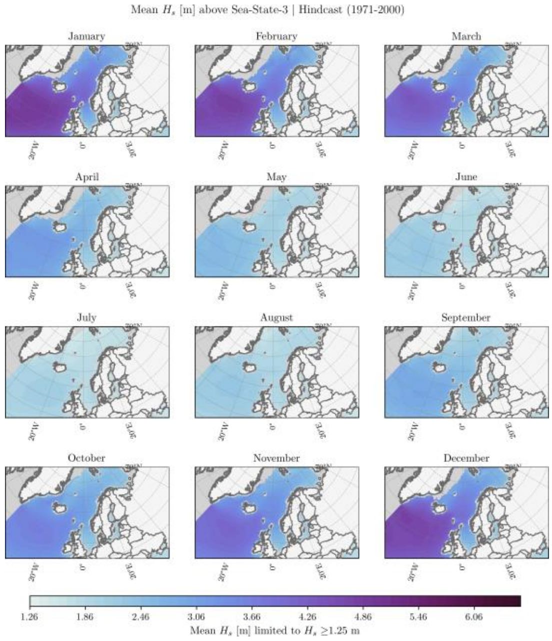


Figure 4. Mean *Hs* over SS-3 threshold in the high-North Seas, per month, for the period 1971 – 2000.

the lowest values are obtained from May to August with mean H_s under 1.85 metres. It is noted that the southern part of the studied area presents consistent mean values of H_s over 4 metres for the winter months. Future changes (Figure 5) for the period 2071 – 2100 indicate a decrease of -0.8 metres for December – March in this region, and decreases of -0.4 metres for April, May, September, and November. For the summer months (June, July, August), decreases of -0.2 metres are indicated. The north-western region shows increases of up to 1.0 metres in the global projection, which could be attributed to a lower sea ice extent and therefore a larger fetch, although this conclusion should be taken with caution as CMIP5 models fail to represent sea ice cover accurately [18].

Figure 6 presents the monthly results of the percentage of sea states above SS-3 for the period 1971 – 2000. Figure 7 presents the future changes of the percentage of sea states above SS-3, per month, between EC-EARTH and the hindcast for the end-of-century period (2071 – 2100). All months show more than 80% of sea states above SS-3 in the southern part of the region and over 30% for all months in the northern part of the region. For the southern part of the region, noticeable future changes (Figure 7) are present for May – September with decreases ranging from -8% (May, June, July and September)

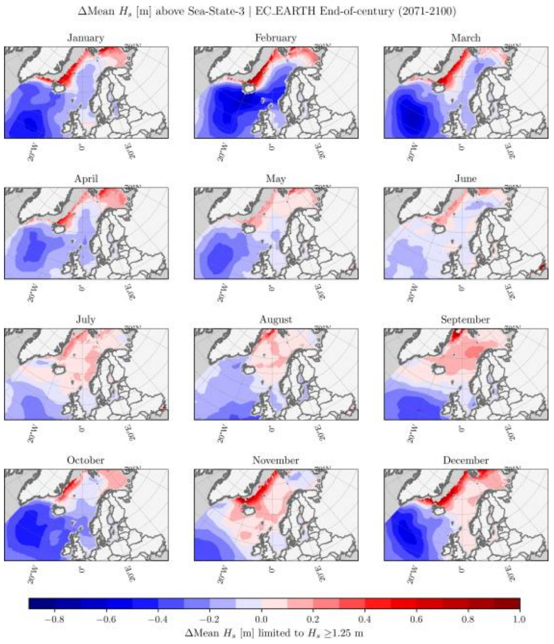


Figure 5. Monthly difference in mean *Hs* over SS-3 between EC-EARTH for end-of-century (2071 - 2100) and hindcast.

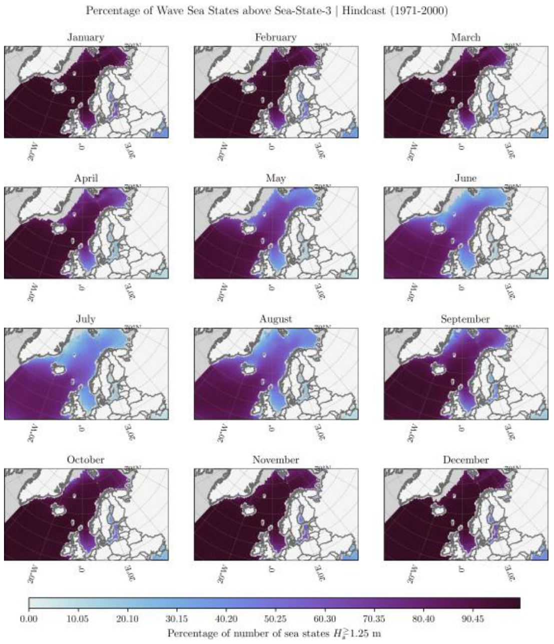


Figure 6. Percentage of sea states where *Hs* exceeds SS-3 threshold in the high-North Seas, per month, for the hindcast period 1971 – 2000.

up to -24% in August. Conversely, the northern part of the high-North Seas region indicates increases of up to 40% for July in the north-west and 25% in the remainder.

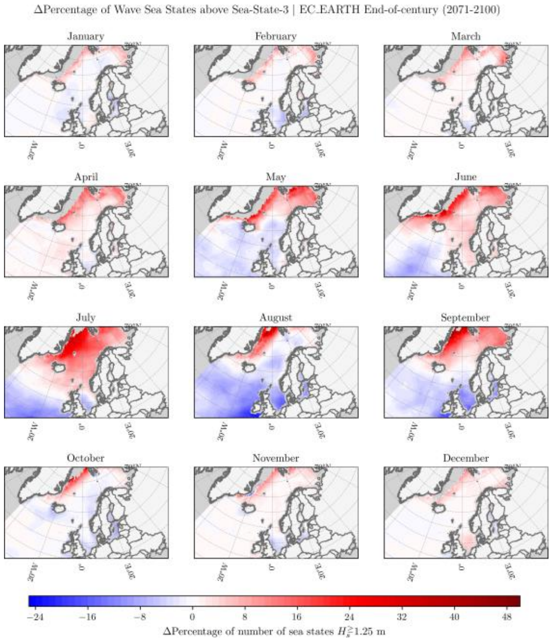


Figure 7. Monthly difference in the percentage of sea states where Hs exceeds the SS-3 threshold between EC-EARTH for end-of-century (2071 – 2100) and hindcast.

4. Acknowledgments

A.L.L. and G.B. acknowledge the CINECA ISCRA-C IsC87-UNDERSEA, IsC87-FUWAMEBI, IsCa2-COCORITE and IsCa2-EXWAMED projects for the computing resources to perform the GCM-RCMs wave projections for the Mediterranean Sea. This study has been partially funded by the NATO Office of the Chief Scientist through its Programme on Climate Change and Security Challenges

References

[1] The WAVEWATCH III ® Development Group, User manual and documentation WAVEWATCH III ® V6.07. Technical Report, 2019

[2] Mentaschi, L et al. (2013). Developing and validating a forecast/hindcast system for the Mediterranean Sea. *Journal of Coastal Research, 65*, 1551-1556.

[3] Mentaschi, L et al. (2015). Performance evaluation of Wavewatch III in the Mediterranean Sea. *Ocean Modelling 90*, 82-94

[4] Jacob, D. et al. (2014). EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change, 14*, 563-578

[5] Jacob, D. et al. (2020). Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. *Regional environmental change, 20*, 1-20

[6] Lira Loarca, A. et al. (2021). Projected wave climate temporal variability due to climate change. *Stochastic Environmental Research and Risk Assessment*

[7] Lira Loarca, A., et al. (2021). Future wind and wave energy resources and exploitability in the Mediterranean Sea by 2100. *Applied Energy, 302,* 117492

[8] De Leo, F., Besio, G., & Mentaschi, L. (2021). Trends and variability of ocean waves under rcp8.5 emission scenario in the Mediterranean Sea. *Ocean Dynamics*, 97-117

[9] Lira Loarca, A., & Besio, G. (2022). Future changes and seasonal variability of the directional wave spectra in the Mediterranean Sea for the 21st century. *Environmental Research Letters, 17*, 104015

[10] Lira Loarca, A., & Besio, G. (2022). Future changes in extreme waves and their seasonality in the Mediterranean Sea. In *Proceedings of the International Conference in Coastal Engineering*, Sydney, Australia

[11] Collins, M. et al. (2013). *Long-term Climate Change: Projections, Commitments and Irreversibility*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029–1136

[12] Aarnes, O. J. et al. (2017). Projected changes in significant wave height toward the end of the 21st century: Northeast Atlantic. *Journal of Geophysical Research: Oceans, 122,* 3394-3403

[13] Aarnes, O. J., & Furevik, B. R. (2023). Regional wam with cmip5 forcing. *Norwegian meteorological institute*

[14] Christensen, J. H. et al. (2008). On the need for bias correction of regional climate change projections of temperature and precipitation. *Geophysical Research Letters, 35*

[15] Teutschbein, C. & Seibert, J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology, 456-457,* 12-29

[16] Lira Loarca, A., Baquerizo, A., & Besio, G. (2022). Assessment of temporal-bias correction methods for wave climate projections in the Mediterranean Sea. In *Proceedings of the Ocean Sciences Meeting 2022*

[17] Lira Loarca, A. et al. (2023). On the role of wave climate temporal variability in bias correction of gcm-rcm wave simulations. *Climate Dynamics*, 1-28

[18] Shen, Z., et al. (2021). Assessment and ranking of climate models in arctic sea ice cover simulation: From cmip5 to cmip6. *Journal of Climate, 34,* 3609-3627

Security of Mediterranean coastal areas under future inundation scenarios

Sergio CAPPUCCI[a] and Adriana CARILLO[a] and Roberto IACONO[a] and Lorenzo MORETTI[a] and Massimiliano PALMA[a] and Alessandro PELOSO[a] and Gaia RIGHINI[a] and Gianmaria SANNINO[a,1]

[a] *ENEA, Department for Sustainability*

ORCiD ID: Sergio CAPPUCCI https://orcid.org/0000-0002-8864-1421, Adriana CARILLO https://orcid.org/0000-0003-4955-3047, Roberto IACONO https://orcid.org/0000-0002-5463-2033, Lorenzo MORETTI https://orcid.org/0000-0002-9998-5369, Massimiliano PALMA https://orcid.org/0000-0002-9125-166X, Alessandro PELOSO https://orcid.org/0000-0002-7541-8044, Gaia RIGHINI https://orcid.org/0000-0002-9466-9615, Gianmaria SANNINO https://orcid.org/0000-0002-3985-9432

Abstract. Sea-level rise, together with human activities, may induce significant coastline modifications that need to be assessed and analysed, to evaluate the future risks of inundation in coastal areas, and the impacts on local infrastructure. In this work, we present an integrated, GIS-based approach to examining this problem that relies on state-of-the-art numerical projections of future sea level in the Mediterranean area, for specific emission scenarios, and on the extrapolation of present trends of vertical ground motion obtained from the Copernicus European Ground Motion Service (EGMS). The approach is applied to five coastal areas hosting important Italian harbours, namely Brindisi, Napoli, La Spezia, Taranto, and Cagliari. Main outcomes of this study are coastal flooding maps at different time horizons. In creating these maps, sea-level rise information from the numerical simulations has been transported to the coast using the "*bathtub*" approach, without considering the effects of the local morphology on the inundation process, which is something to be refined in future implementations. The main assets exposed to flooding risk are low elevation wetlands, and backshore areas, together with coastal infrastructures. The high degree of subsidence of infrastructures during the first years after construction may significantly contribute to the risk of flooding. In these cases, however, predictions based on present EGMS data, with a limited time-span, should be considered with caution. Further investigation of the geotechnical interactions involved, together with the constant update of the Copernicus database, will be of help in making the related projections more reliable.

Keywords. Coastal vulnerability, sea level rise, numerical projections, flooding risk, GIS, EGMS

---

[1] Corresponding Author: Gianmaria Sannino, gianmaria.sannino@enea.it.

1. Introduction

To evaluate future inundation risks in coastal areas and the related impacts on local infrastructure, it is necessary to assess carefully the coastline modifications that may be induced by sea level rise (SLR) and by human activities.

In this study, a detailed projection of future sea level for the Mediterranean basin realized at the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) was used to assess future flood vulnerability of some Italian coastal areas. The projection was realized with a new, high-resolution three-dimensional model of the Mediterranean Sea circulation (MED16) that resolves very accurately the complex dynamics taking place in the Gibraltar Strait, which determine significant differences between the Mediterranean SLR and the global one. The high horizontal resolution of the model (7x7 km) allows capturing of spatial variations of the SLR along the coasts of the basin. Details of the numerical implementation, including an accurate validation against available observations, are described in [1].

Coastal geomorphology is strongly influenced both by SLR and ground motion due to geological factors such as tectonics, volcanic activities, sediment input, subsidence, etc. (see, e.g., [2]). Variability of some of these factors, such as subsidence, can also be influenced by human activities, and can occur on rapid time scales (e.g., [3]). In fact, there are areas in which subsidence is happening more rapidly than SLR and its impact is not fully appreciated at global scale.[2] In this work, the most advanced satellite-derived product for characterizing the coastal environment, provided by the Copernicus European Ground Motion Service (EGMS), has been used to evaluate the contribution of these factors to the flooding risk.

We have chosen the coastal areas of Brindisi, Napoli, La Spezia, Taranto, and Cagliari as representative case studies, since they host important Italian ports and are characterized by remarkable environmental and economic value. Using open-source software, a GIS-based tool has been developed, which is capable of combining the local SLR and EGMS vertical motion, so to obtain a reliable understanding of the coastal evolution in these areas. For the reference years 2040 and 2099, the main results presented in this paper are maps that highlight flooded portions in the coastal areas considered. The maps were obtained by using the “bathtub” approach, that is, without considering the morphological effects during the inundation process [4]. So, the flooded areas are exemplified by raised water levels on a coastal digital terrain model (DTM) that changes its elevation through time as a function of ground motion trends.

2. Input data for the GIS system

2.1 Topography

We employ a high-resolution DTM in the WGS84 - EPSG:4326 geographic projection, obtained through the National Geoportal Webgis, which has been used by many authors in the last decade (see, e.g., [5], and references therein). Data used to build the DTM were collected during a 2010 light detection and ranging (lidar) survey at 2 metres of resolution that covered the first- and second-order river courses (hierarchical order given in the river catalogue by the “Istituto Geografico Militare”) of the entire Italian territory. For the Cagliari area, a 1-metre resolution DTM was used, derived from a Lidar survey on the coastal zone and inland urban centres owned by the Regional Administration of Sardinia.

2.2 MED16 ocean model

The ocean model used in this study, named MED16, has been recently developed at ENEA. MED16 is a new implementation of the global circulation model by the

---

[2] https://climate.nasa.gov/news/2487/big-coastal-cities-sink-faster-than-seas-rise/

Massachusetts Institute of Technology (MITgcm model, [6]) that covers the Mediterranean-Black Sea system and is suitable for climatic integrations. The computational grid has 100 vertical levels and a horizontal spatial resolution of about 7 km. The horizontal detail is further increased at the Gibraltar and Turkish Straits, which are characterized by complex bathymetry and dynamics.

We have performed three simulations: a hindcast simulation (1980–2010), which was needed to verify that the model correctly reproduces the past climate variability; a historical simulation (1981-2005), which provides the initial condition for the scenario simulation; and, a future climate simulation under the RCP8.5 scenario (2006-2099).

Forcing for the three simulations derives from regional high-resolution (about 12.5 km) downscaling made with the SMHI-RCA4 atmospheric model [7], constrained by the ERA-Interim reanalysis [8] (hindcast), by the CMIP5 HadGEM2-ES global model [9] (historical), and by the CMIP5 HadGEM2-ES RCP8.5 (scenario).

Analysis of the hindcast fields has shown that the model results compare favourably with in situ and satellite observations. A first description of the future climate simulation, with particular focus of the projected SLR, together with further details about the implementation can be found in [1]. Maps illustrating the projected SLR, at different time horizons, are shown in **Figure 1**.

2.3. Ground motion

In November 2022, the Copernicus Programme released its last service, the EGMS (https://land.copernicus.eu/pan-european/european-ground-motion-service, [10] [11]). This service is based on the multi-temporal interferometric analysis of Sentinel-1 radar images at full resolution and provides values of the ground motion velocity and of the horizontal deformation on reliable measurement points, i.e., buildings, artificial structures, and non-vegetated areas. EGMS allows the user to investigate ground motion with unprecedented accuracy, over spatial scales that range from that of a nation, or a city, to that of a single infrastructure. Both maps and time series are provided; the latter allow for the computation of vertical velocity trends in the regions of interest, expressed in mm/year. The present dataset, which will be updated with yearly frequency, covers the period January 2016 - December 2020, with a time step of one data item every 12 days until October 2016 and one data item every six days from October 2016 to December 2020, thus collecting almost 250 records over a period of five years with a horizontal resolution of 100 metres. EGMS offers three different map products; here we use the highest-resolution one (L3).

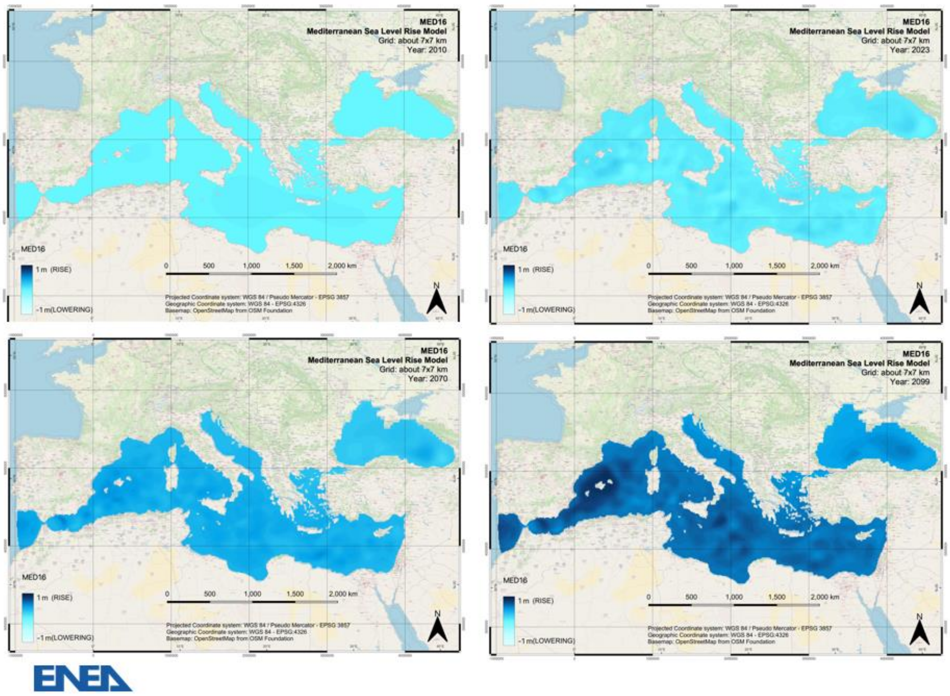


Figure 1. Mediterranean SLR from the MED16 scenario simulation: years 2010, 2023, 2070, 2099.

3. Methodology

Estimates of the future sea level in the study areas have been obtained by combining the sea-level variations predicted by MED16 with projections of the vertical ground motion based on the available EGMS data. The MED16 sea level has been spatially averaged in the study regions, and translated to the coastal area using a simple “bathtub” approach. As for the ground motion, EGMS provides average velocities of vertical displacement for each pixel (100 m x 100 m), averaged over the five-year dataset (2016 – 2020) now available. We found that these average velocities are not uniform along the coastal areas of our study, and consequently decided to use the full available resolution, without performing spatial averages. The present rates of displacement have then been assumed to remain constant during the timespan of the scenario. Of course, this is a limitation of the analysis, because future geological events could modify such rates. However, since the dataset will be constantly updated, uncertainty will eventually reduce in time.

The EGMS displacements and the MED16 sea level data are spread on the high-resolution DTM to obtain the overall yearly movement from 2010 to 2099. The area of interest is extended 10 Km inland from the coastline. A GIS procedure has been implemented using the open-source software QGIS vers. 3.22 with customized plugins. All the input data were managed in a GIS project and tailored to the UTM WGS84 projection according to the Italian Zones 32N and 33N. Using the graphic modeller available in QGIS, a specific and flexible tool was implemented that collects the input data, allows for their processing and produces inundation maps for the areas of interest; a schematic illustration of the procedure is given in **Figure 2**. Using the GIS procedure, we have computed the maximum extension of inundated areas during the periods 2010 – 2040 and 2040 – 2099.

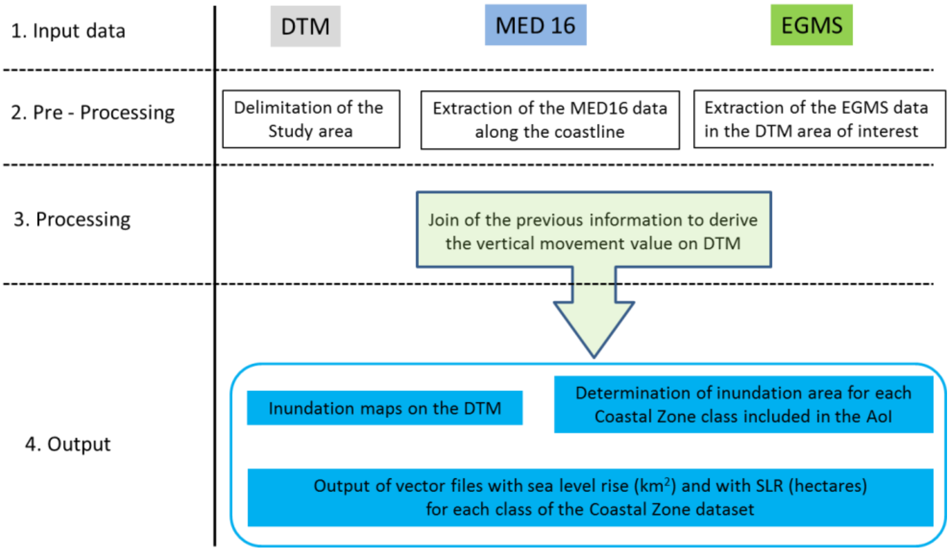


Figure 2. Sea Level Rise – input data, steps of the analysis tool, and output files in the graphic representation of the GIS tool. The tool can be automatized to produce the outputs for the whole period 2010 – 2099 according to customized temporal series, i.e., each year or every five or ten years.

4. Results & Discussions

The main result of the present study is the identification of the submerged area within each of the five coastal sites, at different time horizons. The surface extensions of the inundated areas are reported in **Table 1**.

Table 1. Area (Km^2) beneath sea level in different years.

Sites	Km^2 under SL (2010)	Km^2 under SL (2040)	Km^2 under SL (2099)
Brindisi	0,637	0,764	1,616
Cagliari	2,382	4,849	12,995
La Spezia	0,172	0,227	0,502
Napoli	0,336	0,433	0,693
Taranto	0,883	1,249	2,073

Zooms of the inundation maps for the periods 2010 – 2040 and 2040 – 2099 in the Taranto and Cagliari study sites are shown in **Figure 3**. **Figure 4** presents maps for La Spezia and Brindisi, for the period 2040 – 2099, together with zooms highlighting the areas that are mainly affected by the flooding (areas that in the future will be at a lower elevation compared to the mean sea level; in blue).

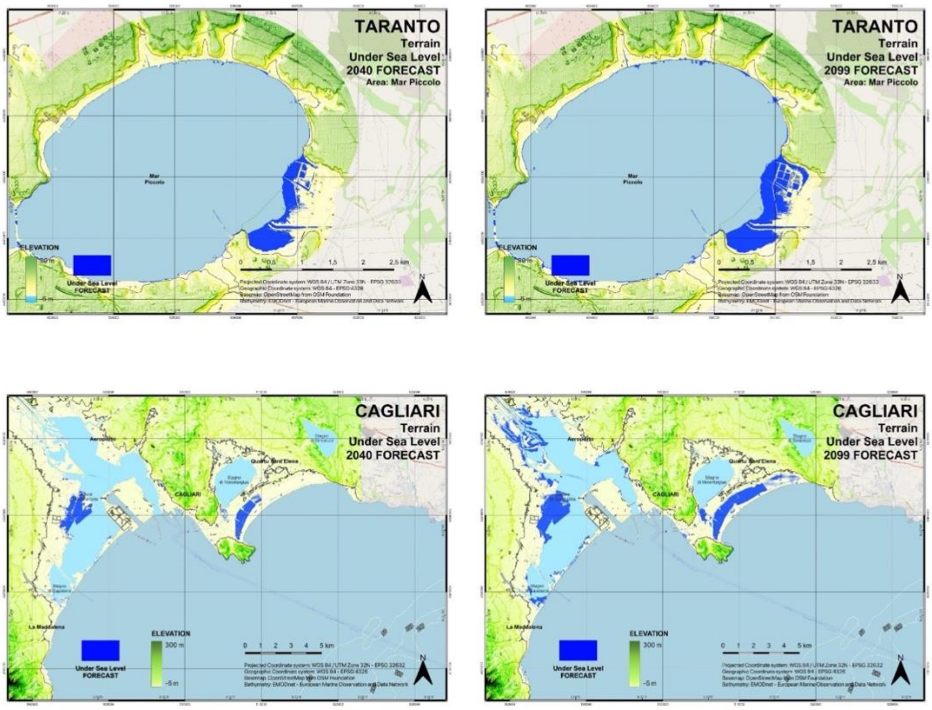
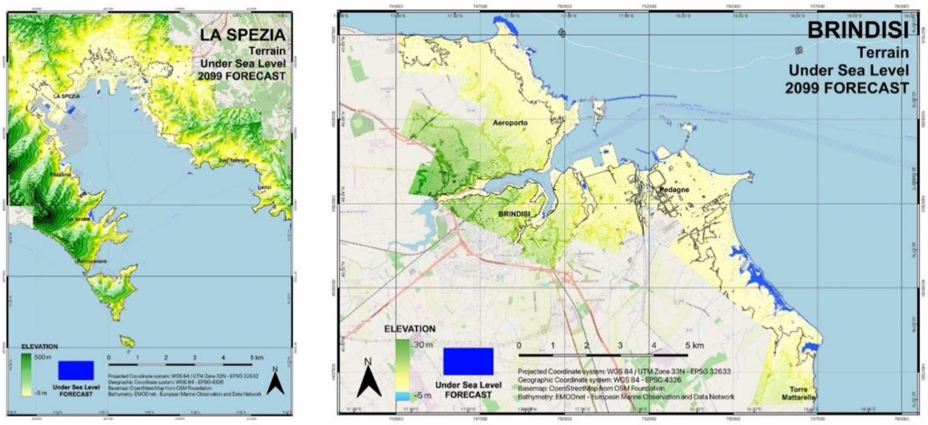


Figure 3. Taranto and Cagliari study sites; inundation maps for the periods 2010 – 2040 and 2040 – 2099.

The quantitative analysis conducted in the present study has shown that the impact of relative SLR is not particularly evident along rocky or heavily infrastructure/urbanized coastlines such as those of Naples (not shown). The impact is more evident in the other coastal areas, as illustrated in **Figure 3** and **Figure 4**.



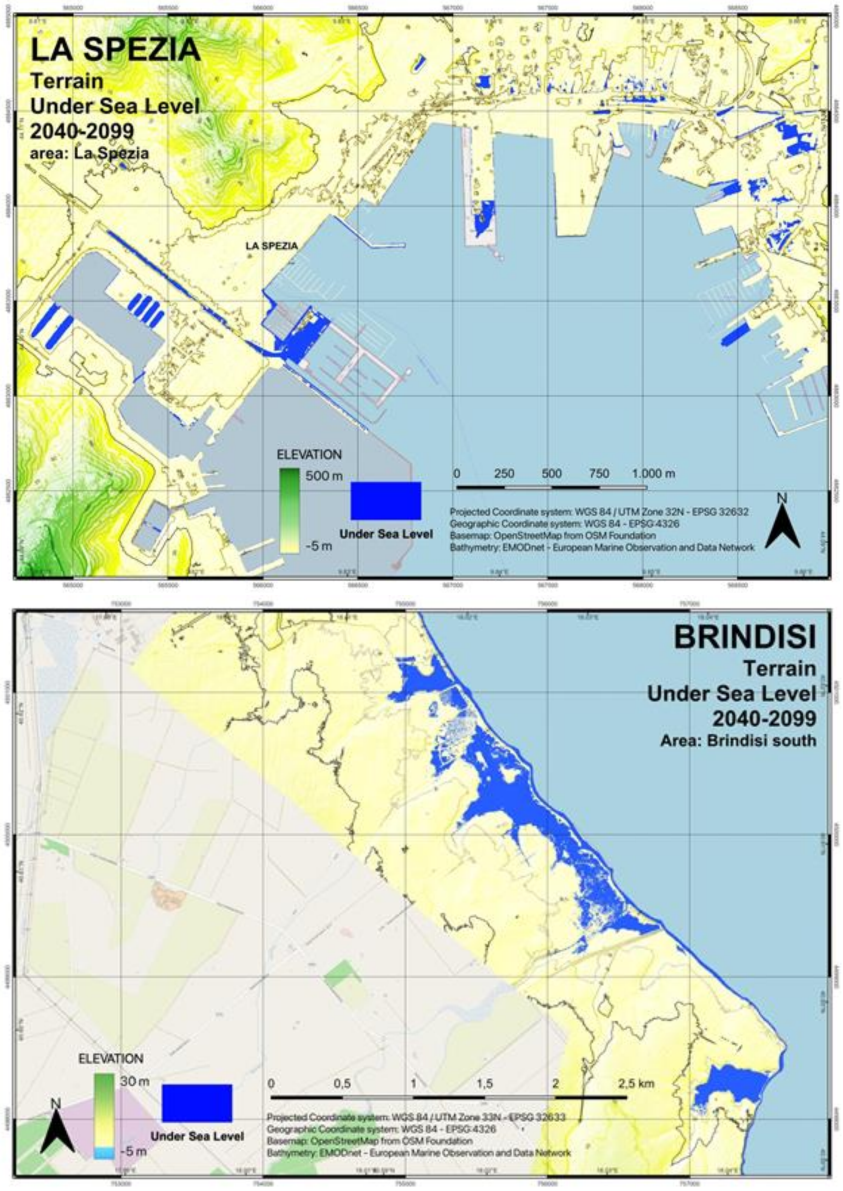


Figure 4. La Spezia and Brindisi study sites (top); zooms of inundation maps for the period 2040 – 2099 that highlight the effects on port infrastructures (middle; Confined Disposal Facilities in La Spezia) and on backshore (bottom; Brindisi).

The main assets exposed to the risk of flooding are:

1. Wetlands. They include habitats of naturalistic value that are located around the Mar Piccolo in Taranto and the Santa Gilla lagoon of Cagliari. In these areas, the contribution of subsidence is significant due to the characteristics of coastal deposits (probably formed by intercalation of sand and silty/clay lenses).
2. Backshore areas. For example, the coastal Plain behind Cagliari's Poetto beach. In this area, the drainage network between the sea and the Molentargius Pond (Quartu Sant’Elena) contributes to the inundation of the coastal zone.
3. Maritime infrastructures. Several piers of the port of Brindisi and some Confined Disposal Facilities (CDFs), recently built within the gulf of La Spezia, are particularly exposed to sinking due to overloading. However, the response of sediment compaction to loading is not a linear process and this means that the present EGMS vertical rate of motion could overestimate the real one in the future.

The risk of flooding for backshore areas and wetlands is readily predictable because it is related to the low elevation of these coastal environments. Even small variations of sea level may have a relevant flooding impact in these areas [12] [13]. For maritime infrastructures, the risk of flooding is increased by the high degree of sinking into the seabed and/or the high degree of subsidence of infrastructures during the first years after construction. In this case, of course, constant maintenance and adaptation of the infrastructures can mitigate the rate of sinking, but in recent years many studies highlighted that this phenomenon is not adequately considered.

Both the SLR and the ground motion components used in this study have limitations. As for the SLR, more scenarios should be considered. Moreover, it is not possible to evaluate the projection's uncertainty by means of a single model simulation. This issue is widely debated in the scientific community nowadays and a possible solution could be to realize ensemble simulations, which are, however, computationally very expensive. The main limitation concerning the ground motion component is associated with the short duration of the present dataset. This will be partially relieved in the future thanks to expected periodic updates of the dataset. Having longer time series available will help in understanding where it is reasonable to extrapolate present rates into the future.

It is also clear that EGMS provides an integrated estimate of all geological contributions to ground motion without discriminating the effect of the single components. In the future, we will further investigate some of these components, acquiring and analysing field data to assess better the reliability of extrapolating present EGMS values into future decades.

References

[1] Sannino, G. et al. (2022). Modelling present and future climate in the Mediterranean Sea: a focus on sea-level change. *Climate Dynamics*, *59*, 357–391, https://doi.org/10.1007/s00382-021-06132-w

[2] Cappucci, S. et al. (2020). Assesment of the anthropogenic sediment budget of a littoral cell system (Northern Tuscany, Italy). *Water*, *12*(11), 3240

[3] Allison, M. et al. (2016). Global Risks and Research Priorities for Coastal Subsidence. *Eos*, *97*. https://doi.org/10.1029/2016EO055013

[4] Gesch, D. B. (2018). Best Practices for Elevation-Based Assessments of Sea- Level Rise and Coastal Flooding Exposure, Front. *Earth Sci*., *6*. https://doi.org/10.3389/feart.2018.00230

[5] Cappucci, S. et al. (2017). Detection of natural and anthropic features on small islands. *Journal of Coastal Research*, *77*, 74-88. https://doi.org/10.2112/SI77-008.1

[6] Marshall, J. et al. (1997). Hydrostatic, quasi- hydrostatic, and nonhydrostatic ocean modelling. J *Geophys Res*, *102*, 5733-5752

[7] Strandberg, G. et al. (2014). CORDEX scenarios for Europe from the Rossby Centre regional climate model RCA4. *Report Meteorology and Climatology*, *116*, 84 pp

[8] Dee, D. et al.: (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*, 553-597. https://doi.org/10.1002/qj.828

[9] W.J. Collins, W. J. et al. (2011). Development and evaluation of an Earth-System model—HadGEM2. *Geoscientiphic Model Development*, *4*, 1051-1075

[10] Costantini, M. et al. (2021). European Ground Motion Service (EGMS). *2021 IEEE International Geoscience and Remote Sensing Symposium*. Brussels, Belgium, 3293-3296

[11] Crosetto, M. et al. (2020). The Evolution of Wide-Area DInSAR. From Regional and National Services to the European Ground Motion Service. *Remote Sensing*, *12*, 2043. https://doi.org/10.3390/rs12122043

[12] Acciarri, A. et al. (2021). Metrics for short-term coastal characterization, protection and planning decisions of Sentina Natural Reserve, Italy. *Ocean Coast*. *Manag*., *201*, 105472

[13] Taramelli, A. Et al. (2021). Assessment of State Transition Dynamics of Coastal Wetlands in Northern Venice Lagoon, Italy. *Sustainability*, *13*(8), 4102. https://doi.org/10.3390/su13084102

Nature-based infrastructure for coastal flooding and erosion: a dual-impact technology?

Giovanni FUSINA[a,1], Enda MURPHY[b] and Jeffrey KING[c]
[a] *Defence Research and Development Canada*
[b] *National Research Council of Canada*
[c] *United States Army Corps of Engineers*

Abstract. “Nature-based infrastructure” technology provides coastal flood and erosion risk management benefits by using natural or built assets that rely on, or mimic, natural system processes and features. This technology has been widely applied in international settings to reduce coastal flood and erosion risk. It tends to incur lower costs, offer greater flexibility, and has greater capacity to adjust to changing environmental conditions than conventional shore protection solutions such as concrete seawalls. In this paper, we present general guiding principles of nature-based infrastructure to reduce coastal flood and erosion risk, and details of an applied research project, which studied the performance of nature-based infrastructure for managing coastal flood and erosion risk in Canadian settings. Finally, we discuss how the United States Army Corps of Engineers’ Engineering With Nature® Initiative is pursuing opportunities for use of nature-based infrastructure to reduce risk of military coastal assets, clearly showing the “dual-impact” of this technology.

Keywords. Nature-based solutions, nature-based infrastructure, coastal erosion, coastal flooding risk reduction, coastal assets, dual-impact technology

1. Introduction

Coastal flooding and erosion driven by the combined effects of high tides, storm surges, high waves and tsunamis are damaging and costly natural hazards for communities in many world nations [1][2][3][4]. For many civilian communities and military installations on the coast, the risks associated with flooding and erosion are expected to increase over the coming decades due to urbanization, rising sea levels, declining sea ice cover, and shifting weather patterns associated with climate change [3][4].

For many communities, purely structural solutions such as concrete seawalls are no longer preferred options due to the potential drawbacks associated with “hard” coastal structures when broadly deployed without adequate consideration to natural processes or system responses. Drawbacks associated with widespread armoring or hardening of coastlines may include: coastal squeeze [5], loss of habitat [6], restricted water access, high capital and life-cycle costs, high carbon footprint, and limited adaptability to changing conditions. New, more sustainable solutions are needed to help communities manage and adapt to the increasing flood and erosion threats caused by climate change — solutions that deliver additional benefits to the environment, and society: “Nature-based solutions” is such a

---

[1] Corresponding Author: Giovanni Fusina, giovanni.fusina@forces.gc.ca.

technology. The United States Federal Emergency Management Agency (FEMA) defines *nature-based solutions (NbS)* as: "*…sustainable planning, design, environmental management, and engineering practices that weave natural features or processes into the built environment to build more resilient communities*" [7]; and the International Union for Conservation of Nature (IUCN) Global Standard defines them as "…*actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature*"[8].

Nature-based infrastructure (NbI) for coastal flood and erosion risk management is a form of nature-based solution, consisting of natural or built assets that rely on, or mimic, natural system processes and features (e.g., beaches, wetlands, reefs, islands, headlands, etc.) to provide coastal flood and erosion risk management [9], while delivering additional environmental and other societal benefits. NbI spans a continuum of human intervention, from "green" or wholly natural systems, to hybrid or "green-grey" systems that combine hard (structural) and natural infrastructure elements [9][10]. NbI has been widely applied in international settings to reduce coastal flood and erosion risk [9] [11] and often incurs higher benefit-cost ratios, offers greater flexibility, and provides more capacity to adjust to a changing environment than purely structural solutions such as concrete seawalls [12]. NbS are receiving growing international acceptance and uptake, and there has been an explosion of research and activity in this field within the past few decades. For example, the United States Army Corps of Engineers (USACE) led the development of the International Guidelines on Natural and Nature-Based Features (NNBF) for Flood Risk Management (FRM), which included contributions from two-hundred practitioners in ten countries [11]. NNBF are broadly synonymous with NbI (and NbS), considering the shared emphases on conserving, restoring, and leveraging the benefits of natural systems to achieve societal and environmental objectives.

It is important to note that NbS can be used to manage natural hazard risk beyond coastal erosion and flooding: storm-water (pluvial) flooding, fluvial flooding, wildfire, wind, extreme heat, drought are hazards for which NbS can be applied. Indeed, the provision of multiple benefits is an inherent advantage of NbS. There is considerable work being pursued within Canada and the United States to advance use of NbS while also quantifying their performance and associated benefits. For example, USACE's Engineering With Nature® (EWN®) initiative continues to pursue applied research and deliver NbS to reduce risks from the aforementioned hazards [8] [11]. Similarly, the National Research Council of Canada's Ocean, Coastal, and River Engineering Centre (NRC-OCRE) and Defence R&D Canada's Centre for Security Science (DRDC-CSS) led a collaborative applied research project (2019-2023) on the performance of NbI for managing coastal flood and erosion risk specifically for the Canadian context [13][14].

The purpose of this paper is to describe the principles of NbI for coastal flood and erosion risk management, and work to advance knowledge, tools and guidance to inform wider deployment of coastal NbI through the NRC-OCRE/DRDC-CSS project in Canada. Further, this paper aims to explore the possibilities surrounding the "dual-impact" (civilian/military) use of this technology for the purpose of protecting NATO maritime infrastructure against coastal flooding and erosion hazards influenced by climate change. Examples of NbS applied by USACE at different coastal military installations to increase resilience to coastal flooding hazards are discussed [15].

2. Overview of Coastal Nature-based Infrastructure Principles, Guidance and Tools

Common examples of interventionist NbS approaches to manage risks associated with coastal erosion, coastal flooding and sea level rise are the restoration, construction, or enhancement of: beaches and dune systems; wetlands and tidal flats (including horizontal levees or living dykes[2]); reef systems; islands; and, submerged aquatic plant systems and kelp beds.[16]

Very simply put, all these approaches aim to provide buffer zones between communities (and infrastructure or valued assets) and the sea, providing storage for flood waters, attenuating the waves and storm surges that drive coastal erosion and flooding, attracting and stabilizing sediments, attracting stabilizing flora and fauna, and serving as adaptive barriers to erosion and sea-level rise.

Challenges associated with the design of NbI include predicting the response and resilience of these dynamic features to changes and disturbances within coastal systems, particularly extreme (storm) events, and quantifying flood and erosion risk management benefits (e.g. wave attenuation or reduced flood extents). Predicting performance is complicated by the complex interactions and feedbacks between built infrastructure, physical processes, biology, water chemistry and other components of the system; demonstrating a requirement to engage multidisciplinary teams. For example, the health and vigour of wetland vegetation — and thus its capacity to perform coastal protection and wave attenuation functions — depends on hydrodynamic conditions, water quality, sediment transport processes, elevation, species distribution and maturity [1], and seasonality (among other factors). Fortunately, technical guidance for design and implementation of NbI exist, coupled with a large body of knowledge gathered from successful NbI implementations (see **Sections 2.1 and 2.2**).

Figure 1 below shows a NbI shore protection scheme on a beach in front of a section of an important highway in the Canadian province of Prince Edward Island (PEI) [9]. In 2016, storm-driven erosion threatened the coastal highway, prompting the development of a NbI solution. The NbI is a hybrid system, consisting of a combination of dune restoration and constructed intertidal reef features, which attenuate waves, and promote sediment deposition on the beach, protecting the highway. The artificial reefs were built using sandstone boulders, which are analogous to the rocky outcrops prevalent on the PEI coast, and provide natural habitat for marine organisms. The small dune was strengthened and restored, using fences to trap windblown sand, and by planting stabilizing vegetation. Construction was completed in March 2018 and post-construction surveys indicated that the NbI performed well during storm events in November 2018 and September 2019 (post-tropical storm Dorian).

Figure 1. NbI for coastal erosion in PEI [9]. Photo credit: M. Davies, Coldwater Consulting Ltd.

In addition to FRM, NbI brings a number of “co-benefits” (or “ecosystem services”) [11] — which cannot be under-stated — and can be broadly categorized as environmental, societal, and economic. Environmental co-benefits include the establishment of habitats for fish (and other) species, climate change mitigation through carbon storage and sequestration; societal benefits include human health and recreation value, and water quality and sediment management; economic co-benefits are created with revenue streams linked to navigation, commerce, fishing, and tourism which result from the environmental and societal benefits.

---

[2] A horizontal levee (or living dyke) consists of a conventional flood protection levee or dyke structure fronted by a gradual ecotone slope (often vegetated) on the seaward side providing natural habitat and flood/erosion risk management benefits [11].

2.1. International Guidelines on Natural and Nature-Based Features for Flood Risk Management

The USACE-led "International Guidelines on Natural and Nature-Based Features for Flood Risk Management" (NNBF for FRM) provide a comprehensive, rational approach to the classification, evaluation, planning, design, operation, management (including repairing and upgrading), and construction of NNBF for coastal and riverine shoreline erosion, coastal and fluvial flooding, and flood risk mitigation [11]. The guiding principles can be summarized as:

- *Using a systems approach:* this means considering all relevant physical, biological, and social processes and their interactions in the area of interest in order to reduce conflict and maximize synergies to produce sustainable solutions.
- *Engaging communities, stakeholders, partners and multidisciplinary team members:* this entails early, broad and professional engagement to meaningfully involve those who may be impacted by a project in decision-making, and convening multidisciplinary teams to work together in innovative, creative, and collaborative ways.
- *Identifying solutions that produce multiple benefits:* this entails identifying multipurpose solutions that provide both sustainability and resilience. These may include combinations of: nature-based features that mimic natural system functions (e.g., constructed wetlands or horizontal levees); natural systems and features that are preserved, restored or enhanced (e.g. wetland, island or reef restoration) to manage coastal flood and erosion hazard impacts; structural engineering (breakwaters, seawalls, and levees or dykes); and, non-structural measures (communication and education that convey information about protecting life and property, enhanced building codes, and established evacuation routes).
- *Anticipating and managing risk*: this entails understanding that there is a level of risk associated every flood and erosion risk management project which must be managed. Risk averse mindsets can be barriers to innovative solutions involving NNBF.
- *Managing expected changes adaptively:* natural coastal systems and the global climate are highly dynamic. In a deeply uncertain future, the adaptability of NbS is an inherent advantage [18], but changes must be anticipated and managed.

2.2. Tools and resources for implementation of NbI

There is a diverse and growing body of tools and resources available to potential proponents of NbI projects, which can help to support the development of innovative, robust solutions, and ensure project success. A non-exhaustive list of examples is given below, demonstrations of which are provided in **Section 3** of this paper.

- *Technical guidance:* The International Guidelines on NNBF for FRM, other guidelines, and the extensive scientific literature on successful NbI implementations (as well as lessons learned from past failures) provide a comprehensive body of knowledge and useful starting points for project proponents. Examples of NBS Guidance, which have been produced by many diverse organizations can be found on the EWN® website [19].
- *Engagement workshops:* Depending on specific goals and audiences, workshops can play a useful role in engagement. Workshops can provide the basis for generating alternatives and solutions, and to connect stakeholders or rights holders with NbI experts. Workshops can also provide a venue for interaction and collaboration within multidisciplinary teams. Stakeholders or rights holders can also provide valuable input to NbI design by sharing local (or traditional) knowledge[3] about the coastal region.

---

[3] By "local knowledge" is meant the written or unwritten understanding of a community's environment that was gained through generational experience.

- *Field monitoring and measurements:* Monitoring baseline conditions and changes in the system are essential for scoping and planning of NbI projects, assessing performance, and informing maintenance and adaptive management. Field measurements can also be used to support the development and calibration or validation of predictive models or design tools.
- *Models:* Models with varying degrees of complexity can be used to study system behaviours across spatio-temporal scales, assess the performance of NbI under extreme conditions or potential future scenarios, and guide design and adaptive management of NbI projects. Examples include:
    - *Numerical models:* Properly validated/calibrated computational models may be employed to simulate system processes, and interactions with NbI at multiple scales. For example, global and regional models may be used to characterize meteorological and oceanographic climate conditions and extreme events at ocean basin scales. Higher resolution models may be used to evaluate nearshore processes, interactions with and performance of NbI features, and coastal flooding and erosion at coastal reach or community scales. Ultra-high-fidelity models, for example relying on computational fluid dynamics techniques, may be applied to study fine-scale processes or details of NbI components affecting performance, often in combination with paired field or laboratory experiments. Increasingly, integrated, multiscale modelling methods are being employed to leverage fully the advantages of different models across the full gamut of spatio-temporal scales [20][21] and to simulate complex system dynamics.
    - *Physical models:* Laboratory experiments that replicate coastal system behaviours or NbI components in controlled settings (e.g., wave flumes or wave basins) can aid the design process, by enabling testing, optimization or validation of solutions. They can also provide insight to the mechanisms by which NbI elements deliver flood and erosion risk management benefits, thus informing design and implementation.

3. The Canadian Safety and Security Program's "Nature-Based Infrastructure for Coastal Resilience and Risk Reduction" Project

NbS are now widely accepted around the world, as exemplified by the numerous case-studies in the USACE's NNBF for FRM guidelines. However, NbS remain underutilized in Canada for coastal flood and erosion risk management, in part due to knowledge gaps surrounding the performance of NbI in the diverse geographies, climates and socio-economic contexts of Canada's coastal regions. [9] This was the main motivation for NRC-OCRE to collaborate with the DRDC-CSS through the Canadian Safety and Security Program[4] to launch a research project (entitled "Nature-based Infrastructure for Coastal Resilience and Risk Reduction") to begin to address gaps for NbI implementation in Canada's coastal regions, bringing together a multidisciplinary, multi-institutional group of collaborators across various levels of government, academia, private/non-profit sector and communities. The project launched in 2020 and will end in 2023. Nature-based solutions are a key focus area within the Coastal Resilience theme of NRC-OCRE's Ocean Program [22], which targets more sustainable management of Canada's ocean resources by 2027. Towards achieving commitments of Canada's National Adaptation Strategy [23], NRC-OCRE recently launched a multiyear research initiative aimed at mainstreaming and

---

[4] The Canadian Safety and Security Program (CSSP) supports federal, provincial, territorial, municipal and Indigenous governments in the development of innovative science and technology advancements that contribute to the safety and security of Canadians. Projects funded by CSSP strengthen Canada's ability to anticipate, prevent, mitigate, prepare for, respond to, and recover from natural disasters, serious accidents, crime and terrorism through the convergence of science and technology (S&T) with policy, operations, and intelligence. It is led by DRDC-CSS in partnership with Public Safety Canada.

scaling up coastal NbI applications, founded on three pillars: (1) continuing collaborative research on NbI pilot projects in diverse Canadian coastal settings; (2) targeted studies to address specific or generic design challenges for coastal NbI; and (3) continual advancement, review, updating and dissemination of design guidance.

This project has informed specific considerations for Canadian coastal communities where implementation of NbI was (or will be) sought, including: the required volumes and geometries of constructed cobble beaches (i.e., dynamic revetments) to achieve acceptable reshaping under storm wave action; species-specific roles and behaviours of wetland vegetation native to Canada; wave attenuation performance of immature (newly planted) salt marshes and mature marshes in mega-tidal environments; the efficacy of innovative marsh edge treatments and stabilization measures for a living dyke; and, the cumulative impacts of multiple managed dyke realignment and marsh restoration projects on regional circulation and water levels. It has also advanced the NbI knowledge base and tools to support their implementation, generating insight to the suitability of different numerical models for predicting NbI performance, and identifying methods for downscaling and use of vegetation surrogates in physical models. The applied research was conducted in collaboration with community partners (including municipal governments and First Nations) to ensure complementarity and synergy with community planning, design and monitoring activities, and to benefit from local knowledge (including First Nations' oral histories and traditional knowledge).

Three locations were the foci of the research for this project:

- A remote northern British Columbia (BC) site — studies conducted on a hybrid shore protection scheme (combining "grey" and natural features) at a remote First Nation community, the first phase of which had been constructed in 2019;
- An urban southern BC site — the location of three planned pilots of a "Living Dyke" concept, developed by local municipal and First Nations communities. Construction began in April 2023; and,
- Chignecto Isthmus, a critical transportation corridor linking Nova Scotia and New Brunswick. Critical infrastructure, several communities, and agricultural land on this low-lying strip of land are partially protected from coastal flooding by an extensive system of legacy dykes (levees), which are aging and vulnerable to the effects of relative sea-level rise. Despite local implementation of several managed dyke realignment[5] and marsh restoration projects, the potential for vegetated foreshore marshes and managed dyke realignment to support flood risk reduction on a larger scale is largely unexplored.

In keeping with the NNBF for FRM guidelines, the project engaged a multidisciplinary team, which undertook coordinated research activities studying the NbI being adopted (or considered) at the three locations mentioned above. This "living laboratories" approach involved: community workshops and engagement; field monitoring; numerical modelling; and, laboratory experiments (physical modelling). Findings and lessons learned from these activities informed the development of new Canadian guidelines for coastal NbI (**Section 3.5**).

3.1. Community Workshops and Engagement

As part of the project, different engagement workshops were conducted. These served to connect community members to technical specialists within the project team, and the project team to stakeholders, rights holders and interested or affected groups. In this way, the different aspects of NbI and the benefits it could bring to communities were highlighted, the project team researchers were exposed to the perspectives of coastal communities adapting to climate change, and research activities were tailored to reflect community values and practitioner needs. Workshops also provided a national forum for engagement, collaboration, critical discourse, and knowledge-sharing to advance coastal

---

[5] Managed dyke realignment involves the purposeful breaching, removal or landward relocation of an existing coastal protection structure, such as a dyke (levee), to restore tidal influence and support restoration of intertidal habitat. [24]

NbI research and practice in Canada. The events brought together multidisciplinary groups of practitioners, researchers, engineers, natural and social scientists, academics, planners, government and Indigenous representatives from across Canada and the United States to network and share insights and build a community of practice [13],[14].

3.2. Field Monitoring

Multiyear field monitoring campaigns at the three NbI pilot sites (e.g., **Figure 2**) have resulted in the generation of large quantities of data, which have been used to optimize design of the Living Dyke pilots, as well as the development, calibration and validation of physical (experimental) and numerical models to predict the performance of different types of nature-based solutions at the northern BC site and the Chignecto Isthmus. Community members participated in field monitoring activities, contributing their understanding of local conditions to the field program, and availing of technical training. Synthesis and analyses of the field data has provided useful insights to guide future NbI implementation, for example by quantifying the influence of vegetation height and marsh morphology on wave attenuation by salt marshes in macro-tidal environments, and characterizing wave transformation in diverse environments ranging from wide, intertidal mudflats to steep, rocky inlets.

Figure 2. Natural Resources Canada researchers aboard a Canadian Coastguard hovercraft, deploying pressure sensors near the southern BC site (left, photo credit: Gwyn Lintern) [25]; pressure sensor from an array installed by Saint Mary's University across intertidal salt marshes at Chignecto Isthmus (right, photo credit: Danika van Proosdij) [14].

3.3. Numerical and Physical Modelling

Numerical models of waves and hydrodynamics for the southern BC site were developed and calibrated using field data, and used to inform the Living Dyke pilots [26].

Numerical wave and morphodynamic models for evaluating the performance of the northern BC site's nature-based shore protection scheme were developed and calibrated using field data (wave measurements and sediment samples), and experimental data derived from a three-dimensional 1:20 scale physical model constructed in NRC-OCRE's Large Area Basin in Ottawa (**Figure 3**).

Figure 3. Three-dimensional 1:20 scale physical model of the northern BC site's shore protection scheme at NRC-OCRE's Large Area Basin in Ottawa.

A numerical model of Cumberland Basin and the coastal floodplain on Chignecto Isthmus was developed and used to assess flood extents under relative sea-level rise scenarios, and to assess the potential impacts of managed dyke realignment and marsh restoration on flood extents and circulation (**Figure 4**).

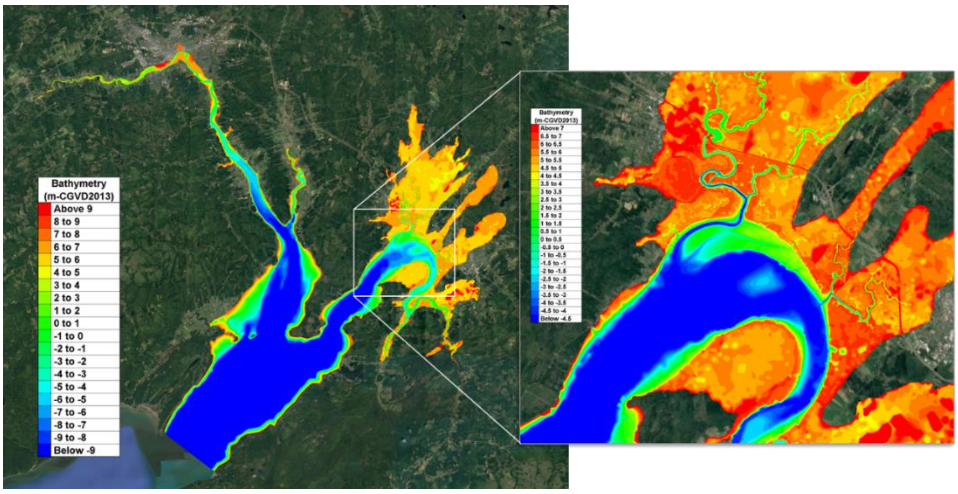


Figure 4. Chignecto Isthmus hydrodynamic model topography-bathymetry.[27]

3.4. Laboratory Experiments

Experimental studies (e.g., **Figure 5**) have provided: new insights to wave-vegetation interaction — including species-specific behaviours of plants native to Atlantic Canada,[28] wave attenuation by immature or newly-planted marshes,[1] and integration of vegetation with dykes in nature-based solutions;[29] design of dynamic revetments (cobble beaches [30]); design of innovative edge treatments for constructed marsh platforms as part of a living dyke; and, techniques for downscaling vegetation in laboratories using surrogates to guide nature-based solutions design.

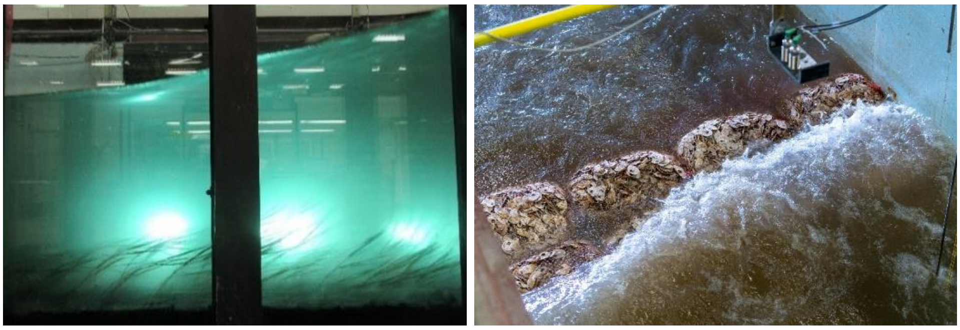


Figure 5. Experimental investigation of wave attenuation by immature salt marsh vegetation (left [1]) and performance of marsh edge protection comprising biodegradable oyster shell-filled mesh bags (right [31]) at NRC-OCRE laboratories in Ottawa, Canada.

3.5. The Canadian Coastal NbI Design Guide

The key project deliverable, a national design guide for coastal nature-based infrastructure, is in the final stages of development. Approximately 60 project partners, experts and practitioners of nature-based solutions from across Canada, as well as several international partners (US Army Corps of Engineers' Engineering With Nature program, and the US National Oceanic and Atmospheric Administration (NOAA)), have contributed to the development of the design guide. Copy-editing is currently underway.

4. The Dual-Impact of Nature-based Solutions

Dual-impact (or "dual-use") technology is defined as technology that is focused on commercial markets and uses for public benefit but may also have defence and security applications.

USACE's 2021 publication entitled: "Engineering With Nature: Supporting Mission Resilience and Infrastructure Value at Department of Defense Installations" [13] describes plans and implementation of NbS at six different military installation across the US. Of these, four specifically target coastal erosion and flooding: namely, the Marine Corps' Camp Lejeune in North Carolina, MacDill Air Force Base in Florida, the US Army's Aberdeen Proving Ground in Maryland, and Naval Base Ventura County in California. These installations are all very important for US Department of Defense (DoD) operations and training. They employ several thousand people, both civilian and military, and are an integral part of the local economies. The NbI solutions planned and implemented at these sites will support continuity of the respective military missions, while simultaneously providing co-benefits to the military and civilian communities within and around the installations.

We highlight a couple of examples from [13]. **Figure 6** below illustrates some examples of the implementation strategies of NbI in controlling coastal erosion at the MacDill United States Air Force (USAF) base: vegetation planting (left) and reef building (left, centre and right). Reef building can also result in the establishment of vegetation without actual planting (centre and right).

Figure 6. McDill, USAF base. Left to right: restored shoreline through the use of a nearshore oyster reef and vegetative plantings; installation of reef-building materials in the nearshore waters parallel to the shoreline resulted in the return of a highly productive and more resilient shoreline; erosion controlled with a dense vegetative buffer which resulted from the installation of a man-made oyster reef. Photo credit: Jason Kirkpatrick [13].

In **Figure 7** (left) MacDill's southeastern corner is depicted from 2008: a nearshore oyster reef resulting in the later establishment of salt marsh and mangrove habitat stabilized the shoreline. In **Figure 7** (right), a dense smooth cordgrass is shown, which was established behind a fabricated oyster reef to stabilize a long-eroding shoreline: previously this area was just bare sand.

Figure 7. MacDill USAF base implementation of NbI. Photo credit: Tampa Bay Watch (left) and Jason Kirkpatrick (right). [13]

Figure 8 below shows the impacts of a NbI project "Vision" for Naval Base Ventura County in California. It consists of defending critical structures on the Base which need to stay in place and moving other non-critical ones to higher ground. These steps will be done in conjunction with the restoration and enhancement of NbI that include beaches, dunes, estuarine and salt marsh habitats located inside and outside 'the fence line' of the navy base. This mosaic approach to pursuing three action categories (i.e., defend, relocate, and remove) represents a comprehensive method for achieving resilience at this installation.

The principles and methodologies used by USACE to manage the risks of coastal erosion and flooding hazards at the different DoD installations are modelled on those described in **Section 2.1**. Communities (both the military and civilian) were engaged, solutions were identified, the predicted risks and changes will be adaptively managed.

These examples clearly illustrate that the "dual-impact" nature of NbI is already a reality.

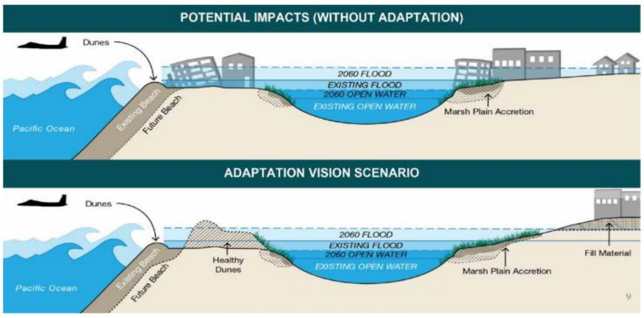


Figure 8. Illustration of potential impacts to a NbI adaptation scenario for Naval Base Ventura County. (Image by Environmental Science Associates) [13]

At present, the USACE's EWN® program is collaboratively working with the US DoD Department of the Navy, Department of the Army, and Department of the Air Force at more than 15 installations across the US to identify opportunities for integrating NbS into installation landscapes. Results of those studies will be made available in 'NbS handbooks' with an anticipated publication date of early spring 2024.

5. Conclusions and Future Work

This paper has described at a high level the foundational concepts and principles underlying the application of NNBF/NbS/NbI for coastal FRM, and provides specific examples of work to advance knowledge, tools and resources to support wider implementation in Canada and the United States. The potential "dual-impact" of this technology was also described through concrete examples of NbS deployed at different US DoD installations.

It is hoped that one of the outcomes of this present CC&S workshop is that NATO will begin to consider more widely adopting NbS as a strategy to protect its installations, in particular maritime infrastructure. Possible ways to do so include the establishment of a NATO Science and Technology Organization (STO) Systems Concepts and Integration (SCI) Panel "Exploratory Team" leading to a "Research Task Group", and/or a working group under the programme of work of the nascent Climate Change and Security Centre of Excellence (CCASCOE). The exploration of NbS for Arctic assets is also a crucial application "use-case" that should be explored.

6. Acknowledgments

We would like to thank the following organizations which made the research on NbI in Canada possible, namely, Indigenous Services Canada, Natural Resources Canada-Geological Survey of Canada, Crown-Indigenous Relations & Northern Affairs Canada, City of Surrey, Metlakatla First Nation, Semiahmoo First Nation, First Nations Emergency Planning Secretariat, TransCoastal Adaptations Centre for Nature-based Solutions at Saint Mary's University, University of Ottawa, Queen's University, Institut national de la recherche scientifique (INRS). Additional funding for the NbI research described in this paper was provided by NRC's Climate Resilient Built Environment Initiative, in support of delivering the Government of Canada's Adaptation Action Plan, and towards achieving commitments under the National Adaptation Strategy.

References

[1] Ebru, K. et al. (2020). Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Scientific reports*, 10 (1): 11629

[2] Tiggeloven, T. et al. (2007). Global-scale benefit–cost analysis of coastal flood adaptation to different flood risk drivers using structural measures. *Natural Hazards and Earth System Sciences*, 20(4), 1025-1044

[3] Hallegatte, S. et al. (2013). Future flood losses in major coastal cities. *Nat. Clim. Change,* 3, 802–806

[4] Hinkel, J. et al. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proc. Natl Acad. Sci. USA*, 111, (2014) 3292-3297

[5] Pontee, N. (2013). Defining coastal squeeze: A discussion. *Ocean & coastal management*, 84, 204-207

[6] Bulleri, F., & Chapman, M.G. (2010). The introduction of coastal infrastructure as a driver of change in marine environments. *Journal of Applied Ecology*, 47(1), 26-35.

[7] United States Federal Emergency Management Agency. (2014). *Building community resilience with nature-based solutions – a guide for local communities*, https://www.fema.gov/sites/default/files/documents/fema_riskmap-nature-based-solutions-guide_2021.pdf

[8] International Union for the Conservation of Nature. (2020). *IUCN Global Standard for Nature-based Solutions - A user-friendly framework for the verification, design and scaling up of NbS, first edition,* https://portals.iucn.org/library/sites/library/files/documents/2020-020-En.pdf

[9] Vouk, I. et al. (2021). Nature-Based Solutions for Coastal and Riverine Flood and Erosion Risk Management. *Canadian Standards Association*

[10] Bridges, T.S. et al. (2015). Use of natural and nature-based features (NNBF) for coastal resilience. *US Army Engineer Research and Development Center*, *Environmental Laboratory*, Coastal and Hydraulics Laboratory

[11] Bridges, T.S. et al. (2021). *International Guidelines on Natural and Nature-Based Features for Flood Risk Management.* U.S. Army Engineer Research and Development Center

[12] Moudrak, B. et al. (2018). *Combating Canada's Rising Flood Costs: Natural infrastructure is an underutilized option. Prepared for Insurance Bureau of Canada. Intact Centre on Climate Adaptation*, University of Waterloo

[13] Murphy, E. et al. (2022). *Applied research to inform Canadian design guidance for nature-based coastal infrastructure.* Climate-Resilient Coastal Nature-based Infrastructure Workshop, Halifax

[14] Van Proosdij, D. et al. (2022). Collaborative living laboratories to inform Canadian design guidance for coastal nature-based solutions, in: *Proceedings of the 37th International Conference on Coastal Engineering (ICCE2022)*, Sydney, Australia

[15] Bridges, T.S. et al. (2021). Engineering With Nature: Supporting Mission Resilience and Infrastructure Value at Department of Defense Installations. *ERDC* SR-21-9. Vicksburg, MS: U.S. Army Engineer Research and Development Center, http://dx.doi.org/10.21079/11681/42207

[16] Bridges, T.S. et al. (2022). Coastal natural and nature-based features: International guidelines for flood risk management. Frontiers in Built Environment 8(22): 904483

[17] Ghodoosipour, B. et al. (2022). *Experimental investigation of wave and current interactions with immature Spartina alterniflora salt marsh canopies, in: Proceedings of the 39th International Association for Hydro-Environmental Engineering and Research (IAHR) World Congress*

[18] Cado van der Lely, A. et al. (2021). Building with Nature: a future proof strategy for coping with a changing and uncertain world. *Ecoshape White Paper* https://www.ecoshape.org/app/uploads/sites/2/2021/01/S20.0022-Whitepaper-uncertainties-def.pdf

[19] United States Army Corps of Engineers, (2023). *Engineering With Nature®, Nature-Based Solutions Guidance*. https://ewn.erdc.dren.mil/nbs-guidance/

[20] Barnard, P.L. et al. (2014). Development of the Coastal Storm Modeling System (CoSMoS) for predicting the impact of storms on high-energy, active-margin coasts. *Natural Hazards* 74, 1095-1125

[21] Menéndez, P. et al. (2020). The global flood protection benefits of mangroves. *Nature Scientific Reports* 10(1), 1-11

[22] National Research Council of Canada. (2022). *Ocean program – Coastal resilience technology theme.* https://nrc.canada.ca/en/research-development/research-collaboration/programs/ocean-program-coastal-resilience-technology-theme

[23] Government of Canada (2023). *Canada's National Adaptation Strategy*. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/national-adaptation-strategy/full-strategy.html

[24] Wollenberg, J. T., Ollerhead, J., & Chmura, G.L. (2018). Rapid carbon accumulation following managed realignment on the Bay of Fundy. *Plos one* 13(3), e0193930.

[25] Côté, M. et al. (2023). *Field monitoring in support of nature-based infrastructure for coastal resilience & risk reduction.* Coastal Zone Canada 2023 conference

[26] Benoit, D. et al. (2023). Modeling storm surge and wave conditions for nature-based infrastructure in Boundary Bay, British Columbia. In: *Proceedings Coastal Sediments 2023 conference*

[27] Vouk, I. et al. (2022). *Numerical investigation of storm- and tide-driven flooding on the Chignecto Isthmus to assess nature-based solutions potential.* Climate-Resilient Coastal Nature-based Infrastructure Workshop 2022

[28] Markov, A. et al. (2023). Deformation of Spartina patens and Spartina alterniflora stems under wave action. *Coastal Engineering Journal,* 65 (2), 325-346. https://doi.org/10.1080/21664250.2023.2195030

[29] Baker, S. et al. (2022). Experimental study of wave attenuation across an artificial salt marsh. *Frontiers in Built Environment,* 8: 893664

[30] Sirianni, D. et al. (2022). Effect of gravel particle size on the reshaping of dynamic revetments, in: *Proceedings 37th International Conference on Coastal Engineering (ICCE2022)*

[31] Provan, M. et al. (2023). Experimental study of wave and sediment interactions with edge treatment features on a living dyke, in: *Proceedings Coastal Sediments 2023 conference*. https://doi.org/10.1142/9789811275135_0199

On the impact of climate change on sonar performance

Victor O. OPPENEER[a,1], Aniello RUSSO[b], Giacomo GIORLI[b], and Robbert VAN VOSSEN[a]
[a] *TNO, Acoustics and Sonar department*
[b] *NATO STO CMRE*
ORCiD ID: Victor O. OPPENEER https://orcid.org/0000-0003-0432-366X , Aniello RUSSO https://orcid.org/ 0000-0003-3651-8146, Giacomo GIORLI https://orcid.org/0000-0003-1230-4901, Robbert VAN VOSSEN https://orcid.org/0000-0003-3497-2839

Abstract. Climate change has a substantial effect on the environment. Consequently, it will also impact sensors that are deployed in these changing environments. This paper investigates the impact of climate change on sonar performance, and aims to identify both direct and indirect relationships. Changes in oceanography, including layering of the water column and modifications of sound ducts, evidently influence the propagation of sound. Furthermore, climate change will change the soundscape, which comprises: environmental noise — generated by wind, rain, waves, and sea ice; biological noise — generated by marine mammals; and anthropogenic noise. The last source needs to be considered, as climate change will change human economic activities. Knowledge whether climate change impacts sonar performance in areas of interest to NATO is important for the planning and execution of anti-submarine warfare operations, and can be used as an indicator of whether environmental knowledge needs to be strengthened to realize an effective capability.

Keywords. Climate change, sonar performance, acoustic environment, ambient sound, ASW

1. Introduction

Climate change has a significant impact on ocean acoustics through temperature changes in the water column altering the speed of sound, and a reduction of pH by dissolving CO_2. Furthermore, melting of ice results in large volumes of water with low salinity. Both factors have a substantial effect on layering of the water column. An example of how much the ocean surface temperature is changing, can be seen in **figure 1**, where in some areas the water surface temperature is 6 degrees higher than it was 40 years ago. Currently, there is insufficient knowledge on the impact on sonar performance in areas relevant to NATO.

---

[1] Corresponding Author: Victor O. Oppeneer, victor.oppeneer@tno.nl.

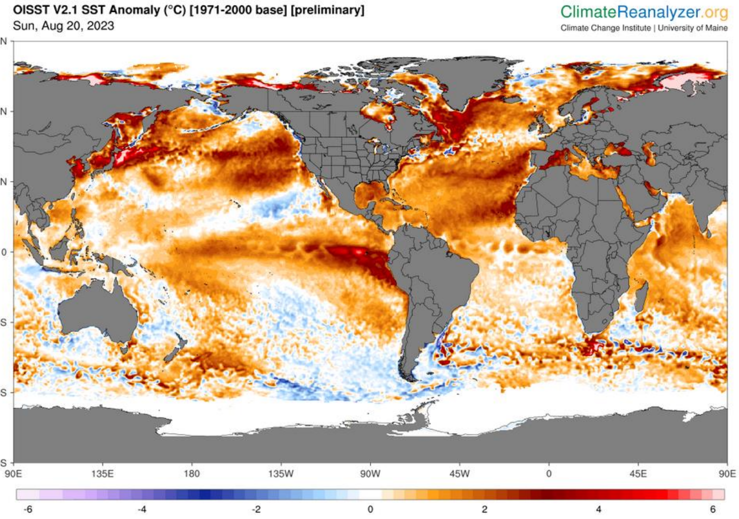


Figure 1. Difference between surface temperatures on August 20th 2023, vs average surface temperature 1971-2000 [1].

1.1. Objectives

A collaboration between the NATO Science and Technology Organization (STO) Centre for Maritime Research and Experimentation (CMRE) and the NLD Organization for Applied Scientific Research (TNO) has been set up to investigate how climate change can alter sonar performance, what is already known, and what still has to be investigated. Particularly, the focus is on the following objectives:

1. Impact of climate change on ambient noise properties;
2. Impact of climate change on propagation conditions / sonar performance;
3. In which areas of interest to NATO is sonar performance likely to be influenced by climate change; and,
4. Recommendations on usage and/or modifications of databases.

This paper presents the initial results of the collaboration, providing a qualitative analysis aiming to provide a better understanding on the impact of climate change on sonar performance.

1.2. Approach

Finding a direct relation between climate change and sonar performance is a complicated task. Therefore, we use both the active and passive sonar equation to decompose sonar performance into individual terms such as target signal/target echo, ambient noise, and reverberation. Subsequently, the impact of climate change on these individual components is analysed.

In chapter 2, the passive and active sonar equations are introduced. Chapter 3 subsequently provides an analysis in which the relationships between climate change and the individual terms of the sonar equations are explicitly identified. This is achieved by analysing the impact of climate change on the acoustic environment (directly), and indirectly by changes in human behaviour, resulting in changes in ocean acoustics, and consequently changes in signal strength, ambient noise, reverberation, and — ultimately — sonar performance.

2. The sonar equations

2.1. The Passive Sonar Equation

A method of acoustically detecting a submarine target is by listening for its radiated sound. The *probability of detection* of the target is related to the *false alarm rate* and the *signal-to-noise ratio* (SNR). In passive sonar, the SNR depends on the strength of the radiated sound in comparison to the ambient noise at a receiver — for example, a sonobuoy. The SNR can be computed as [2]:

$$SNR_{passive} = RSL - PL - NL + AG \tag{1}$$

Here, all the terms are in decibels (dB), with: RSL being the radiated sound level by the submarine; PL the propagation loss from the vessel to the receiver array; NL the ambient noise level; and, AG the array gain — the gain in SNR that comes from having a larger array than a single hydrophone.

Only the propagation loss PL and ambient noise NL will be influenced by climate change. The RSL and AG are dependent on the target submarine and the receiver array, respectively. Although future technology advances are expected to modify the values of these parameters, they themselves do not depend on climate change.

2.2. The Active Sonar Equation

To detect a submarine, active sonar uses a sound source to generate a sound signal in conjunction with a receiver array to detect reflected and scattered echoes . The SNR of a target can be determined by the active sonar equation [2], which is similar to the passive case:

$$SNR_{active} = SL - 2PL + TS - (NL \oplus RL) + AG \tag{2}$$

Again, all terms here are in dB, with: SL being the source level of the sonar source; PL the one-way propagation loss — and therefore $2PL$ the two-way propagation loss; TS the target strength — similar to a radar cross-section; NL the ambient noise level; RL the reverberation level — echoes from the environment, such as waves or rocks; and AG the array gain. $(NL \oplus RL)$ means the sum in linear pressure before conversion back to dBs.

In the active sonar case, only the propagation loss, ambient noise, and reverberation level, will be altered by climate change. The other terms are hardware related, and are not considered in this paper.

3. Relating Climate Change to Sonar Performance

Figure 2 shows causal relations between climate change and sonar performance. Climate change influences human behaviour — changing shipping lanes and regulations — and the acoustic environment, such as altering oceanographic characteristics. The *acoustic environment* is a description of all the environmental factors that influence *ocean acoustics*, where ocean acoustics comprises scattering of sound, sound propagation and ambient noise sources. Ocean acoustics influence sonar performance, which characterizes the performance of either passive or active sonar systems as the ability to discriminate between target signal and unwanted reverberation and measured ambient noise levels. **Figure 2** can be used to assist in determining if there are any gaps in knowledge. In

addition, it can help to understand how changes to the values of the parameters impact sonar performance.
In the next sub-sections, each group — such as the acoustic environment — will be described in more detail and how they are influenced by climate change explained, supported by examples from available literature.

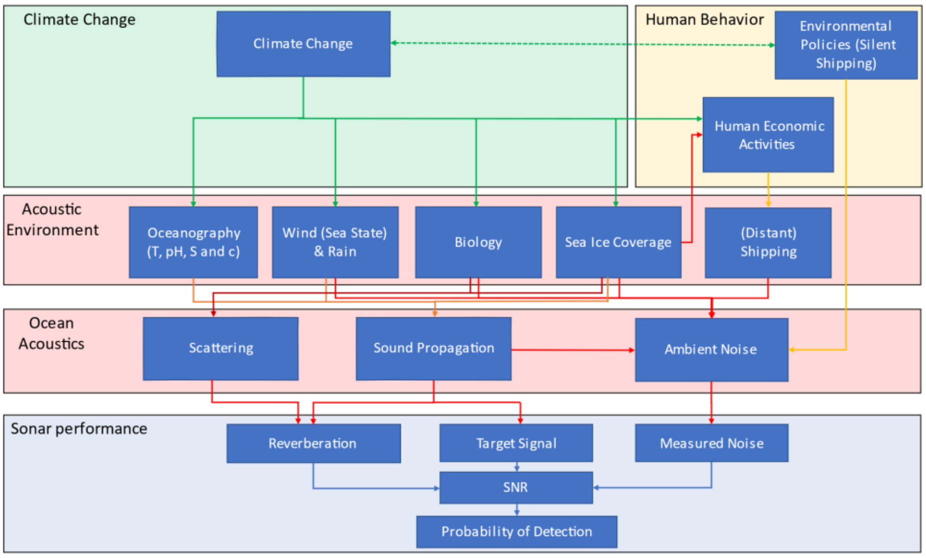


Figure 2. Block diagram relating sonar probability of detection to climate change effects. Each block defines a phenomenon, and the arrows indicate if one block is influenced by another block. The arrows only indicate the influence of one block to another, not its strength nor whether it is positive/negative.

3.1. Acoustic Environment and Human Behaviour

Climate change affects the acoustic environment by influencing:

- The oceanography, by changing the temperature and pH distribution in the water column. From the literature [3], it is known that climate change will increase the temperature of the ocean, most predominantly in the top layer to 400m, but also to a lesser extent at deeper depths. Over time, this means that the occurrence of a downward refracting sound speed profile will be more common. In addition, there will be regions around the Arctic and Antarctic where the melted sea ice would create regions with very low salinity [4], changing the sound speed profile.
- Wind and rain, by changing the occurrence of extreme weather. Although it is not clear if certain regions become more wet or dry [5], it is expected that the likelihood of extreme weather events will increase [6].
- The biological ecosystem in the oceans is expected to change due to rising temperatures and changing pH levels [7] [8].
- Sea-ice coverage is going to decrease [4].

Furthermore, the acoustic environment is influenced by human behaviour. It is estimated that the contribution of ocean shipping to the world gross domestic product is going to be double that of 2016 [9]. The locations of human economic activities may change, for example by shipping goods from China to Europe through Arctic ice-free routes during the summer months, which would increase the distant shipping ambient noise in those areas, and reduce it in the areas where the ships would have sailed if there were sea ice in the Arctic. In addition, international environmental policies are expected to reduce the radiated noise per ship [10], for example, based on strategies such as reducing vessel speed [11]. The combination of these two human behaviours will change the spatial distribution and intensity of ocean ambient noise levels caused by shipping.

3.2. Ocean Acoustics

Changes to the acoustic environment affect the ocean acoustics.
The scattering of sound at the air-water surface, at the ocean floor, and inside the water column is influenced by [12] [13]:

- Wind (Sea State)
- Sea-ice coverage
- Biology

Sound propagation is influenced by:

- Oceanography
- Wind and rain
- Sea-ice coverage

Ambient noise is the cumulative effect of:

- Wind and rain noise
- Breaking ice noise
- (Distant) shipping noise
- Biological noise

3.3. Sonar Performance

Sonar performance defined as the probability of detection of a target submarine is determined from the sonar SNR, both terms — signal and noise — of which are influenced by the changing ocean acoustics.
On the target signal side, performance changes mostly result from changes in propagation loss.
Depending on the type of sonar — passive, or active, noise is changed more drastically by ocean acoustics. For passive sonars, noise is mostly influenced by changes in (distant) shipping noise, which in turn is also modified by changes in sound propagation. For active sonars, reverberation is also affected by the changes in acoustic scattering mechanisms.
It is currently not known if SNRs for both active and passive sonars will increase or decrease because of climate change effects.

4. Conclusion and way ahead

This work presents the initial work done under a collaboration between CMRE and TNO. This paper discusses how sonar performance is (indirectly) linked to climate change. Using the lens of the passive and active sonar equations, some initial observations are made based on a review of the available literature. A block diagram relating sonar probability of detection to climate change effects is the first major result of this collaboration, and will be used to determine if and where there are gaps in our knowledge, thereby informing future research.
Future work will concentrate on the anti-submarine warfare operating areas relevant to NATO, investigating the likely extent of the changes in ambient noise and acoustic propagation caused by climate change, and determining if existing oceanographic databases need to be changed or updated.

5. Acknowledgments

This study has been partially funded by the Dutch Ministry of Defence, the NATO Office of the Chief Scientist through its Programme on Climate Change and Security Challenges, and the Richard Lounsbery Foundation, whose support is gratefully acknowledged.

References

[1] Climate Change Institute – University of Maine. *Climate Reanalyzer: Daily Sea Surface Temperature*. https://climatereanalyzer.org/clim/sst_daily/

[2] Abraham, D. A. (2019). *Underwater Acoustic Signal Processing*. Springer Nature Switzerland AG, Cham, NY

[3] Levistus, S. et al. (2012). World ocean heat content and thermosteric sea level change (0-2000 m), 1955-2010. *Geophysical research letters*, *39*, 1-5

[4] Chief of Naval Operations (2014). *The United States Navy Arctic Roadmap for 2014 to 2030*

[5] Intergovernmental Panel on Climate Change (IPCC) (2023). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157896

[6] Blanchard-Wrigglesworth, E. et al. (2023). The Largest Ever Recorded Heatwave – Characteristics and Attribution of the Antarctic Heatwave of March 2022. *Geophysical Research Letters*, *50* (17), 1-11

[7] Robinson, R. A. et al (2009). Travelling through a warming world: climate change and migratory species. *Inter-Research*, *7*, 87-99

[8] Duarte, C. M. et al. (2021). The soundscape of the Anthropocene ocean. *Science*, *371*, 6529

[9] Organisation for Economic Co-operation and Development (OECD) (2016). *The Ocean Economy in 2030*. OECD Publishing

[10] International Maritime Organization (2023). *Addressing underwater noise from ships - draft revised guidelines agreed*. https://www.imo.org/en/MediaCentre/Pages/WhatsNew-1818.aspx

[11] Findlay, C. R. et al. (2023). Small reductions in cargo vessel speed substantially reduce noise impacts to marine mammals. *Science advances*, *9* (25)

[12] Ainslie, M. A. (2011). Principles of Sonar Performance Modeling. *Springer-Verlag*. Berlin Heidelberg

[13] Jensen, F. B. (2011). *Computational Ocean Acoustics* (2nd edition). Springer, New York

Path-loss analysis in anomalous electromagnetic propagation conditions over oceans induced by climate change: Preliminary results

Alessio DI SIMONE[a,b,1], Cosimo Enrico CARNIEL[c], Walter FUSCALDO[b,d], Leonardo Maria MILLEFIORI[b], Paolo BRACA[b], Aniello RUSSO[b], Sandro CARNIEL[b] and Lakshmi KANTHA[e]
[a] *University of Naples Federico II, Naples, Italy*
[b] *NATO STO CMRE, La Spezia, Italy*
[c] *ETH Zurich, Zurich, Switzerland*
[d] *Consiglio Nazionale delle Ricerche – Istituto per la Microelettronica e Microsistemi, Rome, Italy*
[e] *University of Colorado, Boulder, Colorado, USA*
ORCiD ID: Alessio DI SIMONE https://orcid.org/0000-0003-1374-1871, Cosimo Enrico CARNIEL https://orcid.org/0000-0001-9902-3410, Walter FUSCALDO https://orcid.org/0000-0002-0773-6286, Leonardo Maria MILLEFIORI https://orcid.org/0000-0002-2242-0028, Paolo BRACA https://orcid.org/0000-0002-3762-4373, Aniello RUSSO https://orcid.org/0000-0003-3651-8146, Sandro CARNIEL https://orcid.org/0000-0001-8317-1603, Lakshmi KANTHA https://orcid.org/0000-0002-4968-7101

Abstract. Climate change (CC) is leading to unprecedented impact to the whole Earth ecosystem, including the oceans and atmosphere. In the last decade, some studies have analysed the impact of CC on underwater acoustic communication systems and, more recently, sonar, whereas very little work is devoted to the effects of CC on the performance of microwave technologies, such as radar and wireless communication systems. This work aims at filling this gap and address the potential impact of expected changes in atmospheric ducts on electromagnetic (EM) propagation at microwave frequencies. For this purpose, our analysis is conducted with a reliable EM propagation numerical solver able to account for atmospheric duct characteristics, such as duct height, among other system parameters, e.g., frequency, transmitter and receiver antenna height, and range. Preliminary investigations have revealed that modifications in the spatial distribution of the atmospheric features induced by CC might have a non-negligible impact on EM propagation and, in turn, on the performance of microwave radar systems in terms of path loss and detection range, especially in the equatorial and tropical regions.

Keywords. Climate change, radar, electromagnetic propagation, path-loss analysis, atmospheric ducts, anomalous propagation

---

[1] Corresponding Author: Alessio Di Simone, alessio.disimone@unina.it.

1. Introduction

Global climate change (CC) is a widely accepted phenomenon affecting our daily life and activities. It is also well recognized that CC is leading to unprecedented changes on the whole Earth ecosystem, including the oceans and atmosphere. In the last decade, a number of studies have analysed the CC-induced variations of oceans' parameters and their impact on submarine navigation and underwater acoustic communication systems, e.g., [1] [2], and very recently CMRE started to work on sonar, too [3].

However, very little work on the analysis of CC-induced phenomena on the performance of microwave technologies, such as radar and wireless communication systems, has been carried out, and the research that is available is mainly devoted to rainfall impact [4]. Consequently, the potential effects of CC on such technologies remain largely unexplored. Indeed, among other relevant phenomena, it is expected that CC will lead to significant changes in atmospheric structure and parameters, including the intensity and occurrence of anomalous conditions, e.g., evaporative ducts (EDs).

Under standard atmospheric conditions, the modified refractivity M increases slightly with altitude at a rate of 118 M-units/km causing electromagnetic (EM) waves to bend upwards as determined by Snell's laws. Conversely, atmospheric ducts occur if M decreases with height, thus leading to EM waves bending downwards, and the potential trapping of EM energy. As a result, atmospheric ducts may enable beyond-line-of-sight (bLoS) communications over long ranges. Atmospheric ducts occur mostly in the troposphere (i.e., the bottom layer of the atmosphere) and over oceans. Experimental studies carried out over sea off Malaysian Shores and over the Australian Great Barrier Reef have proven the feasibility of exploiting tropospheric ducts for establishing high-capacity bLoS microwave links [5] [6]. More specifically, in [5] it is demonstrated that a 78-km microwave radio link can be established at 10.6 GHz with a data rate of 10 Mb/s using antennas positioned at 7 m above sea level. However, the received signal strength appeared to be about 34 dB lower than the predicted value, leading to lower than expected availability from the link [5].

This work aims at addressing the potential impact of expected changes induced by CC in atmospheric ducts on EM propagation at microwave frequencies. We made use of a reliable numerical solver [7], based on the parabolic equation (PE) method, to evaluate EM propagation through the atmosphere. The EM propagation analysis exploits climate atmospheric data for both historical and future periods provided by the outputs of the Coupled Model Intercomparison Project 6 (CMIP6) [8] [9], the major international coordinated effort for estimating the future evolution of the earth climatic system.

This paper is organized as follows: Section 2 briefly describes the models and tools adopted to carry out the path-loss analysis; Section 3 presents the climate model adopted; preliminary numerical results are provided and discussed in Section 4; and, Section 5 draws the main conclusions.

2. Large-scale Path Loss Evaluation

2.1. EM propagation simulation

EM propagation through the atmosphere is here simulated by means of PETOOL v2 [7], a freely available numerical solver of the PE based on the split-step Fourier transform (SSFT) method [10]. Among many other features, PETOOL v2 allows for evaluating the path loss in anomalous atmospheric conditions, such as EDs. The modified refractivity profile *M(z)* used as the input climate parameter is computed as:

$$M(z) = M_0 + 0.125z - 0.125\delta \ln\left(\frac{z+z_0}{z_0}\right) \tag{1}$$

where, z is the height coordinate, M_0, δ and z_0 are the base refractivity, the ED height and the surface roughness length, respectively.

The PE method is a two-dimensional approximation of the Helmholtz equation in a narrow region surrounding the paraxial direction that is the preferential propagation direction of the EM source.

A commonly adopted formulation of the PE is the well-known standard PE (SPE), which reads as:

$$\frac{\partial^2}{\partial z^2}u(x,z) + 2jk_0\frac{\partial}{\partial z}u(x,z) + k_0^2(n^2-1)u(x,z) = 0 \qquad (2)$$

where x is the range, $u(x,z)$ denotes the reduced field, i.e., the transverse component of the electric or magnetic field reduced from the propagation factor; k_0 is the free-space wavenumber, n is the air refraction index, which is related to M via the following relation:

$$M(z) = 10^6[n(z)-1] + 0.157z\,. \qquad (3)$$

Note that the last term in (3) is introduced to compensate for the curvature of the earth's surface in wave-propagation models that notably assume the surface is flat. In PETOOL v2, the SPE in Eq. (2) is solved step-by-step in the range direction by means of SSFT, and the path loss P_L is evaluated as follows:

$$P_\mathrm{L} = 20\log10(4\pi|u(x,z)|) + 10\log10(x) - 30\log10(\lambda) \qquad (4)$$

where $\lambda = \frac{2\pi}{k_0}$ is the free-space wavelength.

2.2. Path-loss and detection range evaluation

In free space, the single-pulse power received from a pulse radar system P_r, can be expressed under the hypothesis of uncompressed pulses by means of the following radar equation [11]:

$$P_\mathrm{r} = \frac{P_\mathrm{t}G_\mathrm{t}\rho A_\mathrm{eff}}{(4\pi)^2 f_\mathrm{P} L_\mathrm{S} d^4}\sigma_\mathrm{tg} \qquad (5)$$

where σ_tg is the target radar cross section (RCS), d the target range, and all the remaining parameters of the radiofrequency (RF) system appearing in Eq. (5) are defined in Table 1, where notably P_t stands for the average power, which is related to the peak power through the radar duty cycle. It is worthwhile to recall that the Rx antenna effective area A_eff is related to its gain G through the standard formula $A_\mathrm{eff} = \frac{\lambda^2}{4\pi}G$.

Recalling that the two-way (i.e., back-and-forth) free-space path loss (FSPL) $P_\mathrm{L,free}$ reads as

$$P_\mathrm{L,free} = \left(\frac{4\pi d}{\lambda}\right)^4 \qquad (6)$$

the received power can be expressed in terms of a generic two-way path loss $P_{L,\mathrm{tot}} = P_{\mathrm{L}_1}P_{\mathrm{L}_2}$, with P_{L_1} and P_{L_2} the path loss of the transmitted and the target-reflected echoes, respectively, and reads:

$$P_\mathrm{r} = \frac{P_\mathrm{t}G_\mathrm{t}\rho A_\mathrm{eff}}{f_\mathrm{P} L_\mathrm{S} P_\mathrm{L,tot}\frac{\lambda^4}{(4\pi)^2}}\sigma_\mathrm{tg} \qquad (7)$$

It is noteworthy that, in Eq. (7), the two-way path loss completely characterizes the EM behaviour of the channel, i.e., the troposphere in our analyses. As a matter of fact, its evaluation allows for fully assessing the effects of atmospheric ducts on EM propagation and paves the way for determining the performance of radar operations as well.

Accordingly, our work mainly focuses on a reliable estimation of the path loss in the presence of atmospheric ducts.

As a side outcome of our analysis, we also evaluate the detection range, which is defined as the maximum target range providing a signal-to-noise ratio (SNR) not lower than the minimum one required for achieving acceptable radar operation performance. The latter is typically expressed in terms of false alarm rate and probability of detection, or, equivalently in terms of SNR once a detection/tracking strategy is chosen.

Therefore, a proper evaluation of the detection range calls for rearranging Eq. (7) in terms of SNR. In the hypothesis of coherent integration of n_{P} pulses, the SNR can be expressed as:

$$\mathrm{SNR}_1 = \frac{P_{\mathrm{t}} G_{\mathrm{t}} \rho A_{\mathrm{eff}}\, n_{\mathrm{P}}}{f_{\mathrm{P}} L_{\mathrm{S}} k T_0 F_{\mathrm{N}} P_{\mathrm{L,tot}} \frac{\lambda^4}{(4\pi)^2}} \sigma_{\mathrm{tg}} \tag{8}$$

where SNR_1 is the SNR required as if detection were performed on a single pulse, n_{P} is the number of integrated pulses, $P_{\mathrm{n}} = kT_0 F_{\mathrm{N}}$ is the thermal noise power, with k being the Boltzmann constant, $T_0 = 290$ K the reference noise temperature, and F_{N} the noise figure. Given the minimum SNR_1 $\mathrm{SNR}_{1,\mathrm{min}}$ required for radar operations, the maximum two-way path loss $P_{\mathrm{L,max}}$ supported can be easily found by rearranging Eq. (8), which gives:

$$P_{\mathrm{L,max}} = \frac{P_{\mathrm{t}} G_{\mathrm{t}} \rho A_{\mathrm{eff}}\, n_{\mathrm{P}}}{f_{\mathrm{P}} L_{\mathrm{S}} k T_0 F_{\mathrm{N}} \mathrm{SNR}_{1,\mathrm{min}} \frac{\lambda^4}{(4\pi)^2}} \sigma_{\mathrm{tg}}. \tag{9}$$

It is worth recalling that $P_{\mathrm{L,max}}$ is proportional to the target RCS and inversely proportional to the minimum required SNR. Since the large-scale path loss is an increasing function of distance, the same properties apply to the detection range.

The free-space detection range $d_{\mathrm{max,free}}$ can be easily derived by rearranging Eq. (6) for $P_{\mathrm{L,free}} = P_{\mathrm{L,max}}$, which gives:

$$d_{\mathrm{max,free}} = \frac{\lambda}{4\pi} \left(P_{\mathrm{L,max}}\right)^{1/4} = \frac{\lambda}{4\pi} \sqrt{P_{\mathrm{L}_1}} \tag{10}$$

where we assumed $P_{\mathrm{L}_1} = P_{\mathrm{L}_2} = \left(\frac{4\pi d}{\lambda}\right)^2$ in free space, which requires the reciprocity of the channel.

For detection range evaluation purposes, we then apply the following multi-step procedure:

1. for the scenario under consideration, i.e., for a defined radar system, target, and atmosphere configuration, we first compute the maximum supported one-way path loss, i.e., we apply Eq. (9) under reciprocity;
2. in that same scenario, we evaluate the one-way path-loss range profile at height h_{r} using the numerical solver PETOOL;
3. finally, the detection range is numerically evaluated by definition, i.e., as the maximum distance providing a one-way path loss not larger than $\sqrt{P_{\mathrm{L,max}}}$.

2.3. Radar system

Here we focus our analysis on the Aegis AN/SPY-1 navy radar system, a passive electronically scanned phased array radar providing search, detection, tracking, and discrimination functionalities for air and surface targets, e.g., ballistic and cruise missiles, aircraft. It operates in S-band (2–4 GHz) and, reportedly, can provide detection and tracking capabilities up to 165 km for golf ball-sized targets and 310 km for a ballistic missile warhead in free space [12]. All the radar system parameters required for the computation of the received signal strength are listed in Table 1 for the AN/SPY-1D(V) version and are derived from the open-source estimated values given in [13]. Additionally, we assumed Tx and Rx co-located at a height of 10 m.

Table 1. Aegis AN/SPY-1D(V) parameters [13].

Parameter	Symbol	Value
Carrier frequency	f_0	3.3 GHz
Tx height	h_t	10 m
Rx height	h_r	10 m
Tx power (average)	P_t	77 kW
Tx antenna aperture efficiency	ρ	0.8
Rx antenna effective area	A_{eff}	12 m^2
Tx antenna gain	G_t	41.6 dB
Number of integrated pulses	n_P	10
Pulse repetition frequency	f_P	200 Hz
Cable losses	L_S	10 dB
Rx noise figure	F_N	4.5 dB
SNR for the single pulse	SNR_1	20 dB

3. Climate Model

EM propagation through the atmosphere is affected by —among other parameters related to the RF system and sea surface— the air refraction index *n* (see Eq. (2)) or any equivalent parameter, such as the modified refractivity *M*. In presence of ED, it is evident from Eq. (1) that the *M*-profile is determined by the ED base value M_0, ED height δ, and the surface roughness length z_0. The last two parameters are evaluated through TOGA-COARE stability functions [14], starting from the following climate observables:

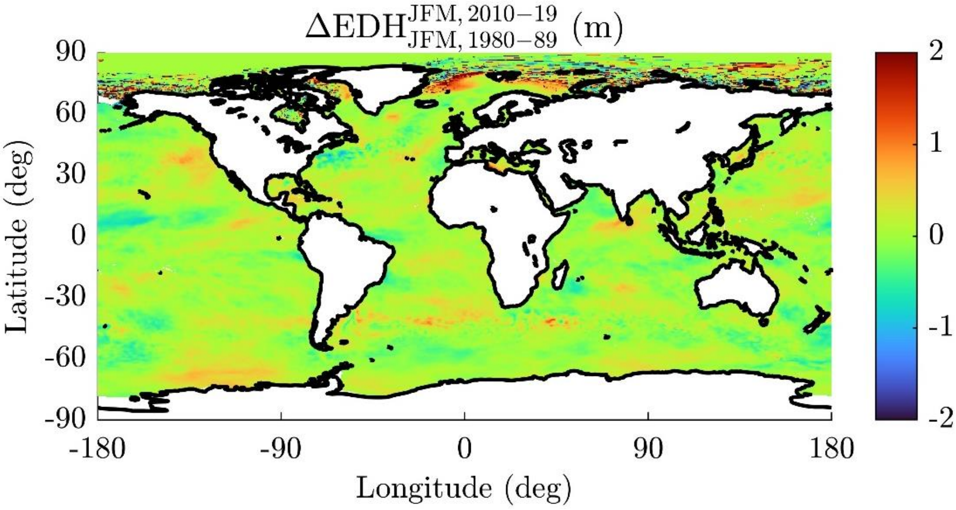
- air temperature at 2 m height;
- air pressure;
- relative humidity at 2 m height;
- wind speed at 10 m height;
- sea surface temperature;
- sea surface salinity;

and, M_0 is set to 330 M-units, as it is expected not to impact EM propagation results for the purposes of this study [10].

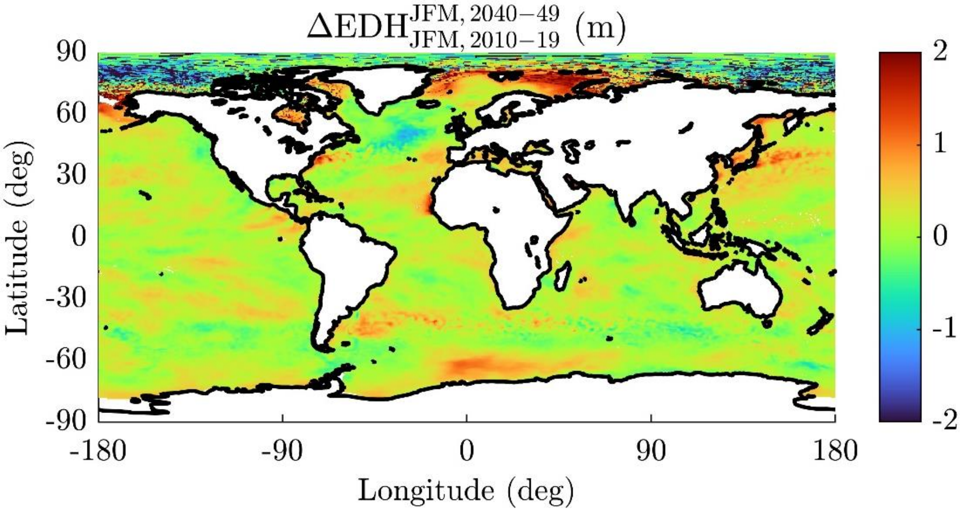
In this study, such climate variables are retrieved from the CNRM-CM6-1-HR climate model at a global scale with 0.5×0.5 degrees spatial resolution and on a monthly basis in the time period 1950–2050 and then used as input to EM transmission models. CNRM-CM6-1-HR is the climate model developed by the CNRM/CERFACS modelling group for contributing to CMIP6. The considered climate scenario is the Shared Socioeconomic Pathway 5-8.5 (SSP585), which represents the worst-case scenario. Our results are not critically dependent on the chosen scenario because the various SSPs follow similar trajectory up to 2050, then diverging during the second half of the century. Without loss of generality, and in order to filter out the seasonal changes from the climate variables, we processed these monthly averaged parameters by considering the seasonal average over January, February, and March (JFM) for three different decadal averages, namely 1980–1989 (past), 2010–2019 (present), and 2040–2049 (future), which are hereafter referred to as [JFM, 1980–1989], [JFM, 2010–2019], and [JFM, 2049–2049].

4. Numerical Results

First of all, we evaluated the ED height as described in Section 3. In order to show how CC is expected to affect atmospheric ducting phenomena, Figure 1 depicts the global distribution of ED height difference ΔEDH (in metres) between [JFM, 2010–2019]-[JFM, 1980–1989] [Figure 1(a)] and between [JFM, 2040–2049]-[JFM, 2010–2019] [Figure 1(b)]. ED height has been evaluated from the seasonal, decadal average of the climate variables obtained from the CNRM-CM6-1-HR model discussed in Section 3. It is clear that CC has led and is expected to lead to significant changes in the global distribution of EDs, with absolute height differences as large as 2 m.



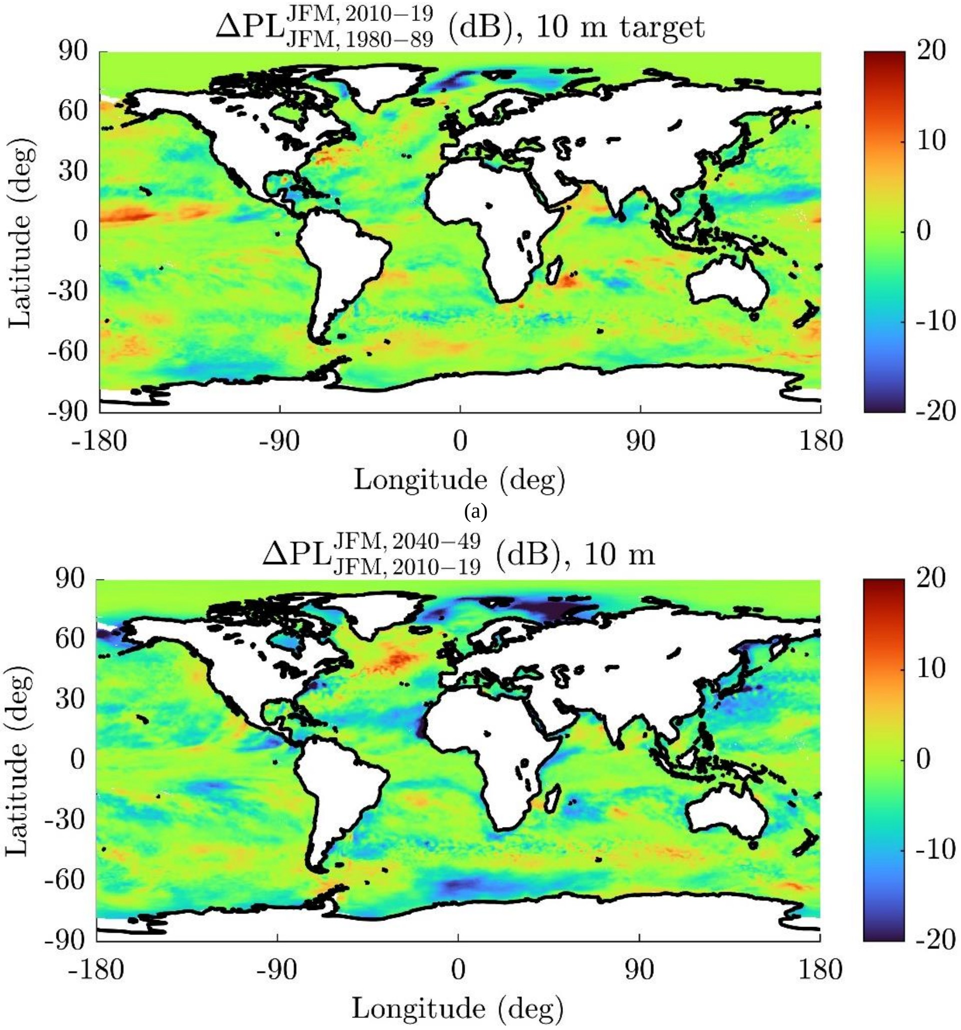
(a)



(b)

Figure 1. Global distribution of ED height difference ΔEDH in metres (a) between [JFM, 2010–2019] and [JFM, 1980–1989] and (b) between [JFM, 2040–2049] and [JFM, 2010–2019]. Climate parameters for ED height evaluation have been averaged over Jan-Feb-Mar.

By using the methodology and the climate variables briefly described in Sections 2 and 3, respectively, we evaluated the two-way path loss (PL) and the detection range (DR) of the navy radar system Aegis SPY-1D(V), described in Section 2. Figure 2 shows the global distribution of PL difference ΔPL (in dB) between [JFM, 2010–2019] and [JFM, 1980–1989] [Figure 2(a)] and between [JFM, 2040–2049] and [JFM, 2010–2019] [Figure 2(b)], where PL is evaluated at a distance of 200 km.

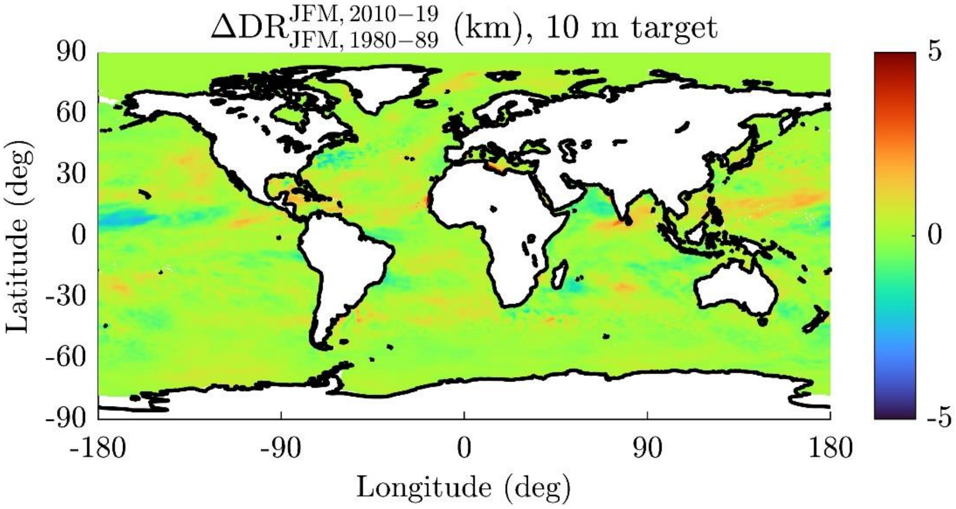


(a)

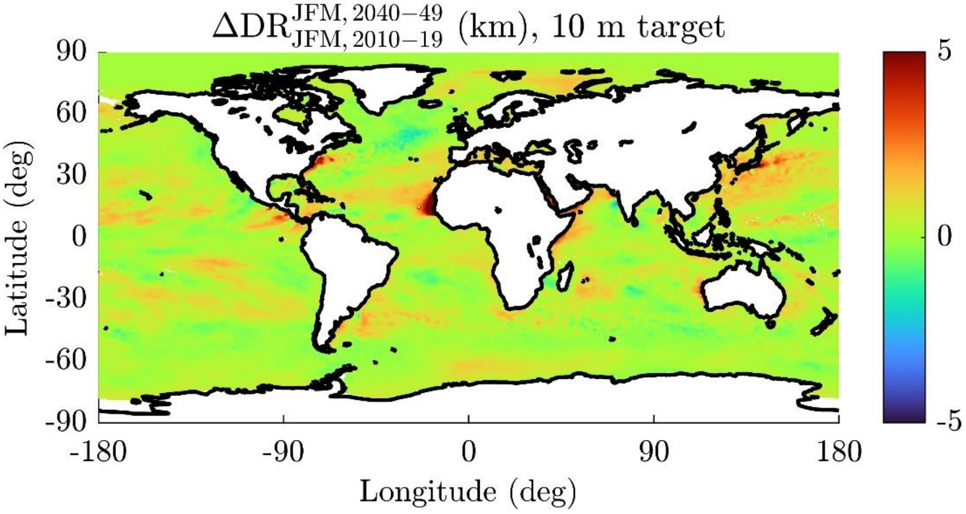
(b)

Figure 2. Global distribution of PL difference ΔPL (in dB) (a) between [JFM, 2010–2019] and [JFM, 1980–1989] and (b) between [JFM, 2040–2049] and [JFM, 2010–2019], where PL is evaluated at a distance of 200 km. Input climate variables have been averaged over Jan-Feb-Mar.

Finally, Figure 3 shows the global distribution of the DR difference ΔDR (in kilometres) between [JFM, 2010–2019] and [JFM, 1980–1989] [Figure 3(a)] and between [JFM, 2040–2049] and [2010–2019] [Figure 3(b)], where DR is evaluated for a target warhead with RCS = -15.23 dBsm at 3.3 GHz and located at 10 m above sea level.



(a)



(b)

Figure 3. Global distribution of the DR difference ΔDR (in kilometres) (a) between [JFM, 2010–2019] and [JFM, 1980–1989] and (b) between [JFM, 2040–2049] and [2010–2019], where DR is evaluated for a target warhead with RCS = -15.23 dBsm at 3.3 GHz and located at 10 m above sea level. Input climate variables have been averaged over Jan-Feb-Mar.

A visual inspection of Figures 2 and 3 reveals that the strong variations in the spatial distribution of ED height likely caused by CC effects (differences are more important in the ‘future’ decade rather than in the ‘past’ decade) are expected to have a potentially large impact on maritime radar operations and performance in terms of path-loss and detection range, especially in the equatorial and tropical regions, where the path loss is expected to change by 20 dB in some limited areas.

5. Conclusions

In this paper, we report on the preliminary results investigating the effects of CC-induced changes of ED characteristics (mainly, duct height) on EM propagation at microwave frequencies. More specifically, we focused on the analysis of path-loss and detection range for the Aegis SPY-1D(V) S-band radar. We adopted the numerical solver PETOOL v2 for a reliable evaluation of the path loss in atmospheric ducting conditions. Additionally, we relied on the CNRM-CM6-1-HR climate data model for atmospheric ducts description. CC effects were analysed on a global scale and averaged over seasonal, decadal averages, namely JFM 1980–1989, JFM 2010–2019, and JFM 2040–2049. Preliminary numerical results revealed that CC-induced changes in the physical characteristics of EDs might have a non-negligible impact on the operations of navy radar systems, such as the Aegis SPY-1D(V), especially in the equatorial and tropical regions. However, a deeper analysis based on climate datasets with a finer time resolution (daily and hourly averages, instead of monthly averages) is required and is currently under investigation.

6. Acknowledgements

This study has been funded by the NATO Office of the Chief Scientist through its Programme on Climate Change and Security (CC&S) Challenges, whose support is gratefully acknowledged.

References

[1] Saynisch, J. et al. (2017). Impact of oceanic warming on electromagnetic oceanic tidal signals: A CMIP5 climate model-based sensitivity study. *Geophys. Res. Lett., 44*(10), 4994-5000

[2] Sehgal, A., Tumar, I., & Schönwälder, J. (2010). Effects of climate change and anthropogenic ocean acidification on underwater acoustic communications. In: *Proc. of the IEEE OCEANS'10*. Sydney, NSW, Australia, 1-6

[3] Lira Loarca, A. et al. (2023). Future climate change-related changes in sonar performances in areas of NATO interest. *CMRE-MR-2023-16*. La Spezia, Italy

[4] Paulson, K. S., Ranatunga, C., & Bellerby, T. (2015). A method to estimate trends in distributions of 1 min rain rates from numerical weather prediction data. *Radio Sci., 50* (9), 931-940

[5] Woods, G. S. et al. (2009). High-capacity, long-range, over ocean microwave link using the evaporation duct. *IEEE J. Ocean. Eng., 34* (3), 323-330

[6] Iqbal, A., & Jeoti, V. (2010). Feasibility study of radio links using evaporation duct over sea off Malaysian shores. In: *Proc. of the 2010 Int. Conf. Intelligent Adv. Systems*, Kuala Lumpur, Malaysia, 1-5

[7] Ozgun, O. et al. (2020). PETOOL v2.0: Parabolic Equation Toolbox with evaporation duct models and real environment data. *Computer Phys. Commun., 256*

[8] Eyring, V. et al. (2016). Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev., 9* (5), 1937-1958

[9] Dingley, B., O'Rourke, E., & Turner B. (2023). CMIP Panel Members, WGCM Infrastructure Panel Members, and CMIP7 Task Team Members. *CMIP Annual Report 2022–2023*

[10] Levy, M. F. (2000). Parabolic equation methods for electromagnetic wave propagation. *IEEE Electromagnetic Wave Series, 45,*

[11] Skolnik, M. I. (2001). *Introduction to Radar Systems*. McGraw-Hill, New York, NY, 3rd eds., pp. 88.

[12] Robinson, A. J. (2004). Force Protection from the Sea: Employing the SPY-1D Radar. *Field Artillery*, 24-25

[13] Lewis, G., & Postol, T. (2012). Ballistic Missile Defense: Estimating the Range of an Aegis Radar against a Missile Warhead Target. https://mostlymissiledefense.com/2012/10/23/438/

[14] Fairall, V. et al. (1996). Bulk parametrization of air-sea fluxes for tropical ocean-global atmosphere coupled-ocean atmosphere response experiment. *J. Geophys. Res., 101*, 3747-3764

Using model ensembles to detect present signs of future climate: the case of the 2022 drought on the Po valley

Davide BONALDO[a,1], Debora BELLAFIORE[a], Christian FERRARIN[a],
Antonio RICCHI[b,c], Lorenzo SANGELANTONI[d], and Maria Letizia VITELLETTI[a]
[a] *National Research Council of Italy, Institute of Marine Science (CNR-ISMAR), Venice, Italy*
[b] *Department of Physical and Chemical Sciences, University of L'Aquila, L'Aquila, Italy*
[c] *Center of Excellence in Telesensing of Environment and Model Prediction of Severe Events (CETEMPS), University of L'Aquila, L'Aquila, Italy*
[d] *Climate Simulation and Prediction (CSP), Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Bologna, Italy*
ORCiD ID: Davide BONALDO https://orcid.org/0000-0003-2458-4963, Debora BELLAFIORE https://orcid.org/0000-0003-2442-3916, Christian FERRARIN https://orcid.org/0000-0003-1172-1463, Antonio RICCHI https://orcid.org/0000-0002-7061-8442, Lorenzo SANGELANTONI https://orcid.org/0000-0002-8838-1391, Maria Letizia VITELLETTI https://orcid.org/0000-0001-9653-5429

Abstract. Climate change can impact a number of strategic assets, from the integrity and operability of infrastructures, to the functionality of risk-prone productive districts and ecosystem services. The severe drought that affected large areas of Europe in Spring and Summer 2022 hit the Po river system with particular intensity, with heavy impacts on productive activities and extensive saltwater intrusion in the coastal areas. Based on the use of observed discharge records and precipitation data from reanalysis and climate models, in this contribution we analyse this event in the framework of the recent past climate and of possible end-of-century scenarios. Our results show that persistent negative rainfall anomalies like the one that characterised the 2022 event, though unlikely to become typical features of the future climate, could remarkably increase their frequency. Furthermore, the impacts of events with similar intensity will be magnified by rising temperatures, enhancing evapotranspiration rates in agriculture and water demand from the mainland, and by rising sea level, leading to a longer and more persistent intrusion of salt water in the river branches and in the neighbouring surface aquifers. Besides framing in a climate perspective a recent severe event that struck an important economic and ecological region, and stimulating the adoption of an integrated source-to-sea approach to climate adaptation in coastal regions, this work shows how available climate ensembles provide a rich, and still only partially exploited, capital of information for strategic applications.

Keywords. Climate change, EURO-CORDEX, Rainfall, Po Delta, Transitional areas

---

[1] Corresponding Author: Davide Bonaldo, davide.bonaldo@cnr.it.

1. Introduction

Due to their position at the interface between land and sea, coastal regions are subject to a complex interplay between marine and terrestrial dynamics, which makes climate change predictions for these systems particularly challenging. On the other hand, the paramount environmental and socio-economical value of coastal systems, documented with an ever-growing branch of scientific literature, makes the urgency for climate change predictions particularly pressing. In this picture, rainfall regimes play a major role with diverse potential effects on both sides of the shoreline, whose actual intensity and spatial distribution depends on the local physical, geographical and socio-economical setting. The Adriatic Sea, an epicontinental basin of the Mediterranean Sea, encloses this multiplicity of conditions and instances in a relatively small area, contained in a number of regional (that is to say, at the Mediterranean or European scale) climate studies but typically lacking a detailed view at the local scale carried out with a basin-wide homogeneous approach. As a dilution sub-basin within the Mediterranean region, its dynamics are strongly controlled by freshwater inputs [1], which play a major role in driving coastal hydrodynamics and biogeochemistry, as well as conditioning the salinity of the basin and the winterly formation of Northern Adriatic Dense Water (NAdDW) which is one of the triggers of the Mediterranean thermohaline circulation [2]. Po is the longest river of Italy and the main freshwater contributor in this system, flowing along the W-E direction for more than 650 kilometres. Its hydrographic basin has a surface area 74000 km^2 (**Figure 1**) and encompasses almost one quarter of the National surface, hosting a number of productive activities that contribute to a large fraction of the Gross Domestic Product of the country and around one third of its agricultural production [3]. Its delta encompasses approximately 400 km^2 of territory in which reclamated agricultural lands coexist with natural areas of outstanding environmental interest are largely located below the mean sea level and exposed to flood and salt intrusion [4]. In 2022 this region was hit by a prolonged drought [5] that kept the freshwater discharge below the climatological values from February to August (**Figure 2**), with severe implications both on the mainland and in the coastal zone. This event showed that river basins are a typical example of how the capability to identify the main features of climate change at regional scale is a primary requirement for a sound identification of adaptation measures as well as for the coordinated evolution of concurrent policies in coastal regions and in the mainland. Stimulated by the implications of the 2022 drought, in this contribution we present an assessment of the performance of a Regional Climate Model (RCM) ensemble from the EURO-CORDEX initiative focusing on a set of hydrological indicators and discuss the relevance of publicly available datasets in strategic studies on climate security [6].

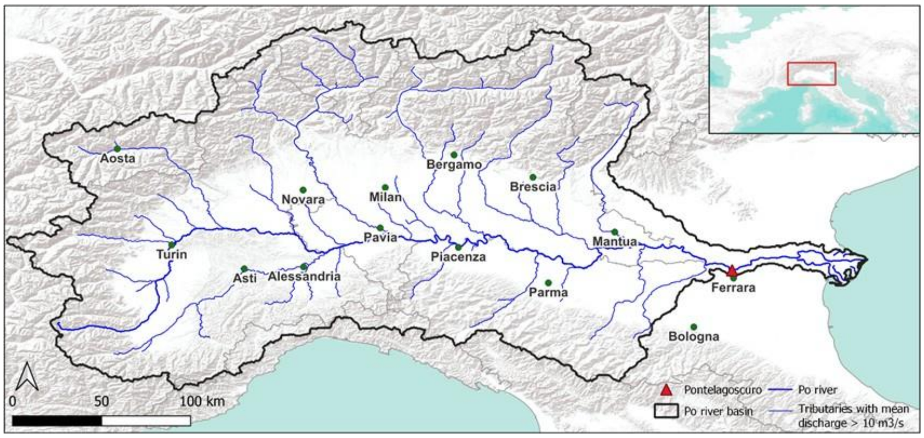


Figure 1. Geographical setting of the Po River catchment and position of the Pontelagoscuro discharge measurement station.

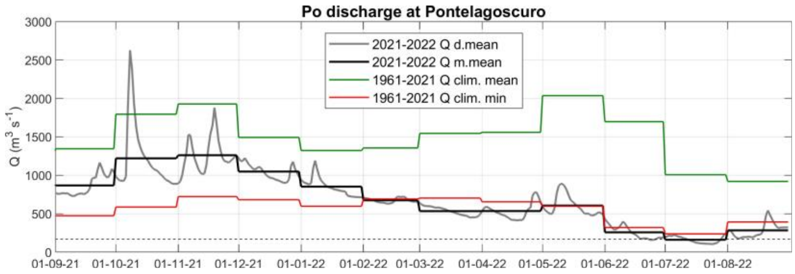


Figure 2. The 2022 Po drought: daily and monthly mean discharge at Pontelagoscuro and climatological mean and minimum values in the 1961-2021 period. Data referred to the Pontelagoscuro monitoring station (approximately 80 km from the Po River mouth) and publicly available at https://simc.arpae.it/dext3r/.

2. Materials and Methods

The analysis considered 0.11-degree, hourly precipitation data resulting from SMHI-RCA4 regional downscaling of different General Circulation Models included in the CORDEX project, retrieved from the Earth System Grid Federation (ESGF) portal [7]. SMHI-RCA4 is one of the best performing RCMs in terms of rainfall and temperature over Europe and among the ones for which the largest number of hourly precipitation data was available at the time of the study [8]. The ensemble strategy adopted aims at encompassing the uncertainty associated with the different response of general circulation, produced by each driving GCM, to changes in radiative forcing. For each combination of driving model and ensemble member, alongside with the historical runs (downscaling RCMs based on observed radiative forcing and spanning from 1970 to 2005), model fields from all the available climate change scenario experiments (based on projected radiative forcing estimated from IPCC Representative Concentration Pathways - RCPs under different hypotheses, from 2006 to 2099) were analysed [9]. **Table 1** summarizes the datasets considered and the available scenarios.

Table 1. Datasets and scenarios available.

Driving GCM	RCP2.6	RCP4.5	RCP8.5
CNRM-CERFACS-CNRM-CM5_r1i1p1		x	x
ICHEC-EC-EARTH_r12i1p1	x	x	x
ICHEC-EC-EARTH_r1i1p1			x
ICHEC-EC-EARTH_r3i1p1			x
IPSL-IPSL-CM5A-MR_r1i1p1		x	x
MOHC-HadGEM2-ES_r1i1p1	x	x	x
MPI-M-MPI-ESM-LR_r1i1p1	x	x	x
MPI-M-MPI-ESM-LR_r2i1p1			x
MPI-M-MPI-ESM-LR_r3i1p1			x
NCC-NorESM1-M_r1i1p1	x	x	x

The validation benchmark is the Multi-Source Weighted-Ensemble Precipitation (MSWEP) v2 precipitation dataset [10], providing three-hourly, 0.1-degree spatial resolution precipitation data based on different sources including satellite, rain gauge and re- analyses from 1979 to near-present. In the wealth of available rainfall datasets, this choice ensured sufficient resolution, coverage and homogeneity both in time and space. Based on the time reference of the available model fields and validation dataset the climatological skills assessment were performed with reference to a Control period (CTR) spanning from 1986 to 2005, whereas end-of century conditions (2070-2099) were considered in the discussion of the possible occurrence of severe events like the 2022 drought in two climate change scenarios (RCP2.6 and RCP8.5). The hydrological basin was identified based on the HydroSHEDS dataset and retrieved from the FAO GeoNetwork portal (http://www.fao.org/geonetwork/srv/en/main.home, last visited November 2nd, 2023).

The model skill assessment and the analysis of future scenarios has been referred to a set of indices based on the standard ETCCDI climate change indices [11] expanded or adapted in order to capture some specific features (see **Table 2** for the list and description).

Table 2. Climate change indices considered in the assessment

Index	Description
prectot	total precipitation
CWD	maximum number of consecutive wet days (precipitation ≥ 1 mm/d)
CDD	maximum number of consecutive dry days (precipitation < 1 mm/d)
SDII	Simple precipitation intensity index (mean precipitation in wet days)
Rx3h	maximum consecutive 3-hour precipitation
Rx1d	maximum consecutive 24-hour precipitation
Rx5d	maximum consecutive 5-day precipitation
R10	count of days with precipitation ≥10 mm
R20	count of days with precipitation ≥20 mm
prec90p	90-percentile daily precipitation among wet days
prec99p	99-percentile daily precipitation among wet days

Indices were computed on an annual basis and subsequently averaged over the period. The performance of each single model was computed in aggregated form: for each period-averaged index, mean and standard deviation were computed throughout the basin, allowing to summarize the model skills in terms of three overall spatial statistics [12], namely the relative bias (BIAS hereinafter), spatial correlation (CORR), and spatial variability ratio (σ_m/σ_o).

3. Results and discussion

Figure 3 summarises the model skills in terms of different statistics and climate indices in the Po basin. The relative bias exhibits a generalised tendency toward rainfall overestimation, both in terms of overall freshwater supply into the basin and in terms of intensity of the rainfall events. While the ensemble members tend to exhibit a relatively good agreement on the indices associated with rainfall intensity (yearly values of SDII, Rx3h, Rx1d and the percentiles), a comparatively larger dispersion appears in the indices associated with rainfall timing (R10 and R20, CDD and CWD). Rx5d deserves a separate mention, as consecutive rainfall longer than 5 days are rare and patchy both in the MSWEP benchmark and in the CORDEX dataset, so the statistics are drawn on a relatively small and rarely overlapping sample. Spatial correlation values are generally clustered around 0.5 for most statistics, and although with moderate dispersion among the ensemble members (except again for CDD and CWD), σ_m/σ_o exhibits the largest variability.

In a future climate condition up to the end of the present century under the severe RCP8.5 scenario, the ensemble foresees an overall increase in total precipitation in winter (DJF) and a decrease in summer (JJA) and autumn (SON) (**Figure 4**). This result has important implications in terms of water resource management and possible occurrence of drought events like the one that hit the Po Valley (as well as a large part of the European territory) in summer 2022. This was precisely the focus of a recent work in which the dataset presented here was analysed [5], together with fields from the ERA5 reanalysis [13], for the characterisation of that event in the framework of recent past climate and its possible recurrence in climate change scenarios. The analysis of monthly precipitation statistics

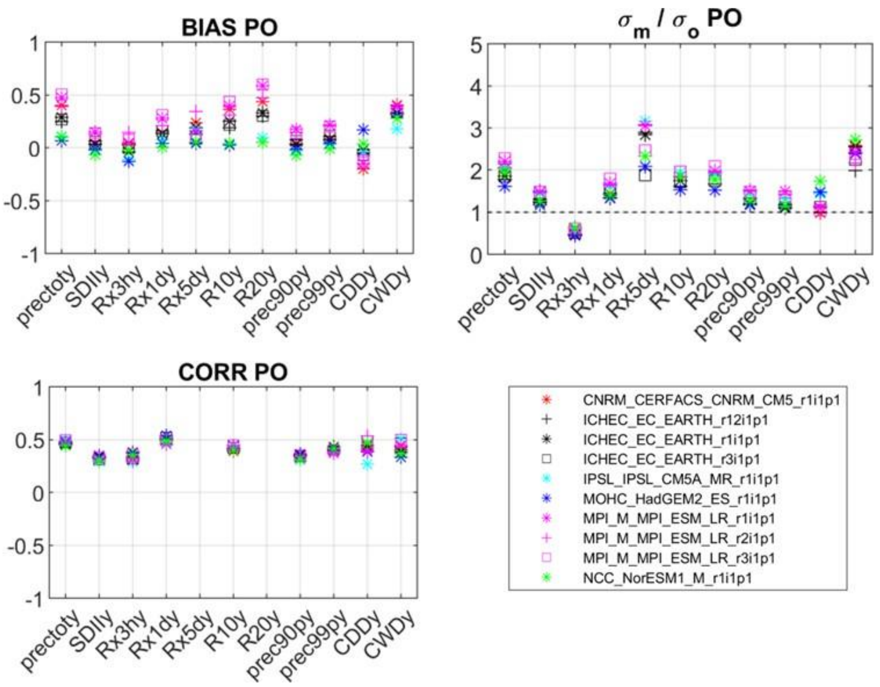


Figure 3. SMHI-RCA4 performance in reproducing climate indices (the suffix indicates the yearly base of the computation) when driven by different CGMs.

over different seasons and cumulated over different periods allowed to point out that, although close to the extremes of the distribution in winter and spring, no singular seasonal anomaly is completely unprecedented in the last decades, and the exceptional character of the drought lies mostly in the unprecedented persistence of the anomaly. In a RCP8.5 end-of-century scenario the probability of occurrence of the same anomalies that characterised the 2022 drought will increase in all seasons, with the largest variation in summer, and severely persistent anomalies will increase their frequency although remaining below the 10th percentile of the distribution.

This notwithstanding, this change in the hydrological regime will take place in concomitance with higher temperatures, which will lead to higher demand for water supply in agriculture, and in the presence of higher sea levels intensifying the pressure of salt water on coastal water bodies.

4. Conclusions

Particularly in the presence of strong anthropic pressures and interests, hydrology-related processes are a primary concern for coastal communities as well as for decision makers at different institutional levels, forced to face a number of environmental and water management challenges with increasing intensity, dealing for instance with:

- salt intrusion and salinization of coastal aquifers;
- accumulation of pollutants as a result of increasing flushing times;
- coastal water quality and balneability issues due to sudden and intense summerly rainfalls;
- soil erosion and intense sediment transport from mountain river catchments;
- flood hazard;
- water management issues in drought conditions;
- waterways operability.

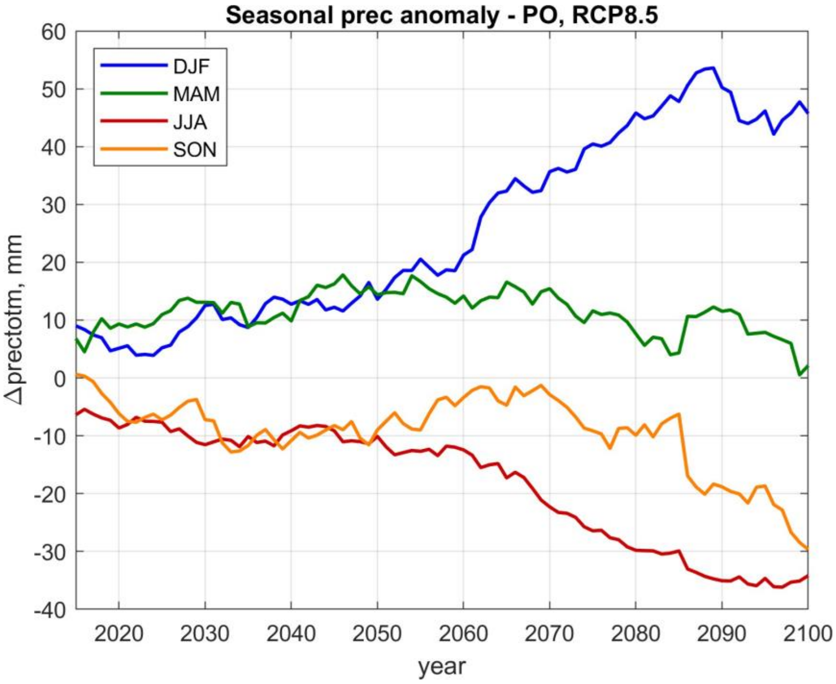


Figure 4. Monthly total precipitation seasonal anomalies in the Po basin (30-y moving average) under RCP8.5 scenario with respect to the 1986-2015 period.

In this direction, publicly available datasets from model ensembles provide a valuable source of information for the characterisation, although possibly in terms of preliminary studies, of the effects of climate change on crucial processes for human activities and coastal sea uses as well as of the associated uncertainties.

References

[1] Brando, V. E. et al. (2015). High-resolution satellite turbidity and sea surface temperature observations of river plume interactions during a significant flood event. *Ocean Science*, *11*, 909-920

[2] Vilibic´, I. & Supic, N. (2005). Dense water generation on a shelf: the case of the Adriatic Sea. *Ocean Dynamics*, *55*, 403-415

[3] Bozzola, M. & Swanson, T. (2014). Policy implications of climate variability on agriculture: Water management in the Po river basin, Italy. Environmental Science and Policy, 43, 26-38

[4] Bellafiore, D. et al. (2021). Saltwater Intrusion in a Mediterranean Delta under a Changing Climate. *Journal of Geophysical Research: Oceans*, *126*, 1-23

[5] Bonaldo, D. et al. (2023). The summer 2022 drought: a taste of future climate for the Po' valley (Italy)?. *Regional Environmental Change*, *23*

[6] Jacob, D. et al. (2014). EURO-CORDEX: New high-resolution climate change projections for European impact research. *Regional Environmental Change*, *14*, 563-578

[7] Samuelsson, P. et al (2011). The Rossby Centre Regional Climate model RCA3: Model description and performance. *Tellus, Series A: Dynamic Meteorology and Oceanography*, *63* , 4-23

[8] Sørland, S. L. et al. (2021). *COSMO-CLM Regional Climate Simulations in the CORDEX framework : a review*, *10*

[9] Church, J. et al. (2013). Sea Level Change. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

[10] Beck, H. E. et al. (2019). MSWep v2 Global 3-hourly 0.1° precipitation: Methodology and quantitative assessment. *Bulletin of the American Meteorological Society*, *100*, 473-500

[11] ETCCDI. *Etccdi climate change indices*, 11-14

[12] Zollo, A. L. et al (2016). Extreme temperature and precipitation events over Italy: assessment of high-resolution simulations with COSMO-CLM and future scenarios. *International Journal of Climatology*, *36*, 987-1004

[13] Hersbach, H. et al. Era5 hourly data on single levels from 1959 to present. Copernicus climate change services (c3s), climate data store (cds)

Climate change as a threat multiplier in the maritime domain: way forward for NATO's climate security engagement

Sherri GOODMAN[a,1] and Pauline BAUDU[b]
[a] *Center for Climate and Security, Wilson Center*
[b] *Center for Climate and Security, UQAM, Arctic360*
ORCiD ID: Pauline BAUDU https://orcid.org/0009-0001-8384-8415

Abstract. Climate change is a threat multiplier, exacerbating resource scarcity, undermining government capacity, and fuelling existing societal tensions. Its impacts are expected to worsen already marginal living standards in many developing nations, contribute to instability and erode economic and environmental conditions. Climate effects have specific ramifications in the maritime domain, with implications for NATO's maritime activities. This paper assesses the diverse and intersecting risks posed by climate and environmental change in the maritime domain, including through three different case studies situated in NATO's maritime area of responsibility: the Arctic, the Atlantic and the Mediterranean. It then provides recommendations for the way forward and on how to better integrate science in NATO's maritime climate-security efforts. It concludes that NATO can lead in advancing climate security in the maritime domain through three essential components: advancing climate-informed decision-making for naval forces, mission planning, and coastal infrastructure protection; decarbonizing defense to support naval operations in contested logistics environments; and engaging in maritime science diplomacy to support the resilience-building of coastal Allies and partners.

Keywords. Maritime, security, climate change, threat multiplier, NATO, plan, responses

1. Maritime security in the age of climate change: How is climate change acting as a threat multiplier in the maritime domain

Climate change is a threat multiplier, exacerbating resource scarcity, taxing government capacity, and fuelling existing societal tensions. Its impacts are expected to worsen already marginal living standards in many developing nations, contribute to instability and erode economic and environmental conditions [1], with specific ramifications in the maritime domain. For the purpose of this analysis, maritime security encompasses a broad conceptualization including the safety and health of people and defence assets at sea, security of land-based populations subject to climate-induced sea-level rise and extreme weather threats, corresponding threats to marine life, and degradation of the oceans' capacity to sequester atmospheric carbon. This analysis explores maritime climate security: the threats to maritime security that emanate from or are amplified by the climate crisis.

---

[1] Author: Sherri Goodman, sherri.goodman@wilsoncenter.org. The authors contributed equally to this paper.

1.1. Physical impacts

Rising greenhouse gas levels in the atmosphere are warming air, water, and land-based environments worldwide, intensifying climatic phenomena and ecological shifts. Warmer air carries more humidity, making storms larger and more powerful. As storms intensify, mean precipitation escalates, increasing flood risk. When glacial melt reaches the sea, it increases the volume of ocean waters and further compounds sea-level rise and its cascading effects, including erosion and salinization of low-lying agricultural areas. Warming seawater absorbs carbon dioxide, leading to ocean acidification endangering marine health and marine ecosystems. Sea-based species either migrate towards cooler water, change sizes and reproduction patterns or begin to die off. In 2019, a new study suggested that marine species were disappearing from their habitat twice as fast as their land-based counterparts [2]. Such studies are a foreboding signal of the ocean's rapidly deteriorating health, and the record breaking temperatures on both land and sea during the summer of 2023, with forecasts portending more heat trapped in ocean basins to come, further presage turbulent weather patterns ahead.

1.2. Human impacts

For coastal communities, sea-level rise is a growing danger to lives and livelihoods. Storm strength, storm surge, and over-use of local freshwater sources further exacerbate the challenge. At least 267 million people are at risk of inundation today, with almost 60% of those living in Asia [3]. Dwindling fish stocks due to warming and acidifying waters, combined with economic inequalities and weak governance, can prompt illegal, unreported, and unregulated (IUU) fishing, as fishing communities struggle to maintain their trade. Coastal agricultural areas face a similar challenge [4]. Salinization, which affects 20% of irrigated cropland today, could increase to over 50% by 2050, leading to loss of livelihoods and displacements [5].

1.3. Security impacts

Naval installations face the same physical impacts as other important coastal infrastructures. Sea-level rise endangers coastal military infrastructure, subject to flooding and loss of access. Decision makers will face billion-dollar decisions in the coming years as infrastructure from dry docks and ports to base housing and offices contend with impending floods. At the same time, extreme-weather events increase the demand for naval forces in humanitarian assistance and disaster response (HADR) missions.

The physical destruction wrecked by climate events, compounded by the associated competition for scarce resources, and loss of the roads, bridges, power plants, water delivery, and other infrastructure critical for the functioning of modern society, strains states, particularly those already stressed by under-development. Climate impacts are also expected to amplify drivers of population movements, including cross-border migrations through increasingly dangerous waters. Competition for sea-based minerals and hydrocarbons is another category of maritime flashpoint, as economic dependence is growing upon oceans for fossil fuel deposits, renewable energy sources, and the minerals essential for the green energy transition. The location of deposits in contested territorial waters further complicates matters, as does the absence of comprehensive and widely accepted governance regimes. Finally, sea-level rise impacts marine territorial boundaries, many of which are already disputed.

2. Case studies: Climate change is shaping NATO's maritime area of responsibility

The diverse and intertwined climate implications outlined above are unavoidably shaping security challenges in NATO's maritime area of responsibility. Yet, climate change and coastal ecosystems degradation impact maritime security differently around the world, depending on: (1) the physical impact of climate change on the regions; (2) the dependence of local communities on affected ecosystems for food security or incomes; (3) the resources available to local communities to prepare for, and adapt to, climate impacts; and, (4) governance capacity to manage or invest in these resources [6]. The following case-studies, from the High North to the Mediterranean, illustrate the scope of climate impacts on maritime security, and their implications for NATO's operating environment.

2.1. The opening, yet unpredictable High North

The Arctic is warming at least three times faster than the rest of the globe, and its unique ecosystems are among the world's most vulnerable to climate change. Direct climate impacts in the Arctic include: new sea and air temperature extremes; decline in Arctic sea-ice extent and thickness; permafrost thaw; rapid oceanic acidification; and, related biodiversity changes [7] [8]. The melting sea ice is expected to lead to an increase in navigable surfaces and to a relatively easier access to natural resources in the medium-term. The related environmental and noise pollution from increased shipping further impact the region's marine biodiversity [9]. Lastly, the melting ice also generates destructive feedback loops further aggravating global warming: thawing permafrost releases high amounts of methane contributing to global warming; and melting sea ice exposes larger parts of a dark ocean absorbing more heat. And new research published in March 2023 revealed two new tipping points for the Greenland Ice Sheet: releasing 1000 gigatons of carbon into the atmosphere (of which we are halfway through) will cause the southern portion of the ice sheet to melt; and, about 2500 gigatons of carbon means permanent loss of nearly the entire ice sheet. Should it melt entirely, global sea level would inevitably rise about seven metres [10]. Climate-altered maritime dynamics have crucial impacts on human security, of which Indigenous communities are on the front lines. Isolated coastal municipalities, especially in the US and Canadian Arctic, face existential threats from sea-level rise, storm surges (against which sea ice is no longer acting as an effective natural buffer), and endangered critical infrastructure due to permafrost thaw. Climate change is also a threat to human health, with biological and environmental risks emerging from expanding toxic algae and from the collapse of industrial, nuclear, and oil and gas infrastructure built on thawing permafrost [9]. In addition, as the sea ice melts, competing interests add strain to global power relationships and challenge maritime governance frameworks and the strategic status quo. A recent paper published by the UK Royal United Services Institute (RUSI) mentioned that shifting fish stocks and declining sea-ice coverage risk triggering a "race to fish" in the Arctic, where stocks could face exploitation by a wider range of actors beyond national jurisdiction despite existing regulation frameworks [4]. Russia has been hyper-securitizing its economic assets for Arctic resource exploration, and its provocations have included a strong maritime component, increasing the likelihood of escalation due to the risk of accidents at sea or misunderstandings. Lastly, climate effects are challenging military readiness for NATO nations' forces at sea: in addition to threatened coastal military installations, the growing volume of maritime traffic in more challenging sea conditions will put a strain on security forces to address a surge in concurrent emergencies such as search-and-rescue and environmental-disaster response.

2.2. Rising seas and shifting currents in the Atlantic

Climate change is also having significant impacts on the Atlantic Ocean, affecting both its physical characteristics, the ecosystems it supports, and coastal civilian — and military — communities. One of the most noticeable impacts of climate change in the Atlantic, along with ocean acidification, warming sea-surface temperatures and biodiversity shifts, is rising sea levels due to glaciers melt and water expansion. Coupled with more intense storms, it is causing increased coastal flooding.

This severely undermines naval readiness, as sea-level rise and severe weather are already damaging the US Navy's and NATO's bases. A well-known example is the Naval Station Norfolk, in Virginia. The largest naval complex in the world, home to both NATO Allied Command Transformation's and NATO Joint Force Command Norfolk headquarters, faces increasing flooding from sea-level rise. Naval Station Norfolk has recorded a rise of over 45.7 cm in sea level in the past 100 years, and the projected rise is at least 50.9 cm by 2050 [11]. Pier inundation occurs monthly and is expected to get worse. As flagged in NATO's second Climate Change and Security Impact Assessment released in June 2023 [12], flooding in Norfolk affects the Navy's installations, training, readiness, contingency plans and logistics, and highlights the importance of adaptation and resilience measures. In 2020, Virginia unveiled a new resilience master plan, developed by Rear Admiral (Ret.) Ann Phillips, prioritizing nature-based solutions beneficial to ecosystems. The plan involves raising infrastructure, reinforcing floodwalls, and enhancing naval assets' recovery capacities. However, the Norfolk base may still need to relocate some of its assets and residents to safer locations in the future [13].

Finally, the Atlantic is also home to a potential tipping point in the weakening of the Atlantic Meridional Overturning Circulation (AMOC), a critical ocean current system that helps regulate climate patterns. Climate change can disrupt and significantly slow the AMOC, leading to altered weather patterns, including more extreme weather events and changing weather patterns — temperatures and precipitation — in other parts of the world [14].

2.3. Boiling waters and humanitarian emergencies in the Mediterranean

In the Mediterranean Sea, where NATO is carrying out Operation Sea Guardian, climate change has far-reaching consequences for the environment, human populations, and naval security forces. With rising sea level, coastal communities are increasingly vulnerable to flooding and saltwater intrusion. These trends are disrupting livelihoods and exacerbating freshwater scarcity, particularly in the regions where freshwater aquifers are close to the coast — including Greece, Italy, Spain, Tunisia, Algeria, and around the Nile Delta [15]. Rising sea levels also accelerate coastal erosion and the loss of valuable beaches, with implications for tourism on which Mediterranean coastal communities rely heavily [16]. In addition, warming waters also affect fish distribution and threaten fisheries, further contributing to the loss of livelihoods.

One of the worst impacts of climate change in the region is also that it increases the frequency, duration and intensity of heatwaves, both on land and at sea. On land, heatwaves threaten human health and increase the risks of wildfires (see Greece, Portugal, Sardinia, Croatia…), straining Mediterranean nations' response capacities and challenging early warning systems. Just this year, by July 2023, fires had claimed five lives in Italy and 34 in northeast Algeria [17]. At sea, marine heatwaves have massive effects on marine species mortality, with broader consequences for marine habitats, fisheries, and for the rest of the globe as this reduces valuable time for adaptation to climate change [18]. In the waters off Israel, Cyprus, Lebanon and Syria, average sea temperatures in the summer are now consistently over 31° C [19].

Finally, the Mediterranean Sea constitutes one of the most travelled and dangerous routes for migrants in search for a safer future in Europe, with boats sinking frequently and thousands of deaths registered annually — although the exact number is uncertain and likely much higher. According to the United Nations High Commissioner for Refugees (UNHCR), the Central Mediterranean crossing from North Africa to Italy, in particular, accounted for more than 75% of migrant deaths in the Mediterranean over the past decade [20]. Although environmental factors have always been migration drivers intertwined with complex political, societal and economic factors, climate change is only exacerbating the already dire humanitarian issue, as it disrupts ecosystems, exacerbates resource scarcity, threatens livelihoods and amplifies pre-existing contexts of instability. A wide array of policy responses is needed at the national and regional levels to anticipate and respond to this situation in a proactive and humane way. At sea, this highlights the importance of domain awareness, search-and- rescue capacities, and security capacities to identify and address human-trafficking situations.

3. Way forward: What role for NATO and the Centre for Maritime Research and Experimentation (CMRE)?

NATO's 2022 Strategic Concept describes maritime security as "the key to our peace and prosperity". In its maritime area of responsibility, NATO is committed to upholding freedom of navigation, securing maritime trade routes and protecting the Alliance's main lines of communications. Climate security impacts constitute new challenges for the effectiveness and sustainability of NATO's missions. In advancing its Climate Change and Security Action Plan at sea, NATO has the opportunity to leverage expertise from the CMRE, with a special focus on the role of science.

3.1. Awareness and Adaptation: The importance of science in NATO's predictive capabilities and operational decision-making

In order to improve Allied awareness of the security impacts of climate change on NATO's maritime domain, climate prediction and modelling must be part of the regular planning process – both for military and civilian planners. NATO planners need reliable weather and climate prediction for military defence planning purposes. Today's weather forecasts are reliable for 7 - 10 days. Global climate models provide estimates for longer periods, often in decades or longer. Knowing that the temperature may rise globally by several degrees by the end of the century is not sufficient for defence planning purposes. NATO planners need to know how the changing climate will affect base infrastructure, military operations and forces in the timeframes relevant to defence decision-making. NATO decision makers face a growing misalignment of time scales that describe the accelerating rate at which climate is changing, globally and regionally. Even though global climate models continue to improve, there is currently a gap in modelling at operationally relevant timescales of 1 - 10 years. There is also a gap in downscaling global climate models to make accurate predictions at the regional scales of military operations planning, such as for the Mediterranean, Arctic, and Atlantic. Finally, there is a lack of sufficient data to understand the coupled land/sea/atmosphere earth system, and how it is altered by climate change.

We need three new ingredients to get us to more reliable near-term climate prediction. One ingredient is a scientific advance in earth systems modelling, another is to harness today's advanced technologies such as artificial intelligence to improve modelling and predictions, and the third is making the improved modelling and forecasting operationally-relevant for defence planners. Investment in these solutions will depend on the "demand signal" from the military and related users of climate intelligence to produce more downscaled models and analysis of real-world military challenges. To accelerate climate-relevant decision-making for national security, NATO decision makers need to integrate operational weather and climate models with improved understanding of what humans do when faced with climate and other stress. We need to couple best-in-class weather and climate forecasting capabilities, the first ingredient above, with the ability to model human-domain systems. Lastly, in order for NATO to anticipate better the adjustments needed to adapt to climate-driven risks, and to inform decision making, wargaming and tabletop exercise scenarios should systematically integrate climate data in every aspect of the simulation, exercise, and planning cycle.

3.2. Climate mitigation and conservation in maritime security: priorities for NATO forces at sea

Another central pillar of NATO's climate efforts in the maritime domain will be the commitment of NATO navies to contribute to climate mitigation and environmental conservation. Efforts to curb fossil fuel use, accelerate the renewable energy transition, electrify buildings and vehicles, and advance carbon dioxide capture in the oceans and atmosphere should involve all maritime stakeholders, including navies, ship owners, and fisheries. Many militaries are actively investing in technologies for more sustainable and more effective operational energy use. New propulsion systems for ships and aircrafts are more efficient, and navies are investigating sustainable maritime fuels. One set of promising technologies to scale back fossil fuel use is Prepare Ships (Copernicus), a project developed by Swedish research and corporate entities to improve both the safety and efficiency of shipping. The US Navy is also researching and developing direct ocean-and-air capture solutions to tackle operational carbon (Operational Endurance from Environmental Carbon), which can then be converted directly on-board into vessel fuel (Magill 2020).

Leadership in climate readiness is an investment in mission assurance. In an increasingly contested logistics environment, becoming less reliant on increasingly outdated infrastructure and being able to power forces without refuelling — thanks to improved batteries and safer nuclear technology — increases operational capacity and resilience, both in humanitarian missions and on the battlefield. Furthermore, funnelling military procurement monies into advanced energy efficiency and new fuels also accelerates their testing and scale economics, making them cheaper for government and private sector actors.

Navies, like other military forces, bring multiple strengths to the arena of climate mitigation. Their incisive analysis, precision in procurement specifications, capacity to fund research, and ability to scale demand are exceedingly valuable. As to NATO, the Alliance has recently released a new Greenhouse Gas Emissions Mapping and Analytical Methodology, providing guidelines and tools to calculate emissions from NATO's civilian and military facilities, and reasserting NATO's long track record as a standard setter. This methodology should be used by NATO to institutionalize and mainstream decarbonized defence approaches for maritime forces. In addition, through its standardization agreements (STANAGs), NATO can also set standards not only on how Allied militaries operate, but also on advising on the interoperability requirements for and types of equipment they operate. As such, the Alliance can lead the way in trying to ensure that Allied military equipment is not only climate-friendly, but also effective under extreme weather conditions. NATO can also take the lead in guiding the way forward on research and development of alternative fuels and propulsion systems for military applications. This would also ensure that NATO's naval forces continue to be interoperable [21].

Equally important are ocean conservation efforts. Investments in nature-based solutions to protect and restore water sources, marshes, mangroves, and other natural infrastructure can provide ongoing erosion control, pollution abatement, pollination, and biodiversity support in a manner that no single technology could deliver. Navies have, overtime, come to recognize their environmental stewardship responsibilities. In response to requirements of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (or the 'London Convention'), the US Navy developed a plastics waste processor that today operates aboard all naval vessels to compact plastic trash for safe disposal on land. Navies have also improved their protection of marine mammals. To avoid harming these, the US Navy conducts pre-exercise screening of waters and often reroutes activity, particularly in shallow waters, to avoid ship strikes and reduce harm. Conservation in the marine environment is also benefiting from growing interest in establishing Marine Protected Areas (MPAs), supported by the 2020 intergovernmental High Ambition Coalition initiative to protect 30% of land, freshwater, and ocean areas by 2030 [22]. One key question will be the extent to which navies will be called upon to enforce MPAs. To do so, navies will need further training on working with local communities to respect local practices and customs, and to leverage local communities' domain awareness in an inclusive, non-extractive way.

3.3. Consolidating outreach: Cooperation and the role of science diplomacy

Lastly, NATO's vast cooperation network in the maritime domain with the United Nations, the European Union, and other regional organizations such as the Organization for Security and Co-operation in Europe, and the African Union, provides opportunities to consolidate outreach on climate security and to leverage the wide array of benefits offered by science diplomacy.

Science diplomacy — i.e. the use of scientific collaborations and partnerships between countries to address global challenges — has proved a valuable soft power tool to improve international relations, mitigate tensions, and help manage geopolitical competition. In the Arctic, ocean science diplomacy with Russia and non-Arctic nations has allowed Arctic states not only to advance their understanding of the region's unique challenges, but also to limit the spillover of global tensions into regional relations [23].

Ocean science diplomacy also plays a crucial role in strengthening the resilience of vulnerable coastal nations with limited marine scientific research capacities to cope with increasing climate disasters. In the Caribbean, training and capacity-building initiatives led by scientific organizations have helped improve climate modeling and infrastructure resilience. Informed policies and practices ultimately help protect the livelihoods of local communities [24].

Finally, climate science diplomacy plays a crucial role in facilitating the regional integration of Mediterranean coastal countries by fostering dialogue, data sharing, and joint efforts to address transboundary challenges such as water scarcity, sea-level rise, and extreme weather events. Joint water management, for instance, helps minimize tensions over resources and fosters sustainable practices. The Mediterranean region’s natural conditions also offer significant potential for upscaling marine renewable energy, such as marine solar panels, tidal energy and wind power [25] [26]. Science diplomacy encourages cross-border collaboration in business development into these renewable energy resources, ultimately advancing energy security and sustainability.

4. Conclusion

NATO is well placed to be a leader in climate security for the maritime domain. This leadership has three essential components: advancing climate-informed decision-making for naval forces, missions, planning, and coastal infrastructure protection; decarbonizing defence to support naval operations in contested logistics environments; and, engaging in maritime science diplomacy to support the climate-resilience of coastal Allies and partners. Global security and stability cannot be achieved alone. NATO’s strength is inherent in its 31 -member strong alliance, and Putin’s war in Ukraine has strengthened Allied resolve. This commitment to diplomatic engagement should be extended to a new suite of maritime climate security engagements that address Allies and partner needs and help build resilience to future climate impacts.

5. Acknowledgements

Section 2 and 3 of this paper derive from the following chapter, co-authored by the authors of the present paper: Goodman, S., Baudu, P., & Fleishman, R. (2023). Maritime response to climate change. In: *Climate Change, Conflict and (In)Security-Hot War* (4th ed.). Clack, T., Meral, Z., & Selisny, L. (eds.). Routledge.

References

[1] Goodman, S. et al. (2007). "National Security and the Threat of Climate Change". The CNA Corporation. 2007. https://www.cna.org/archive/CNA_Files/pdf/national%20security%20and%20the%20threat%20of%20climate%20change.pdf

[2] Pinsky, M. L., et al. (2019). Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*, *569*, 108-111

[3] Hooijer, A., & Vernimmen, R. (2021). Global LiDAR land elevation data reveal greatest sea-level rise vulnerability in the tropics. *Nature Communications, 12*, 3592

[4] Young, L. et al. (2023). Future Illegal, Unreported and Unregulated Fishing Trends in a Warming World. *RUSI*. https://static.rusi.org/future-iuu-fishing-in-a-warming-world-a-global-horizon- scan.pdf

[5] Singh, A. (2021). Soil salinity: a global threat to sustainable development. *Soil Use and Management*,*38*(1), 39-67

[6] Pörtner, H.O. et al. (2019). *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. IPCC

[7] Guy, K., A. et al. (2021). *Temperatures and tensions rise: security and climate risk in the Arctic*. Woodwell Climate Research Center & Council on Strategic Risks

[8] NOAA Arctic Program 2023. *Arctic report card*. NOAA. https://www.arctic.noaa.gov/Report- Card/Report-Card-2023

[9] Maddox, M. (2021). Climate-fragility risk brief: the Arctic. *Climate Security Expert Network/ Adelphi*. https://5g.wilsoncenter.org/sites/default/files/media/uploads/documents/csen_risk_brief_arctic.pdf

[10] American Geophysical Union (2023). *The Greenland Ice Sheet is close to a melting point of no return, says new study*. Phys.org. https://phys.org/news/2023-03-greenland-ice-sheet.html

[11] Malmquist, D. (2020). *Sea-level report cards: 2019 data adds to trend in acceleration*. Virginia Institute of Marine Science. https://www.vims.edu/newsandevents/topstories/2020/slrc_2019.php

[12] NATO (2023). *Climate Change and Security Impact Assessment*. https://www.nato.int/nato_static_fl2014/assets/pdf/2023/7/pdf/230711-climate-security-impact.pdf

[13] Turken, S. (2020). *Virginia unveils new framework to deal with sea level rise*. WHRO. https://whro.org/news/local-news/14390-virginia-unveils-new-framework-to-deal-with-sea-level-rise

[14] Bassetti, F. (2023). Is the AMOC one of the planet's most vulnerable tipping points?. *Climate Foresight*

[15] Bellafiore et al. (2021). Saltwater Intrusion in a Mediterranean Delta under a Changing Climate. *JGR Oceans*, *126*(2). AGU. https://doi.org/10.1029/2020JC016437

[16] Henley et al. (2023, June 3). *Fires, floods and disappearing beaches: can Mediterranean holidays survive?*. The Guardian. https://www.theguardian.com/environment/2023/jun/03/fires-floods-and-disappearing-beaches-can-mediterranean-holidays-survive

[17] Garric, A. (2023, July 29). *Why the Mediterranean basin has become the climate crisis 'hotspot'*. Le Monde. https://www.lemonde.fr/en/environment/article/2023/07/28/why-the-mediterranean-basin-has-become-the-hotspot-of-climate-crisis_6070940_114.html

[18] Benedetti-Cecchi, L. (2021). Complex networks of marine heatwaves reveal abrupt transitions in the global ocean. *Sci Rep.*, *11*, 1739. https://doi.org/10.1038/s41598-021-81369-3

[19] Giles, C., & Ben Zion, I. (2022, August 16). *Scientists warn of dire effects as Mediterranean heats up*. CTV News. https://www.ctvnews.ca/climate-and-environment/scientists-warn-of-dire-effects-as-mediterranean-heats-up-1.6030380

[20] UNHCR (2023). *UNHCR, UNICEF, IOM: deepest condolences for those involved in yet another shipwreck in the Mediterranean Sea* – Press Release

[21] Goodman, S., & Kertysova, K. (2022). NATO: An unexpected driver of climate action?. *NATO Review*. https://www.nato.int/docu/review/articles/2022/02/01/nato-an-unexpected-driver-of-climate-action/index.html

[22] O'Shea, H., Smith, Z., & Poole, K. (2021, May 6). Biden administration lays out 30x30 vision to conserve nature. NRDC. https://www.nrdc.org/experts/helen-oshea/biden-administration-lays-out-30x30-vision-conserve-nature

[23] Zaika, Y., & Lagutina, M. (2023). Arctic science diplomacy in new geopolitical conditions: From "soft" power to "hard" dialogue? *Polar Record, 59*, E23

[24] Polejack, A., & Fernandes Coelho, L. (2021). Ocean Science Diplomacy can Be a Game Changer to Promote the Access to Marine Technology in Latin America and the Caribbean. Frontiers in Research Metrics and Analytics. *Sec. Research Policy and Strategic Management*, 6. https://doi.org/10.3389/frma.2021.637127

[25] Onea, F., & Rusu, E. (2022). A spatial analysis of the offshore wind energy potential related to the Mediterranean islands. *7th International Conference on Advances on Clean Energy Research*, 2022 April 20-22, Barcelona, Spain. https://doi.org/10.1016/j.egyr.2022.10.249

[26] Staschus, K. et al. (2020). *Study on the offshore grid potential in the Mediterranean region – Final report*. European Commission, Directorate-General for Energy. https://data.europa.eu/doi/10.2833/742284

Alternative future visions for NATO maritime operational energy and power

Francis GRIFFITHS[a,1], Lisa HAMMOCK[b] and Andrew TATE[c]
[a] *Royal Navy Develop Directorate*
[b] *Royal Navy Climate Change & Sustainability Head*
[c] *Defence Science & Technology Laboratory*

Abstract. There has been much discussion regarding the global maritime energy transition and what this will mean for NATO maritime forces. Whilst there is potential for it to present major challenges in sustainment and freedom of action and manoeuvre, there are also opportunities which could deliver enhanced operational capability — through identifying ways to operate differently with new technology. To mitigate risks and exploit opportunities, NATO maritime forces will need a shared head mark for the future maritime operational energy system. Building on previous work in this area, this concept study proposes a selection of alternative future visions for NATO Maritime power and energy, in the 2045 – 2055 timescale, in the form of five "Operational Views" (OV-1) and energy flow diagrams. The intent is to bring these options to life to assist in stimulating structured discussion and debate, including drawing out national perspectives. This in turn should assist in prioritizing areas for NATO and national science and technology, including consideration of potential "moon-shot" higher risk ideas.

Keywords. Operational Energy, Fuel, Climate Change, Sustainability, Energy Vectors, Nuclear Power

1. Introduction

It is now widely recognised that a global energy transition is underway in response to climate change and a move towards greater sustainability [1] with many NATO member states and partner countries committed to achieving Net Zero by 2050 [2]. Aligned with the International Maritime Organisation's Strategy [3], the global shipping community is at the early stages of reducing emissions. Major reductions in emissions will require a move away from fossil fuels with platforms designed for alternative energy sources [4]. The impact this diversification of maritime fuel supplies will challenge the current model of sustainment and freedom of action and manoeuvre for NATO maritime forces. However, it has also been argued that changes represent a "moment of maritime opportunity" [5] for operational energy. When considered alongside other developments in the maritime battlespace — including Artificial Intelligence, increasingly autonomous systems and future sensors and effectors — there is potential to move from thinking about platforms to a "force mix of complex or simple, crewed or uncrewed assets to meet capability needs" [6], leveraging dual-use technology developments.

---

[1] Corresponding Author: UK Navy CMD Francis Griffiths, francis.griffiths756@mod.gov.uk. The views presented are those of the authors and do not necessarily represent the views of the Ministry of Defence.

NATO’s 2023 Climate Change and Security Impact Assessment notes that a priority for the NATO naval armaments community will be research into alternative fuels whilst reducing the Carbon Intensity (CI) of warships. The way in which NATO maritime forces operate and are sustained through replenishment of common fuels means that any future operational energy solution must be taken forward with interoperability as a priority [7].

To mitigate risks and exploit opportunities, NATO maritime forces will need a common vision of the future maritime operational energy[2] [8] system and to consider how capabilities will be delivered from future platforms and achieve “Energy transition by design” [9]. This shared vision should enable coherence in NATO and member state science and technology (S&T) activity in addition to leveraging commercial developments to achieve operational advantage.

This concept study proposes a selection of alternative future visions for NATO maritime energy and power, building on previous work to present future options in the 2045 – 2055 timescale. These are shown in the form of five “Operational View” (OV-1) and energy flow diagrams, with associated S&T focus areas. The aim is to bring future maritime operational energy vector options to life and assist in stimulating structured discussion and debate, drawing out national perspectives and shaping NATO S&T priorities.

In generating these visions, the aim has been to represent options, which NATO maritime forces can directly influence or address. This accepts that defence has limited ability to predict and influence the future geographic availability, net quality, CI and production volumes of alternative energy sources and fuels.

The selected visions aim to capture the S&T enablers that would allow navies to respond to potential changes to markets and technology. These responses include options that allow them to adapt better and follow the market, or to become more independent of the market, through energy efficiency, generation of their own energy or fuels, or by delivering future capability in new, less energy intensive ways. Vector options range from those that impact whole fleet design and interoperability within NATO, to those which are more platform focused. Whilst presented as five courses of action, multiple combinations would be possible and, to an extent, desirable.

OV-1 diagrams aim to illustrate impacts to naval operation and capabilities. Each energy vector diagram illustrates a “well to platform wake or effect”[3] energy flow (key at **Figure 1**), highlighting the scale and scope of the vector discussed. Based on baseline supporting commercial technology and potential energy market in 2045 – 2055 and expected needs of naval forces, navy specific S&T needs to make the vector viable are drawn out. Both the minimum S&T technology and analysis needs are highlighted, along with higher-risk “moon-shot” S&T options that could radically change the applicability and achievability of the energy vector.

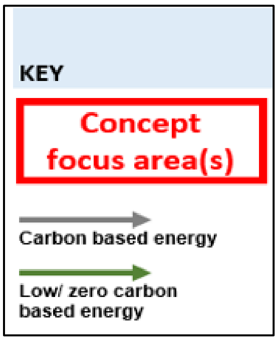


Figure 1. Key for energy vector flow diagrams

---

[2] Defined by the US Navy as: “Operational energy is required for training, moving, and sustaining military forces and weapons platforms for military operations. It includes energy used by ships, aircraft, combat vehicles, and tactical power generators.”

[3] Including power and energy requirements of off-board platforms and systems

2. Vision 1: NATO “Owns” More of the Energy Supply Chain

Retaining operational benefits of carbon-based fuels while decreasing Well-To-Tank (WTT) CI, utilising common fuels across full range of platforms.

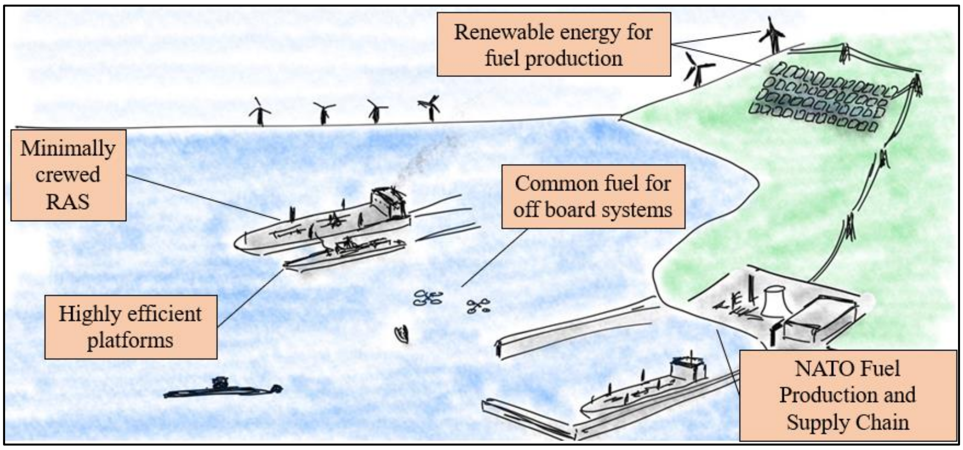


Figure 2. Vision 1 Operational View

2.1. Vision Overview

Continue to use carbon-based liquid fuel (for interoperability, energy density and survivability benefits), but “own” aspects of the supply chain to manage WTT CI & availability risks. Platforms use a mix of drop-in fuels, allowing growth in use of bio-derived or synthetic fuels as availability increases. Potential for single NATO fuel across domains via global NATO fuel network. Minimise net impact to platforms & capability.

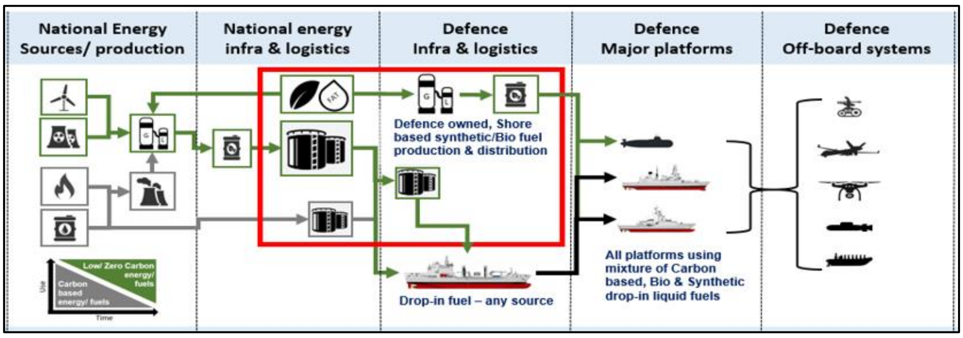


Figure 3. Vision 1: Energy Flow

2.2. Key enablers for vision:

- NATO fuel strategies and infrastructure.
- Effective use of NATO real estate to support energy generation and fuel synthesis.
- Ability to manage and track CI of supply chains.

2.3. Essential S&T and Analysis needs:

- Focus on efficiency – minimise the energy demand.
- Limited materials compatibility work and trials.
- Analysis: scale/locations of fuel production/storage/distribution systems.
- By 2050: S&T may need to support continued use of Internal Combustion Engines if commercial maritime move to alternative fuels.
- Higher Risk “moon-shot” S&T: None required**.**

3. Vision 2: NATO Aligns to Commercial Shipping

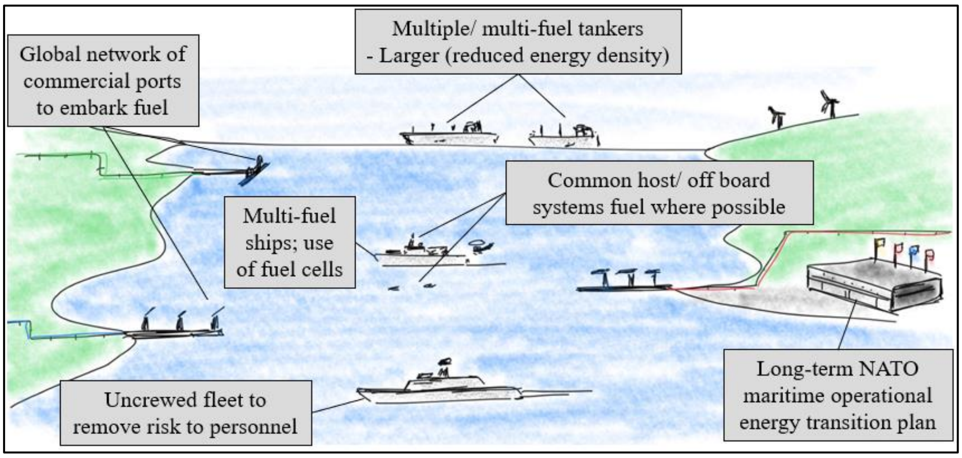


Figure 4. Vision 2 Operational View

3.1. Vision Overview

Follow and benefit from commercial developments and availability in alternative fuels (gaseous & liquid) that reduce Well-To-Wake (WTW) CI. May also require intervention in supply chains, or ownership of key parts of supply chains. Significant impacts to platform design and defence logistics to manage changes in energy density, replenishment, safety & survivability aspects.

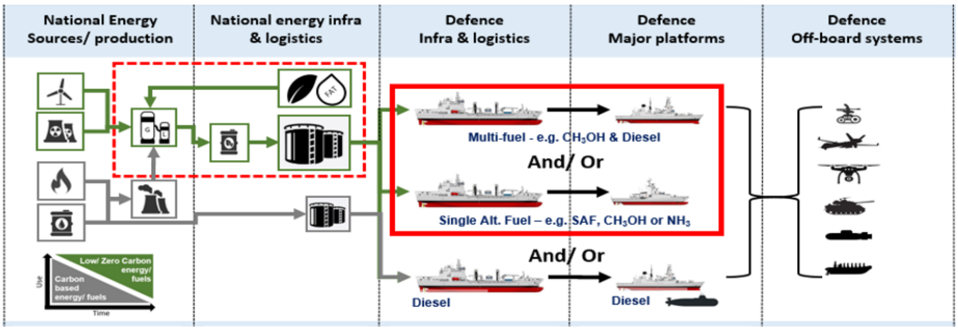


Figure 5. Vision 2 Energy Flow

3.2. Key enablers for vision:

- NATO energy/fuel strategies and infrastructure; alignment of transition.
- Technologies and design options to manage survivability of naval platforms with selected alternative fuels.
- Replenishment technologies for selected alternative fuels.

3.3. Essential S&T and Analysis needs:

- Technologies and design options to manage survivability of naval platforms.
- Replenishment technologies for selected alternative fuels.
- Higher Risk “moon-shot” S&T:
    - Use of autonomy, system of systems approach to reduce risk to life.
    - More automated, faster replenishment of selected alternative fuels.

4. Vision 3: NATO Interoperability is “Electrical by Default”

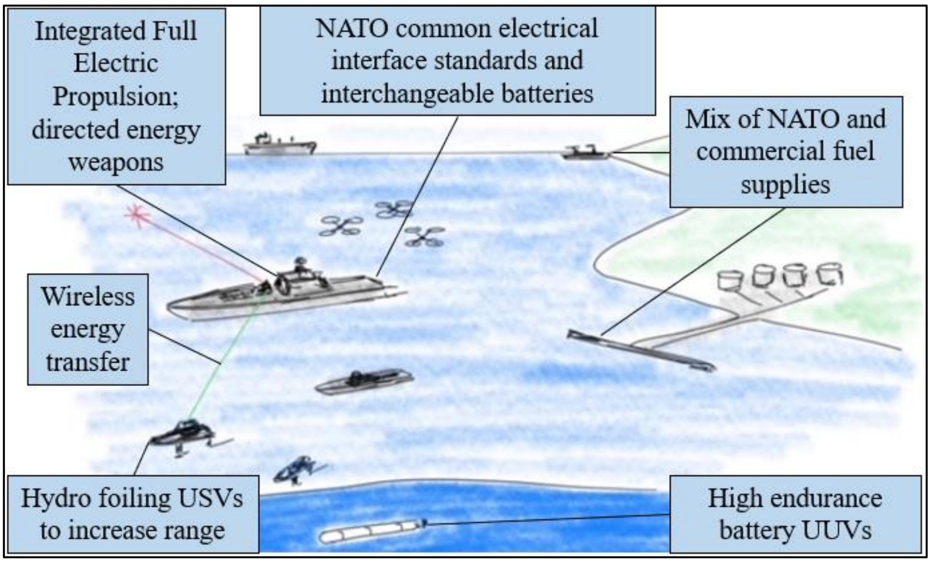


Figure 6. Vision 3 Operational View

4.1. Vision Overview

Key energy enabler to manage complex networks of platforms & highly capable, long endurance off-board systems. Independent of fuels used throughout any green transition. At-sea micro-grids providing power, energy storage, connectivity to a range of platforms with defined and common interface/battery standards, assuming electricity is the default energy vector. Leverage commercial advances in technology; military S&T if required.

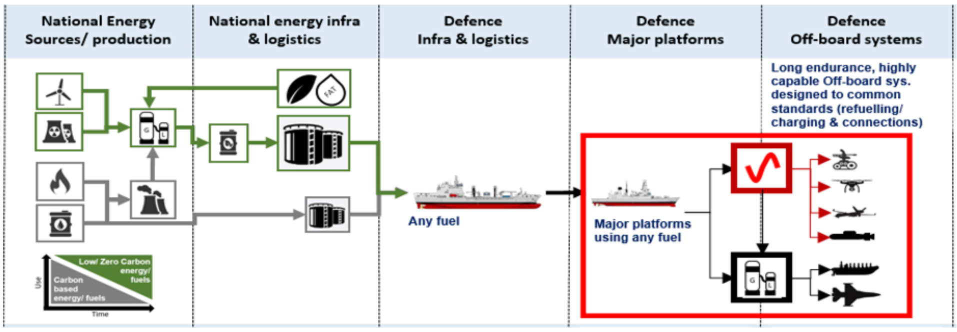


Figure 7. Vision 3 Energy Flow

4.2. Key enablers for vision:

- NATO interface standards and policies.
- Technologies and design options to manage survivability of energy storage/transfer.

4.3. Essential S&T and Analysis needs:

- Focus on platform efficiency — minimise energy demand.
- High-density energy storage — technologies beyond commercial requirements.
- Development of charging/battery exchange systems to reduce interface risks.
- Higher Risk “moon-shot” S&T:
  - Use “Smart Fleet” energy management in connected platforms and uncrewed vehicles (UxV).
  - Ultra dense energy storage to maximise capability/reduce transfers.

  - Develop concepts such as wireless energy beaming.

5. Vision 4: Operational Energy Independence via at-sea Nuclear

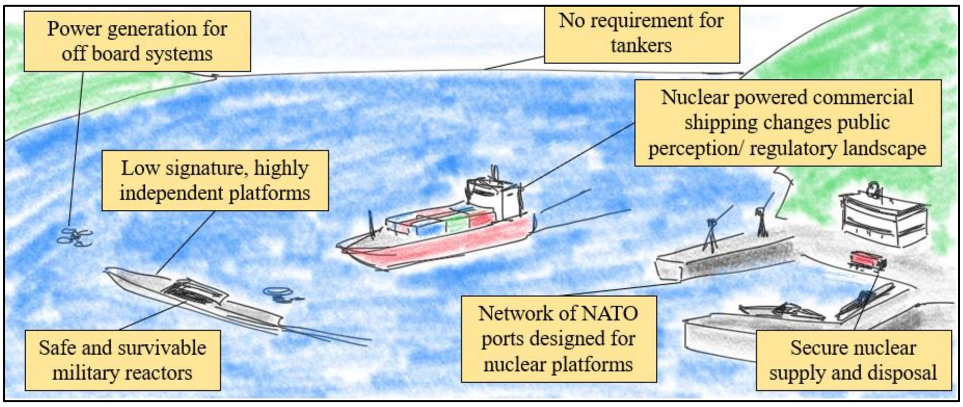


Figure 8. Vision 4 Operational View

5.1. Vision Overview

Utilising developments in civil nuclear industry and wider defence nuclear enterprises to achieve operational energy independence for key platforms. Includes the potential use of Gen4 and micro reactors as direct power sources on major platforms. Potential opportunity to produce synthetic low or zero-carbon fuels either at sea on generation-after-next replenishment platforms.

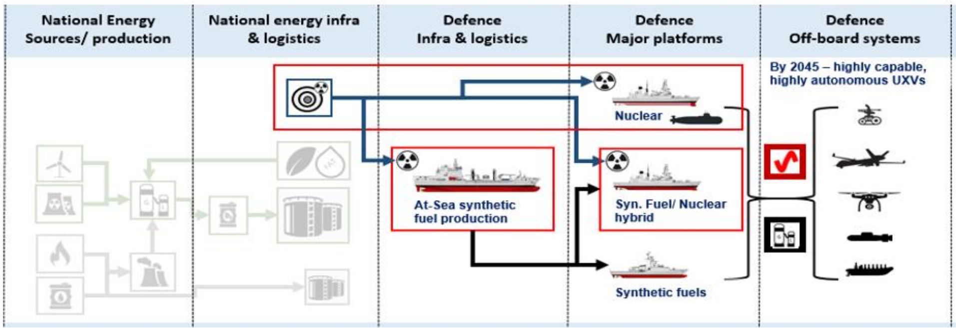


Figure 9. Vision 4 Energy Flow

5.2. Key enablers for vision:

- Surface platform nuclear based designs to meet political, regulatory, safety, survivability and disposal needs.
- More favourable political, public and regulatory environment.
- Compact and efficient nuclear powered synthetic fuel production.

5.3. Essential S&T and Analysis needs:

- Analysis of regulatory issues of portable reactors.
- Platform designs that safely and effectively integrate civil nuclear technologies.
- Low size, weight and power marine synthetic fuel production systems.
- Analysis to inform/understand concept of operations for “more” nuclear fleets.
- Higher Risk “moon-shot” S&T:
  - More radical platform designs optimized for integration of emerging reactor technologies.

- o Technologies that radically improve efficiency of nuclear-to-electricity energy conversion.

6. Vision 5: Leveraging Novel Technology to Deliver Effects Differently

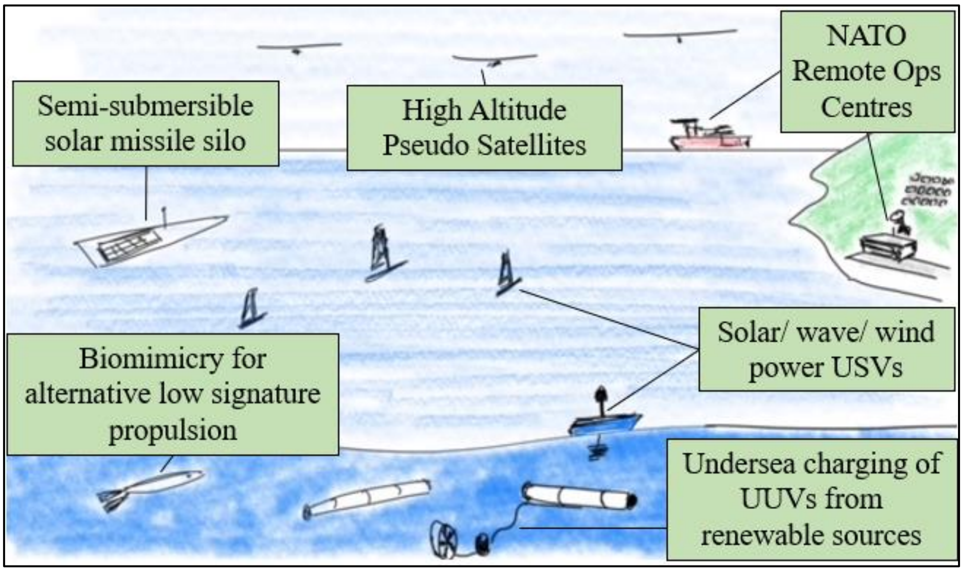


Figure 10. Vision 5 Operational View

6.1. Vision Overview

Take a "System of Systems Approach" to maritime capabilities. Reducing overall energy demand through the use of alternative capability delivery approaches — e.g. through the wider use of uncrewed systems, networked systems & novel platforms & sensors. Benefits also arising from decoupling effect from speed and significantly improving persistence & endurance — operational energy delivery becomes less of a limiting factor.

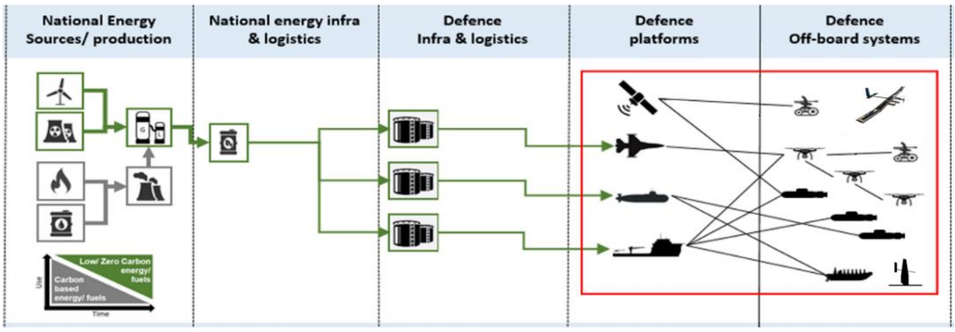


Figure 11. Vision 5 Energy Flow

6.2. Key enablers for vision:

- Command and control in a denied or degraded environment (C2D2E).
- Novel, compact and energy efficient platform and payload elements (in system of systems).

6.3. Essential S&T and Analysis needs:

- Development of high-density, high-efficiency payloads — e.g. sensors.
- Development of enabling AI, autonomy and controls.

- Analysis to understand operational effectiveness and energy demands of distributed networks of systems.
- Higher Risk “moon-shot” S&T: Persistent, long endurance uncrewed platform concepts powered by renewable energy**.**

7. Conclusion

As stated in the NATO 2022 Strategic Concept [10], the Alliance will reduce emissions, improve energy efficiency and invest in the transition to clean energy sources – leveraging green technologies while ensuring military effectiveness. The global maritime energy transition presents a threat to the current model for naval surface platform sustainment, due to reduced access to current fuels, in addition to tighter restrictions on emissions. Achieving a NATO maritime operational energy transition by design will be shaped and enabled by S&T: delivering beneficial and timely impact; focusing on addressing areas where there is a “defence delta”; connecting across borders; and, linking the S&T and operator communities. The visions in this paper aim to support these goals. The NATO Compendium of Best Practice is a great example of sharing national perspectives [11].

Whilst this paper presents five separate visions, elements of these could be merged to generate combinations which enable operational advantage, aligning solutions with operating concepts. However, it is unlikely that all visions could be successfully pursued in parallel; there will therefore be choices for NATO in the very near future — noting the enabling changes to energy supply chains, platform designs and operating concepts. A delay in making a decision is, in itself, a decision; in this case to move forward with vision 1 by default. Any transition period will require NATO coordination and management.

Across all courses of action, pursuing greater energy efficiency supported by enhanced energy data and digitization of platforms will enable informed decision making; common methodologies in NATO could assist with this. However, the biggest gains will come from thinking differently and delivering effects through alternative means. Enabled by some of the higher risk moon-shot operational energy S&T ideas proposed in this paper, the next two decades present a “once-in-a-generation” opportunity to deliver a step change in maritime capability with a more distributed force. It is in the development of alternative concepts of operations, enabled by new technology, that there is real potential to exploit opportunities and reduce vulnerabilities to deliver operational advantage in the maritime domain.

References

[1] International Energy Agency (2022). *World Energy Outlook 2022*. https://www.iea.org/reports/world-energy-outlook-2022

[2] ZeroTracker.net (2023). *Data Explorer*. www.zerotracker.net

[3] International Maritime Organization (2023). *International Maritime Organisation Strategy on Reduction of Greenhouse Gas Emissions from Ships*. Resolution MEPC.377(80) Annex 1, 2023.

[4] Det Norske Veritas (2023). *Maritime Forecast to 2050 Report*. https://www.dnv.com/publications/maritime-forecast-to-2050-2023-edition-246744

[5] Sturtevant, G.H. et al (2022). A moment of maritime opportunity? The operational energy challenge. *International Naval Engineering Conference 2022*. https://rdmobile-palermo-production.s3.amazonaws.com/053d3008-58b0-411c-b767-7ccb1e73476b/event-15236/310315042-INEC_2022_paper_25.pdf

[6] Skarda, R. et al (2022). The Future Naval Battlespace and implications for Key Enablers. *International Naval Engineering Conference 2022*. https://rdmobile-palermo-production.s3.amazonaws.com/053d3008-58b0-411c-b767-7ccb1e73476b/event-15236/310556862-INEC_2022_paper_54.pdf

[7] NATO (2023). *Climate Change and Security Impact Assessment, 2nd Edition*. The Secretary General's Report. nato.int/nato_static_fl2014/assets/pdf/2023/7/pdf/230711-climate-security-impact.pdf

[8] U.S. Fleet Forces Command Website. https://www.usff.navy.mil/Organization/Headquarters/Fleet-Installations-and-Environment/Energy/

[9] NATO (2022, June 28). Opening speech by NATO Secretary General Jens Stoltenberg at the High-Level Dialogue on Climate and Security. https://www.nato.int/cps/en/natohq/opinions_197168.htm

[10] NATO (2022). *NATO Strategic Concept*. https://www.nato.int/cps/en/natohq/topics_210907.htm

[11] NATO (2023). *Climate Change and Security Action Plan Compendium of Best Practice*. 230710-climate-change-best-practices.pdf

A systems-thinking approach addressing the impact of climate change on naval defence operations

Titia A. KUIPERS [a,1] and Rob P. M. VAN WAAS[a]
[a] *TNO, Department of Military Operations*
ORCiD ID: Titia KUIPERS https://orcid.org/0009-0005-0293-9809

Abstract. Dynamics resulting from climate change that significantly affect planning and operations of the Alliance can be better understood by applying a systems-thinking approach. A systems-thinking approach allows us to gain insight into complex systems and its (in)direct effects, like the effects of climate change on naval defence operations. This paper presents the application of systems thinking to naval defence operations in the High North region, in order to better understand the added value of systems thinking in this context. For this purpose the following steps have been taken: 1) collection and analysis of trends in different domains (demographic, economic, social, technological, ecological, and (geo)political); 2) capturing these trends and their interdependencies in a causal loop diagram; 3) validation of the model; and, 4) use of the model to explore mechanisms relevant to naval defence operations, and to support the mapping of the first and second order effects of climate change on variables of interest in the use case of the High North region.

Keywords. High North, Naval Defence, Systems Thinking, Climate Change, System Dynamics, Causal Loop Diagram, MARVEL

1. Introduction

Our changing climate has a significant impact on ocean acoustics, which in turn has a direct impact on submarine warfare and anti-submarine warfare operations. Anticipated alterations in ocean acoustics are expected in propagation conditions and ambient noise levels. The ambient noise landscape is intrinsically tied to factors such as sound speed and absorption characteristics, both of which are poised to be influenced by shifts in temperature and oceanographic currents. Furthermore, climate change is expected to exert substantial influence on the geographical distribution of ambient noise sources [1]. This is due to factors such as alternations in marine biology, temperature fluctuations, melting of sea ice and consequently increased human-made noise from expanded shipping activities. Shifts in sound speed profiles and their consequential effects on propagation conditions will affect the performance of sonar systems.
As various factors influence sonar performance – and sonar performance in turn exerts a direct impact on submarine warfare and anti-submarine warfare operations, it is crucial to gain more knowledge on these topics.

---

[1] Corresponding Author: T.A. Kuipers, titia.kuipers@tno.nl.

1.1. Scope

Due to the exploratory nature of this research, and to be able to conduct a more in-depth detailed examination of the phenomenon, the High North region is selected as a case study. This region was selected due to the strategic importance of the Arctic to NATO [2]. The Arctic is undergoing rapid and unprecedented changes, characterized by rising temperatures, dwindling sea ice cover, melting glaciers and shifting weather patterns. These transformations have far-reaching implications [3] [4]. New maritime routes due to melting ice in the Arctic has the potential to reshape global trade and transportation patterns, making it a critical area for economic and geopolitical analysis. The region's accessibility to vast reserves of natural resources, including oil, natural gas, minerals and fisheries, underscores its strategic importance for energy security and economic development. At the same time, climate conservation efforts in the Arctic are pivotal for preserving fragile ecosystems, biodiversity, and mitigating the release of potent greenhouse gases from thawing permafrost. Altogether, the region is witnessing increasing territorial claims and geopolitical tensions, making it essential to assess the complex interplay of international interests and governance in this rapidly changing environment.

1.2. Goal

The objective of this paper is to illustrate to what extent a systems-thinking approach can support gaining insights into the complexities and potential (indirect) consequences and effects of climate change on naval defence operations, and specifically, the ability to detect underwater vessels using passive sonar technology.

1.3. Disclaimer

The aim of applying the systems-thinking approach is to explore mechanisms within NATO's future operating environment (for ocean acoustics), rather than providing a definitive answer.

2. Methodology

A systems-thinking approach requires taking a sequence of steps. The first step is to collect and analyse trends according to DESTEP (demographic, economic, social, technological, ecological, and (geo)political) method. The next step is to build a MARVEL model, which is an approach developed by TNO [5]. The acronym MARVEL stands for Method to Analyse Relations between Variables using Enriching Loops. The next step is to face-validate the model with input from subject matter experts. The final step is to use the model to explore mechanisms in the naval defence domain and conclude on our main research question. The following paragraphs briefly describe how we performed each step in relation to our case study. Please note that building the model requires us to make a large number of causality assumptions. We conducted validation interviews with subject matter experts to test the validity of these assumptions.

2.1. Collect and analyse trends

To have a starting point for our modelling effort, we first collected trends relevant to the case and broader context. For this study, we made use of existing findings from other TNO studies [6]. From this we extracted: mega-trends — strategic forces that cannot easily be turned around by society: e.g. climate change, urbanization; trends — discernible patterns of change or specific direction of change e.g. extreme weather variants, increasing number of megacities; and, signals — individual events: e.g. average temperature of the Arctic, number of people moving from rural to urban. The long list of mega-trends, trends and signals divided into DESTEP categories served as the starting point for model building.

2.2. Build a MARVEL model

For this study, we enhanced an existing causal loop diagram originally created for broader foresight applications [5]. We tailored this to our requirements by introducing variables and causal connections within the context of our use case. This process is facilitated through the utilization of the MARVEL method.

MARVEL causal loop diagrams use the concepts of variables, relations and feedback loops. Variables are defined as concepts that can increase or decrease. For example *amount of perennial sea ice*, or *urbanization within Arctic*. Variables are connected by causal links between them. These causal links have a direction (a cause and effect) and can be positive or negative. In practical terms, a positive link will imply that as the cause increases, the effect will likewise exhibit a higher value over time than it otherwise would. Conversely, a negative polarity implies that when the cause increases, the effect will exhibit a lower value than it otherwise would have exhibited, and when the cause decreases, the effect will exhibit a higher value over time.

In causal loop diagrams, special attention is given to feedback loops. In a feedback loop, a variable has a reinforcing or balancing effect on itself. In climate change, there are several impactful reinforcing feedback loops. For example, an increase in greenhouse gas emissions leads to global warming, which leads through thawing permafrost to the release of more greenhouse gasses. An example of a balancing feedback effect could be an increase in Arctic drilling activities, which leads to more accidents affecting the Arctic ecosystem, motivating more international regulations that in turn limit the amount of Arctic drilling activities.

The MARVEL tool allows us to identify feedback loops and causal pathways in our model, which can provide valuable insights into how interconnected factors interact.

2.3. Model validation by subject matter experts

In order to assess the structural validity of the MARVEL model built in step two, several subject matter experts were consulted [7]. Often the validation process leads to new insights and additions to the model. This also occurred in relation to our case study. Hence, steps two and three were reiterated wherever deemed necessary.

2.4. Use model to explore mechanisms in the naval defence domain

The resulting causal loop diagram from step three serves as a basis for exploring different mechanisms in naval defence operations, and supports investigating the first (direct) and second order (indirect) effects of climate change on variables of interest.

3. MARVEL model naval defence in High North

The resulting MARVEL model contains variables within each of the DESTEP domains: demographic (purple) — e.g. the concentration of people in larger urban areas and the decline of smaller settlements in the High North region is of influence; economic (blue) — e.g. the presence of natural resources such as oil and gas; social (yellow) — e.g. more attention to protecting the arctic driven by the indigenous population; technological (grey) — e.g. the development of unmanned vehicles to operate in the arctic waters; ecological (green) — e.g. the impact of activity in the arctic on the mammal population; and, (geo)political (light-tan) — e.g. the establishment of research bases and their potential to act as a cover for militarization of the Arctic by world powers.

3.1. *MARVEL model*

The resulting MARVEL model consists of 57 variables and 154 causal connections between them. The connections were established by using the MARVEL software, by briefly assessing and discussing the expected relative strength and influence of the loop on the system, based on experience, expertise and logical thinking. Figure 1 provides an illustration of the MARVEL model used for this study and is only readable on a full screen.

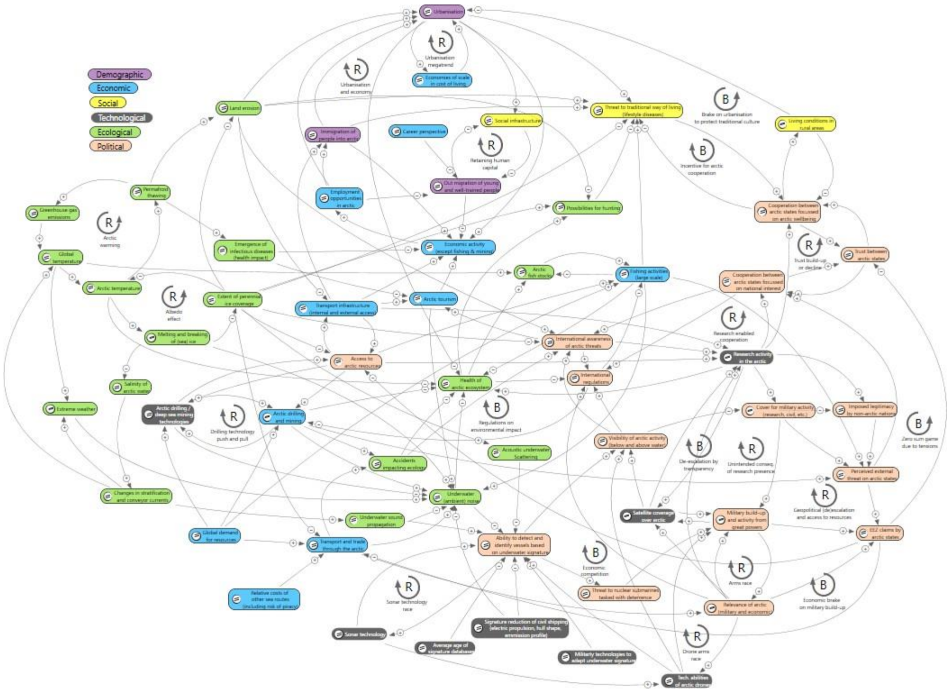


Figure 1. An overview of the complete MARVEL model used for this study.

3.2. *Validation of model*

The model structure was validated using interviews with six subject matter experts within the TNO organisation. Their expertise comprised of different fields relevant to the case study, such as (military application of) acoustics and sonar, offshore engineering, maritime system innovation, and naval defence. During the interviews, we asked questions to validate, challenge or underpin parts of the model. After each interview, changes to the model were made in areas related to the specific field.

4. Application of the model to a specific variable (vessel detection)

The model in **Figure 1** is used to explore first and second order effects of climate change on variables of interest. In the following section, the model will be utilized to delve into the mechanisms influencing a specific variable of interest, which is central to the case study: the *ability to detect and identify vessels based on underwater acoustic signature.*[2]

4.1. *Effects of an increase in global temperature on the ability to detect and identify vessels based on underwater signature.*

Figure 2 and **Figure 3** provide a visual highlight of the first and second order effects for both an increase and decrease of the *ability to detect and identify vessels based on underwater signature* within the economic, ecological and (geo)politics DESTEP domains. The *ability to detect and identify vessels based on underwater signature*, depends on *underwater (ambient) noise*, and *underwater sound propagation*, which in turn are influenced by an increase in *global temperature*s in different ways:

- An increase in global temperatures is expected to lead to fish migrating into the

---

[2] In the remainder of this paper, signature refers to acoustic signature.

cooler Arctic waters. As *Arctic fish stocks* become more available, *fishing activities* will increase which will lead to more *underwater (ambient) noise* caused by fishing boats and thus interfere with the *ability to detect and identify*.

- Increase in *extreme weather events* also leads to more *underwater (ambient) noise*, through the physical forces of turbulence, intensified winds and changed water quality, all of which collectively contribute to a noisier underwater environment, reducing the *ability to detect and identify*.
- An increase of *melting and breaking of (sea) ice* also leads to less *perennial ice coverage*, opening new maritime routes as a result of which *transport and trade through the Arctic* will increase, leading to more *underwater (ambient) noise*, hampering with the *ability to detect and identify*.
- As *melting and breaking of (sea) ice* increases, fresh water is released back into the ocean, which decreases the *salinity of arctic water* causing *changes in stratification and conveyor currents*, *which* lead to a decrease in *underwater sound propagation*, and thus interfere with the *ability to detect and identify*.
- Perennial ice acts as a barrier to sound propagation, reflecting and scattering sound waves as they encounter different ice structures. Less *perennial ice coverage* means fewer barriers in the water, leading to less *acoustic underwater scattering*, resulting in an increase in the *ability to detect and identify*.
- As *Arctic temperatures* rise, the *health of the Arctic ecosystem* deteriorates, which negatively influences the *Arctic fish stock*. As a reaction, the international community will establish more *international regulations*, regulating (large scale) *fishing activities*, which has a direct impact on the reduction of *underwater (ambient) noise. International regulations* will also control *Arctic drilling*, which will lead to less *underwater (ambient) noise*, and in turn increase the *ability to detect and identify*.

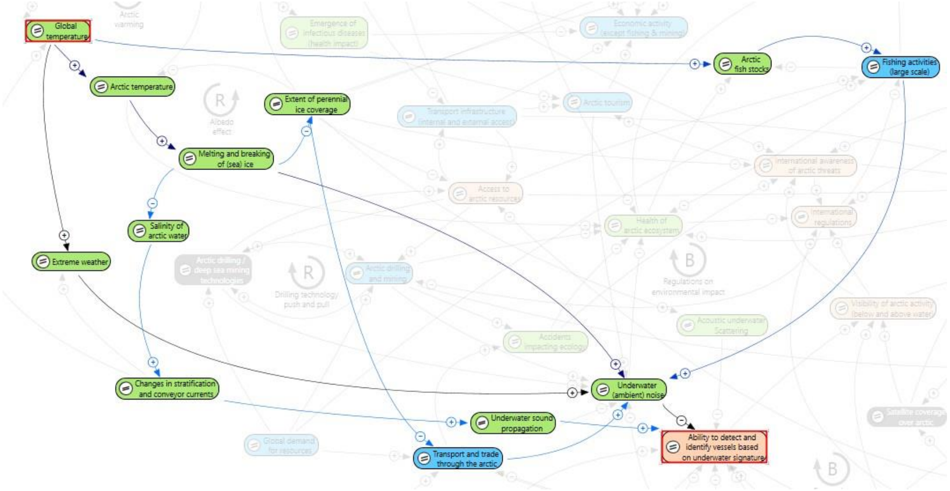


Figure 2. Positive polarity of an increase in *global temperature* on *the ability to detect and identify vessels based on underwater signature*.

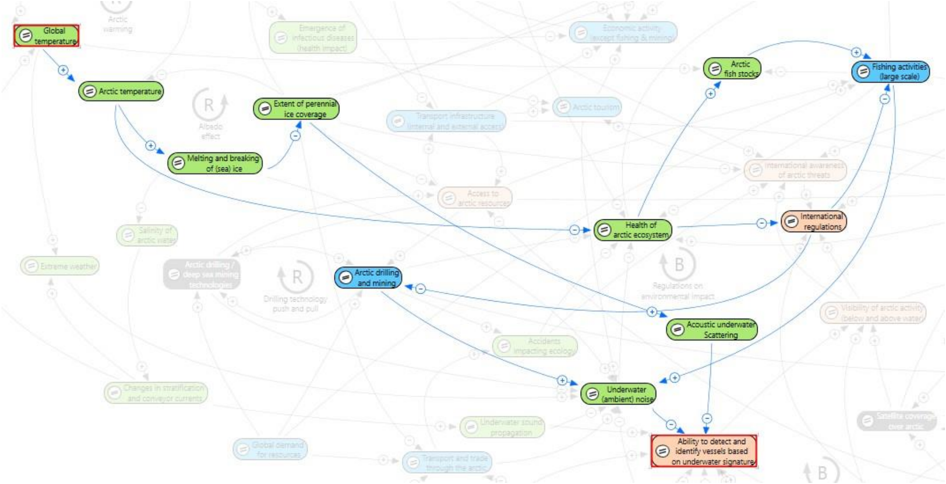


Figure 3. Negative polarity of an increase in *global temperature* on the *ability to detect identify vessels based on underwater signature*.

4.2. Effects of a change in the ability to detect and identify vessels based on underwater signature

In the previous section, pathways leading to both an increase and decrease of the *ability to detect and identify vessels based on underwater signature* were identified. **Figure 4** provides a visual highlight of the first and second order effects for both an increase and decrease of the *ability to detect and identify vessels* within the technological and (geo)political DESTEP domains.

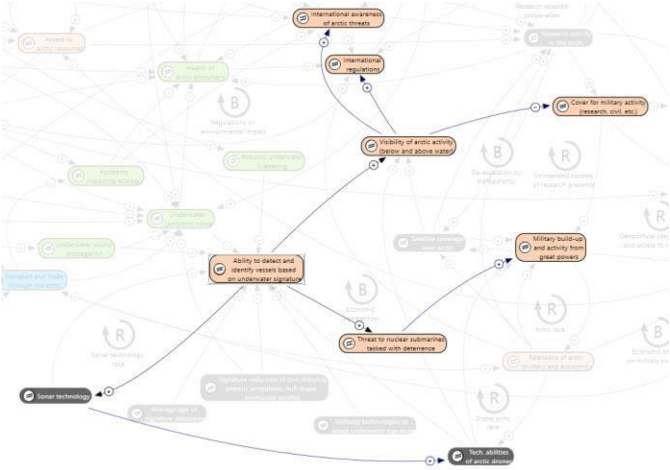


Figure 4. First and second order effects from *ability to detect and identify vessels based on underwater signature*.

- Firstly, regarding the technological domain, there is a direct causal link with sonar technology. If the ability to detect and identify vessels increases, it is expected that this will accelerate the development of *sonar technology*. This is linked to a feedback effect of a ‘sonar-technology race’, and applies to the learning effects between using and developing sonar technology. Following an advancement in sonar technology, a second order effect can be seen. This indirect effect is related to the *technological ability of Arctic (underwater) drones*, since they directly depend on sonar technology for sensors and communication.

- Secondly, in the (geo)political domain, the *ability to detect and identify vessels based on underwater signature* has a first order effect on the *threat to nuclear submarines tasked with deterrence*. Submarines equipped for Arctic operations can take advantage of the ice cover and use the veil of the Arctic to hide from adversary forces. By understanding the local oceanographic conditions, submarines can adjust their depth and speed to minimize sound emissions and maximize their stealthiness. Concurrently, these submarines may make use of the ice-related noises, mammals and other natural sounds to mask their own engine and propulsion noises, while advancements in stealth technology may reduce their acoustic signature. Likewise, by navigating through ice formations, they may break line-of-sight with adversary sensors, making them less detectable. A change in detectability could however trigger an effect in military build-up. This is an interesting causal pathway to take into account, especially if at the same time, the *ability to detect and identify* increases. Another first order effect is the *visibility of Arctic activity* which in turn influences *international awareness of Arctic threats* and (the enforcement of) *Arctic regulations*, which can consequently hinder the potential *cover for military activity* (by for example research, tourism or search and rescue activities).

5. Conclusions and future work

The objective of this paper is to illustrate to what extent a systems-thinking approach can support gaining insight into the complexities and potential (indirect) consequences and effects of climate change on naval defence operations. Specifically, the ability to detect underwater vessels using passive sonar technology.

In conclusion, application of a systems-thinking approach as defined in section 2 offers a transformative lens through which we can view complex problems such as climate change and its intricate relations with naval defence operations. Following the DESTEP method and linking factors found in mega-trends, trends and signals, unlocks a potential for profound insights in mechanisms caused by climate change, that might otherwise stay hidden in isolated analysis. An example of such insight is an increase in detectability of adversary nuclear submarines tasked with deterrence, which could trigger an effect in military build-up.

A systems-thinking approach enables a comprehensive and shared understanding of the web of factors shaping challenges and opportunities. We found the model structure to be helpful in engaging with subject matter experts in different fields, and creating a common picture about the High North region and the implications of climate change on underwater acoustics.

In this paper, we only highlighted one variable of interest, the *ability to detect vessels based on underwater signature.* We expect our findings to be applicable to other variables in other domains of the model.

5.1. Recommendations

This research revolves around a particular variable of interest; the one of underwater vessel detection. However, this method enables the investigation of the wider impacts of climate change, and could thus be applied in other cases and areas of interest to NATO.

It is advised to develop the model further with experts and validate the model with subject matter experts in all demographical, economic, sociological, technological, ecological and geopolitical fields.

In the future, this approach or model could be used as a starting point to explore the first and second order effects of naval defence interventions. This can be essential for informing policy decisions, driving international cooperation, and advancing our collective efforts to combat existential challenges.

6. Acknowledgements

The research presented in this paper is part of the TNO Defence research programme V2370 *Impact of Climate Change on Sonar Performance*, in cooperation with the Netherlands Armed Forces and CMRE. This research also builds on the TNO Defence Risk-bearing exploratory research *‘Integrated Strategic Foresight’*. Special thanks to our colleagues Robbert van Vossen, Victor Oppeneer, Jeroen de Jonge, Jurrit Bergsma, Marco Huisman and Eric Engelbrecht, Carolina van Weerd, Eefje Smits-Clijsen and Caroline van der Weerdt from TNO, who greatly assisted this research by providing their insights and expertise.

References

[1] Affatati, A. Scaini, C., & Salon, S. (2022). Ocean sound propagation in a changing climate: Global sound speed changes and identification of acoustic hotspots. *Earth's Future*, *10*. https://doi.org/10.1029/2021EF002099
[2] NATO ACT (2023). *The Future of the High North*. The Future of the High North - NATO's ACT
[3] Congressional Research Service (2023). *Changes in the Arctic: Background and Issues for Congress*. CRS Report
[4] Mehta, K. et al. (2023). *Existing and Emerging Topics and Potential Priorities for the Safety and Security of the Maritime Environment*. RAND Corporation. https://www.rand.org/pubs/perspectives/PEA2110-1.html
[5] Veldhuis, G. et al. (2015). Collaborative problem structuring using MARVEL. *EURO Journal on Decision Processes*, *3*(3), 249-273
[6] van Waas, R. et al. (2023). *TNO RVO Challenge Integrated Strategic Foresight*
[7] Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics, *System Dynamics Review*, *12*(3), 183–210, 1996. 10.1002/(SICI)1099- 1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4

Climate Change, Arctic Security and Future Operations (CLIMARCSEC): a Multinational Capabilities Development Campaign (MCDC) project

Maria-Emanuela MIHAILOV[a], Tobias ETZOLD[b,1], William SPOON[c] and Albert CHAN[d]
[a] *Maritime Hydrographic Directorate, Constanta, Romania*
[b]*Norwegian Institute of International Affairs (NUPI), Oslo, Norway*
[c]*US Coast Guard, Joint Staff (J7) - Allies and Partners Force Development Division, Suffolk/Virginia*
[d]*Department of National Defence, Canada*
[a] ORCiD ID: Emanuela MIHAILOV https://orcid.org/0000-0003-4398-8891

Abstract. “Climate Change, Arctic Security and Future Operations” (CLIMARCSEC) is a new project within the 2023-24 project cycle of the Multinational Capabilities Development Campaign (MCDC), forming a US-led partnership of 23 nations/International Governmental Organizations (IGO), to create non-materiel capabilities to support multinational force operations and exercises by resolving or at least diminishing common military problems. With Norway as project lead, 19 states and IGOs participate in CLIMARCSEC as contributors or observers. Climate change occurs at some of the highest rates in the Arctic regions resulting in both emerging risks and new opportunities. The opening of the Arctic provides non-Arctic states/actors with easier access to the Arctic Ocean. In combination with changing geopolitical/strategic conditions and growing political and military tensions, climate change makes the Arctic strategically important for Multinational Forces (MNF) but also exacerbates an already challenging field for operations. These factors increase the need for stronger MNF situational awareness, operational capability, coordination, and policy changes. So far, various capability and coordination gaps (e.g., resource constraints, no joint MNF/NATO command structures in the Arctic) restrict MNF abilities to address the current and future challenges adequately.

Enhancing MNF’s Arctic capabilities requires a robust policy framework and better coordination of policies and activities to maintain a strong and effective security presence in the region and to ensure an operational advantage towards competitors in a rapidly changing — climate and threat-based — environment. All physical domains are relevant to the operational environment for this problem set — land, maritime, air and space — with a focus on the first two.

CLIMARCSEC will contribute to the analysis and make suggestions as to how existing and potential coordination and capability gaps could be closed and how future coordination and capability requirements could be met. To support this main goal, CLIMARCSEC will analyse how the implications and consequences of climate change will impact policy, strategy, arrangements for deterrence and defence, military assistance, planning, preparedness, and exercises and operations in the Arctic. It will also inform military and political decision makers of the current and projected state of security operations.

---

[1] Corresponding Author: Tobias ETZOLD, e-mail: tobias.etzold@nupi.no.

Keywords. Climate Change and Security, Arctic, Multinational Capabilities Development Campaign (MCDC), Multinational Forces (MNF), Military Operations, Capability and Coordination Gaps, growing political and military tensions.

1. Introduction

The Arctic has emerged as a focal point of global attention due to the unparalleled rates of climate change occurring within this remote region. The Arctic Ocean, which dominates the region, is a single basin primarily covered by sea ice, which connects the Pacific and Atlantic Oceans (**Figure 1**) through various straits and passages [1].

Dramatic environmental transformations are not only altering the Arctic landscape but also reshaping its geopolitical dynamics, presenting a unique confluence of emerging risks and new opportunities [2]. This paper introduces the recently established project CLIMARCSEC within the Multinational Capabilities Development Campaign (MCDC) [3] which examines the multifaceted relationship between climate change, evolving geopolitical conditions, and the strategic significance of the Arctic, particularly for Multinational Forces (MNF).

Figure 1. Arctic topographic map [4]

The Arctic is experiencing climate change at an accelerated pace compared with the rest of the planet. This phenomenon has been extensively documented in scientific literature. The Arctic Climate Impact Assessment (ACIA) [5] emphasized the region's vulnerability to rising temperatures, noting the alarming reduction in sea ice cover and the thawing of permafrost. These changes not only have profound implications for Arctic ecosystems but also contribute to global sea-level rise, as underscored by the Intergovernmental Panel on Climate Change (IPCC) [6]. This interconnectedness between Arctic climate change and its global ramifications and consequences forms the backdrop against which — among other issues such as economic and societal — security considerations must also be examined.

The melting of Arctic ice is ushering in an era of increased accessibility to the Arctic Ocean, facilitating navigation, resource extraction, fisheries and ecotourism. This transformation has captured the interest of non-Arctic states and actors, who are seeking to exploit the aforementioned emerging opportunities in the region. This trend has been observed and analysed in numerous academic studies [7][8], highlighting the strategic importance of the Arctic in a global context.

In tandem with these climate-induced changes and shifting geopolitical dynamics, the Arctic is witnessing growing political and military tensions, so far mainly spilling over from the outside, especially the deteriorating East-West relations in the course of Russia's war against the Ukraine. In combination with an at least theoretical prospect of territorial disputes and competition for resources in the Arctic itself, which however so far have not occurred to the scale anticipated by many observers in the past, such deteriorating relations have led to increased military presence and exercises. The relevance of the Arctic in global security discussions has been addressed by prominent scholars [9][10][11], who underscore the complexities and risks associated with these developments. The nexus between climate change and shifting geopolitical conditions also becomes evident when considering that transboundary threats such as climate change require international cooperation [12]. But under the current circumstances with the ongoing war in Ukraine, the so far well-functioning cooperation involving Western states and Russia is halted on most levels, for example in the intergovernmental Arctic Council, and in many policy areas.

Apart from hard security risks, also severe health risks could emerge as a consequence of melting ice. Scientists have found viruses and bacteria in the remote Arctic regions that could impact people in the Arctic as well as beyond the Arctic regions from which they originate [13]. There's at least one recent known case of infections and a death due to a virus released by the warm temperatures. The melting of the Arctic ice and the thawing of permafrost have health implications that are unknown to the general population, MNF and those who work in humanitarian and disaster reliefs. It is worth noting that the military will need to take into account of such potential risks for forces operating in the Arctic.

Thus, many factors will influence the structure and the operational tempos of future forces. Factors include climate change, geopolitics, resource exploitations and commercial competitions. Additionally, factors such as increased health risks, deployments of greater frequencies and/ or long deployment periods will cause additional stress on military members and families. Operations in the new environment may necessitate the modernization of forces, in terms of structure, recruitment and retention, education and training and military family support. CLIMARCSEC and future projects will help inform decision makers on the requirements for future forces.

Against the backdrop of these considerations, the Arctic is becoming strategically more important for MNF. Having become an area of low tensions after the end of the Cold War, this is in the process of changing due to global warming and increasing strategic competition [14]. Both aspects make the necessity for military operations more likely but at the same time more difficult as operating in this evolving environment presents a myriad of challenges. They range from ensuring situational awareness in a rapidly changing climate [15], resulting in extreme and unpredictable weather conditions and permafrost thaw, undermining military infrastructure, ports and runways [16], to addressing capability gaps [17] and establishing effective combined command structures that do not currently exist for western forces. New climatic conditions could also reduce constraints for force projection in the Arctic. The increasing accessibility of the Arctic and new economic opportunities and related changes in the Arctic bring forward "new security realities, including the potential for increased drone, submarine, and intelligence-gathering activities, and concerning signs of a strategic capabilities arms race starting in the region" [18]. The need for a comprehensive and coordinated approach is underscored by the limited capacity of MNF (in terms of resources, equipment and workforce) to address current and future challenges adequately.

Enhancing MNF's capabilities in the Arctic necessitates a robust policy framework that not only recognizes the significance of the region but also addresses the coordination gaps that impede effective operations. Achieving an operational advantage over competitors in this dynamic environment demands synchronized efforts across all land, maritime, air, cyber and space domains. The significance of such coordination and policy changes in the Arctic security context has been highlighted by recent policy reports and analysis [19][20][21]. In light of these interconnected challenges and opportunities, the

MCDC CLIMARCSEC project as outlined in this paper seeks to provide a comprehensive analysis of the evolving Arctic security landscape. By exploring the interplay between climate change, geopolitics, and MNF operations, we aim to contribute to a deeper understanding of the strategic imperatives in the Arctic region and underscore the pressing need for coordinated, forward-looking policies and military strategies to safeguard security interests effectively.

2. MCDC - Climate Change and Security Projects

The MCDC represents a vital and collaborative force development endeavour aimed at tackling the complexities inherent in conducting coalition and multinational operations. It brings together a consortium of 25 partner nations/international organizations, each actively contributing to the identification of capability gaps within multinational force contexts as well as the solution of multi-national military problems. MCDC's motto is to "develop non-materiel solutions to military problems". Moreover, these dedicated partners collectively engage in the conceptualization and development of innovative capabilities designed to bridge identified capability gaps, ultimately strengthening the effectiveness and adaptability of multinational forces in an ever-evolving global security landscape.

The MCDC project cycles embody the spirit of international cooperation and shared responsibility, standing as a testament to the commitment of partner nations to address collectively the multifaceted challenges that arise when working together on complex security missions. This collaborative force development effort is an indispensable element of contemporary defence strategy, recognising that no single nation in isolation can fully address the diverse challenges posed by today's global security environment.

2.1. MCDC 2021 - 2022 "Climate Change, Global Security, and Future Operations (CLIMSEC)" Project

The link between the MCDC project 2021-2022 "*Climate Change, Global Security, and Future Operations* (CLIMSEC)" and 2023-2024 " Climate Change, Arctic Security and Future Operations" (CLIMARCSEC) is palpable in their shared commitment to understanding the complex interplay between climate change and security while addressing critical questions related to military operations.

The objectives set forth in CLIMSEC served as the foundation upon which the subsequent emphasis on the Arctic of CLIMARCSEC was built. Both projects are indispensable elements of a comprehensive strategy aimed at addressing security challenges triggered by climate change.

CLIMSEC's first objective was to identify the most significant new global security threats indirectly resulting from climate change. It laid a foundation by prompting an exploration of the global security threats stemming from the indirect effects of climate change. It encouraged researchers to identify and understand the emerging security challenges associated with climate-induced phenomena, such as population displacement, resource scarcity, and extreme weather events. These insights provided a global perspective on the security implications of climate change.

CLIMSEC's second objective was then to identify the direct military-operational consequences of climate change in terms of the efficacy and viability of different types of military and other measures. Expanding on the knowledge acquired through the initial objective, the second objective within CLIMSEC refined its attention to military-operational outcomes directly influenced by climate change. It investigates how shifting environmental conditions affect the efficacy and viability of diverse military strategies. This problem statement further enhanced our comprehension of the relationship between climate change and military operations, paving the way for a more comprehensive exploration.

The CLIMSEC project was structured into three distinct sub-groups, each tasked with investigating specific aspects related to climate change and its impact on military operations: Sub-group 1 with a focus on Sustainability and Mitigation of Climate Effects on Infrastructure and Personnel, concentrating its efforts on examining how climate change would influence military infrastructure and the development of military technologies; sub-group 2 with an emphasis on Climate Change and its Impact on Demand for Military Capabilities in Disaster Relief and Stabilization Missions, exploring the implications of climate change on the demand for military capabilities in disaster relief and stabilization missions; and sub-group 3 with a focus on the examination of the Role of Climate Change in Interstate Conflicts and Regional Power Competition, developing an understanding how climate change impacts interstate conflicts and regional power competition, with a specific focus on the Arctic Region.

Through these three sub-groups, the CLIMSEC project sought to explore comprehensively the multifaceted impacts of climate change on military operations, from infrastructure and technology to disaster relief, stabilization missions, and regional power dynamics. Throughout its two-year implementation period, the CLIMSEC Project generated three publications, one for each of its constituent sub-groups:

1. Sub-group 1: "‘Greening’ and ‘Prepping’ military organizations: Towards Sustainable Armed Forces and the Mitigation of Climate Effects on Infrastructure, Equipment, and Personnel";
2. Sub-group 2: "Consequences of climate change for military operations: Increased demand on military capabilities in humanitarian assistance and disaster relief and stabilization missions", and
3. Sub-group 3: "The Climate Security Multinational Military Operational Science & Technology Framework (C-MMOST)".

2.2. Transitioning from CLIMSEC to CLIMARCSEC

The evolution from CLIMSEC to CLIMARCSEC is marked by a shift in focus to the Arctic region, which is particularly susceptible to the effects of climate change and holds unique security implications. In this context, CLIMARCSEC's objectives are refined and extended to encompass the Arctic environment's specific challenges and opportunities.

Whereas CLIMSEC has laid the groundwork by identifying global security threats associated with climate change, CLIMARCSEC takes these insights a step further by specifically addressing the governance/coordination and capability gaps that affect military operations in the Arctic. This transition acknowledges that climate change's impacts in the Arctic require specialized attention to ensure the effectiveness of MNF.

Therefore, CLIMARCSEC expands the scope to include a thorough analysis of how climate change implications and consequences will affect policy, strategy, deterrence and defence arrangements, and military assistance in the Arctic. It encompasses planning, preparedness, exercises, and operations in this unique environment, emphasising the need for tailored adaptations.

In sum, the transition from CLIMSEC to CLIMARCSEC reflects a natural progression from understanding the broader global security implications of climate change to addressing the region-specific challenges, requirements and opportunities in the Arctic. Together, these projects offer a comprehensive approach to climate-induced security challenges, positioning MNFs and decision makers to navigate effectively a rapidly changing security landscape.

3. MCDC 2023 – 2024 “Climate Change, Arctic Security and Future Operations” (CLIMARCSEC) Project

The guiding research question for CLIMARCSEC is formulated along the lines of aforementioned considerations: What are the current challenges to the military operating environment caused by climate change and competitive activity in the Arctic and how could existing gaps in operational capability and governance/coordination of MNF be closed and future capability requirements be met?

The military problem for the project takes into account that climate-change occurs at some of the highest rates in the Arctic regions resulting in both emerging risks as well as new opportunities. As outlined above, in combination with changing geopolitical/strategic conditions and growing political and military tensions, the risks and opportunities created by climate change make the Arctic not only strategically important for MNF but also simultaneously exacerbate an already challenging field for operations. Taken together, these factors increase the need for stronger MNF situational awareness, operational capability, coordination and policy changes. Resources (personnel, equipment, finances) are likely to be further challenged given the necessity to respond to the compounding effects of climate change on domestic and/or regional environments (e.g. search and rescue and environmental disaster response). Extreme weather conditions will potentially restrict military mobility, survivability and sustainability, and also cause indirect implications such as resource fragility, and follow-on effects to governments and societies.

Various capability and coordination gaps (e.g. insufficiency in resources and modern equipment, missing combined command structures and a lack of persistent domain awareness from sea floor to space) restrict MNF abilities to address these arising challenges adequately. CLIMARCSEC analyses the current situation and challenges and contributes with suggestions, how existing and potential gaps, mainly coordination but also capability gaps as far as known, could be closed and how future coordination and capability requirements could be met in ever changing conditions. All physical domains as recognized by NATO are relevant to the operational environment for this problem set: land, maritime, air and space, with a focus on the first two.

One of the main recommendations will be that enhancing MNF’s Arctic capabilities requires a robust policy framework and better coordination of MNF policies and activities in order to maintain a strong and effective security presence in the region and to ensure an operational advantage at the appropriate stage within the competition continuum, in a rapidly changing — climate and threat-based — environment.

In terms of objectives, the CLIMARCSEC project will as its main goal identify viable options for the MNF Commands in order to overcome the existing coordination and capability gaps by addressing relevant operational issues. In support of the main goal, CLIMARCSEC will analyse how the implications and consequences of climate change will impact policy, strategy, arrangements for deterrence and defence, military assistance across the competition continuum, including planning, preparedness, and exercises and operations in the Arctic. This analysis will be carried out and the results published in the form of a multi-national concept.

Furthermore, in the tradition of the previous CLIMSEC project, it will inform and consult military and political decision makers responsible for current and projected states of security operations, considering climate change in the Arctic environment and the necessary adaptations to existing command and control (C2) and coordination structures required to adapt to the future operating environment. CLIMARSEC will contribute to developing curricula and other educational materials used in primarily military education organizations working on the Arctic to promulgate awareness and equip MNF commanders to make better decisions regarding operations in the Arctic. Finally, the CLIMARCSEC project will support military planners in preparation for military and security operational and strategic concepts and multinational force coordination.

In the ideal case, the project, once concluded will contribute to: firstly, the conduct of effective military activities in the Arctic; secondly, making forces and headquarters better prepared to adapt to a changing environment; and, thirdly, developing the ability to apply adapted policy, procedures, technologies, and updated operational concepts.

4. Conclusions and recommendations

In conclusion, the MCDC CLIMARCSEC project holds great promise for addressing the multifaceted challenges posed by climate change in the Arctic region. This initiative's overarching goal, which is to analyse and provide recommendations for closing existing and potential coordination and capability gaps while identifying future capability requirements, is both timely and essential. As discussed throughout this paper, the profound impacts of climate change in the Arctic extend beyond the environmental sphere, necessitating a comprehensive examination of their implications on policy, strategy, deterrence and defence arrangements, military assistance, planning, preparedness, and military exercises and operations in the Arctic.

One of the critical contributions of CLIMARCSEC is its commitment to assessing how climate change will reshape the security landscape. By recognising that climate change is not solely an environmental issue but a security imperative, this initiative acknowledges the imperative to adapt and innovate in response to evolving threats and opportunities. Climate-induced shifts in the Arctic will have far-reaching consequences, influencing not only military operations but also political decision-making processes on which the former are based.

In this context, CLIMARCSEC has the potential to serve as a valuable resource for military and political decision makers. By providing a comprehensive analysis of the current and projected state of security operations in the Arctic, it will contribute to equipping leaders with the knowledge and insights necessary to formulate informed policies and strategies. This initiative's capacity to inform and educate stakeholders about the security implications of climate change fosters a proactive and adaptive approach to Arctic security challenges.

Furthermore, CLIMARCSEC contributes to identifying coordination and capability gaps and in ensuring that MNF are adequately prepared to address the emerging security landscape. As the Arctic becomes increasingly geopolitically significant, the need for effective cooperation, coordination, and capabilities cannot be overstated. By pinpointing areas where improvements are necessary, CLIMARCSEC will contribute to enhancing MNFs' capacity to respond effectively to Arctic security challenges.

In summary, CLIMARCSEC represents a forward-looking and holistic approach to understanding and addressing the complex interplay between climate change, security, and MNF operations in the Arctic. Its focus on analysis, coordination, and capability enhancement is a testament to its commitment to safeguarding security interests in the face of a rapidly changing climate situation and evolving and altering geopolitical dynamics. As the Arctic continues to evolve as a critical arena for global security, initiatives like CLIMARCSEC will have a critical role to play in ensuring the resilience and adaptability of MNF and contributing to the broader conversation on climate change and security in a region of growing strategic significance.

References

[1] Polyakov, I., Pnyushkov, A., & Timokhov, T. (2019). Observational program tracks Arctic Ocean transformation. *EOS, Transactions American Geophysical Union 100*(11), 22-27

[2] Maynard, J. R. et al. (2010). *Petroleum Geology Conference Series, 7,* 589-590, Geological Society, London. https://doi.org/10.1144/0070589

[3] Multinational Capability Development Campaign (MCDC). https://wss.apan.org/public/mcdcpub/default.aspx

[4] GRID-Arendal, image. https://www.grida.no/resources/7738

[5] Arctic Climate Impact Assessment (2005). Arctic Climate Impact Assessment. *ACIA Overview report*. Cambridge University Press.

[6] Pörtner, H. O.et al. (eds.) (2019). Intergovernmental Panel on Climate Change. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp.

[7] Brigham, L. W. et al. (eds.) (2020). The Arctic in World Affairs: A North Pacific Dialogue on Will Great Power Politics Threaten Arctic Sustainability? In: *North Pacific Arctic Conference Proceedings*

[8] Byers M. (2013). *International Law and the Arctic*. Cambridge University Press.

[9] Brigham, L. (2020). U.S. Security Starts in the Arctic. In: *The Hill*, Washington DC

[10] Huebert, R. The Arctic and the Strategic Defence of North America: Resumption of the “Long Polar Watch”. In: Leuprecht, C., Sokolsky, J., & Hughes, T. (eds) (2018), *North American Strategic Defense in the 21st Century*. Advanced Sciences and Technologies for Security Applications. Springer, Cham

[11] Huebert, R., Lackenbauer, P. W. (2021). Debating Arctic Security: Selected Writings, 2010-2021. In: *NAADSN Engage Series no. 7*

[12] Gricius, G., & Marinova, I. (2023). *A Path to Dialogue: The Arctic for EU-Russia Relations. Commentary*. The Arctic Institute

[13] Geddes, L. (2022, October 19). Next pandemic may come from melting glaciers, new data shows. In: *The Guardian*. https://www.theguardian.com/science/2022/oct/19/next-pandemic-may-come-from- melting-glaciers-new-data-shows. Hunt, K. (2023, March 8). Scientists have revived a ‘zombie’ virus that spent 48,500 years frozen in permafrost. In: *CNN*. https://www.cnn.com/2023/03/08/world/permafrost-virus-risk-climate-scn/index.html

[14] NATO (2023). *The Secretary General’s Report - Climate Change and Security Impact and Security Impact Assessment*. Second Edition. climate-security-impact.pdf (nato.int)

[15] Fitzgerald, D. M., & Hughes, Z. (2019). Marsh Processes and Their Response to Climate Change and Sea-Level Rise. *Annual Review of Earth and Planetary Sciences 47*(1), 481-517

[16] Maddox, M. (2023). Implications of climate change for military operations in the Arctic. In: Friis, K., et al. (eds.). *Report: Navigating Breakup: Security realities of freezing politics and thawing landscapes in the Arctic. Input Report for the Arctic Security Roundtable at the Munich Security Conference 2023*. MSC ASR Input Report 2023 Navigating Breakup.pdf (wilsoncenter.org)

[17] International Institute for Strategic Studies (2020). *The Military Balance*. Abingdon, Routledge

[18] Goodman, S. et al. (2021). *Climate Change and Security in the Arctic*. The Center for Climate and Security, Council Strategic Risks and Norwegian Institute of International Affairs. Climate Change and Security in the Arctic « The Center for Climate & Security (climateandsecurity.org)

[19] European Parliament (2023). Report on the Arctic: opportunities, concerns and security challenges. In: *Procedure: 2020/2112(INI)*, Committee on Foreign Affairs. REPORT on the Arctic: opportunities, concerns and security challenges | A9-0239/2021 | European Parliament (europa.eu)

[20] European Parliament (2020). A Balanced Arctic Policy for the EU. In: *Policy Department for External Relations, Directorate General for External Policies of the Union*, PE 603.498. Balanced Arctic Policy for the EU (europa.eu)

[21] Stockholm International Peace Research Institute. *SIPRI Research: Conflict, peace and security*. Climate change and security | SIPRI

Security implications of climate change in the Arctic maritime domain and priorities for NATO Climate Change and Security Action Plan

Fabio LISSI[a,1] and Pauline BAUDU[b,2]
[a] *NATO STO CMRE, La Spezia, Italy*
[b] *Arctic360, Center for Climate and Security, UQAM, Montreal, Canada*
ORCiD ID: Fabio LISSI https://orcid.org/0009-0001-8795-6624, Pauline BAUDU https://orcid.org/0009-0001-8384-8415

Abstract. Climate Change (CC) has been described in the last NATO Strategic Concept (SC) as "[…] a crisis and a threat multiplier". The same document, released in June 2022, mentions the High North for the first time as an area of priority where Russia poses a strategic challenge. Indeed, no other region in the world is more affected by CC than the Arctic, which is estimated to be warming nearly four times as fast as the rest of the globe. In addition to posing significant threats to human security, ice sheet melting, permafrost thaw and other physical phenomena impact NATO's infrastructure, all subject to logistical stress and extreme-weather events, and influence the strategic decision-making of Arctic nations, thus ultimately altering NATO operating environment. As NATO released its Climate Change and Security Action Plan (CCSAP) in June 2021, this paper aims to explore the key strategic and operational implications of CC in the Arctic maritime domain, as well as the priorities to consider for the regional implementation of the CCSAP. Building on three of the Plan's main pillars, we will attempt to address three main sets of research questions. (1) Increasing Allied awareness of the strategic impacts of CC in the Arctic: what are the main drivers of competition in the Arctic, and what is their relationship with CC in the maritime domain? How can Allies improve their awareness of the way CC will affect strategic decision-making in the region? (2) Adapting to CC: what are the main challenges for NATO to adapt its planning and maritime capabilities to the changing Arctic environment? (3) Mitigating CC: how can Allies minimize their carbon and environmental footprint when operating in a changing Arctic maritime domain? This work intends to be an introduction for a more comprehensive research project on the topic, aiming at formulating policy recommendations for the application of NATO's CCSAP in the Arctic maritime domain.

Keywords. Climate Change, Arctic, Maritime Domain, NATO, Action Plan, Defence, Security

---

[1] Corresponding Author: Fabio Lissi, fabio.lissi@cmre.nato.int.
[2] The authors contributed equally to this paper.

1. Introduction

Climate Change (CC) has been described in the last NATO Strategic Concept (SC) as "[…] a crisis and a threat multiplier" [1]. The same document, released in June 2022, mentions the High North for the first time as an area of priority where Russia poses "a strategic challenge". Indeed, the Arctic is particularly vulnerable to CC, which affects all aspects of its security environment. In addition to posing significant threats to human security and safety, ice sheet melting, permafrost thaw and other physical climate phenomena impact NATO infrastructure, all subject to logistical stress and extreme weather events, and influence the strategic decision-making of Arctic nations. Such effects are particularly prevalent in the maritime domain, which is at the forefront of CC and stands as a predominant domain in Arctic security because of the Arctic's geographical significance, resource richness, and specific security and environmental considerations. As NATO released its Climate Change and Security Action Plan (CCSAP) in June 2021 [2] and the following Impact Assessments (CCSIA) [3] [4], the Alliance has set the aim of becoming the leading international organization in dealing with the security aspects of CC [6][5] [6]. This short paper aims to outline the key strategic and operational implications of CC in the Arctic maritime domain, and to reflect on priorities for NATO to consider when operationalizing the CCSAP in the context of the Arctic. The aim is to set the ground for a more ambitious research project that will explore these aspects in greater depth and will provide further policy recommendations.

2. Awareness of the strategic impacts of CC in the Arctic

For the past three decades, the Arctic has been considered an exception in international relations due to its presumed "invulnerability" to external tensions. While central in Russian deterrence and key for other Arctic states' national security, relations in the High North were mostly revolving around dialogue and cooperation. The 1987 Murmansk Initiative, and the creation of the Arctic Council in 1996, both testify to the then-regional focus on dialogue and stability [7] [8]. The full-scale Russian invasion of Ukraine in February 2022, added to prior strategic developments that had been unfolding in the Arctic in recent years, and dramatically contributed to the intensification of tensions and the growingly competitive rhetoric. However, not all variations in regional dynamics can be attributed to political behaviour. The changing climate, whose effects are multiplied in the High North, has already disrupted peaceful dialogue, and is expected to increasingly affect geopolitical and strategic developments in the region in the medium-term.

2.1. Impacts of CC on strategic competition

CC has both a direct and a multiplier effect on strategic competition. More specifically, we can observe three main climate-related drivers of strategic instability in the Arctic. First, ice melting is expected to open new navigable routes and possible sites for exploitation of natural resources, both on land and in the ocean [9]. These prospects, as well as their economic viability, are uncertain owing to the region's particularly challenging navigation conditions. However, they have already led to a "hyper-securitization" of economic assets for resource exploration. This is especially visible along the Northern Sea Route (NSR) running along the Russian Arctic, where the Kremlin is studying a toll road plan, with the creation of private military companies (PMCs) affiliated to oil industries, the reopening of military facilities, and a military build-up never seen since the Cold War. Second, a warmer climate is likely to attract higher international interest for areas so far barely inhabited. Increased navigation and massive investments in the extraction of natural resources can represent a challenge for local communities, as well as a risk of foreign penetration and malicious interference from potential adversaries, such as in the case of China [10]. On the other hand, Russia's overall climate-vulnerability can shape Moscow's future strategic decision-making, thus further deteriorating the already unstable strategic environment. For example, increased vulnerability owing to the loss of sea-ice coverage protecting Russian nuclear ballistic submarines (SSBNs) can translate into a repositioning of Russia's fleet northwards, and a more assertive force posture by Moscow fearing an expansion of NATO's military presence in the region. Ultimately, in dealing with the increasingly complex interaction between CC and security considerations in the High North, great powers risk facing a "security dilemma", where their efforts to increase their security inevitably brings further instability and risk of escalation, whereas a failure to act is seen as a risk to lose ground in favour of an adversary. Such is the case for NATO and Russia. On one hand, it is in the interest of the Alliance to ensure a stronger deterrence and defence of its Arctic members and to increase its presence in their waters to respond to the specific challenges posed by a changing environment. On the other hand, Russia will see a greater presence of NATO maritime forces in the High North as a threat, and may in turn deploy more capabilities in the region, multiplying the risk of accidents and escalation.

2.2. Opportunities for increased Allied awareness

The first pillar of NATO's CCSAP sets out the goal of increasing Allied awareness of the security implications of CC on NATO's strategic environment and operations. To do so, NATO has pledged to "integrate CC considerations into security risk and resilience assessments [...] in regions of key interest to the Alliance", by leveraging Science and Technology (S&T) to support research [11]. There is a vast toolset of possibilities to build and share awareness, both within the Alliance and with partners, about the impacts of CC on NATO's Arctic maritime domain and overcome the significant gaps in Maritime Situational Awareness (MSA) in a region that is especially challenging to navigate. In particular, information sharing and access is key when dealing with climatic predictions and modelling. NATO should capitalize on existing technology and invest in AI-based solutions to integrate climate data together with data on military and security developments in the region, and to improve early-warning systems and detect change in real-time. Another important step forward would be mainstreaming the climate factor into NATO war-gaming and table-top exercises (TTX). Climate-informed TTX scenarios factoring all aspects of climate and environmental risks in Arctic seas (from the climate-vulnerability of military installations to climate-risks on local communities) would significantly improve NATO's risk-assessment, prediction, and anticipation capabilities.

3. Adapting to Climate Change

The second pillar of NATO's CCSAP lies in the Alliance's adaptation to CC, both at the strategic and operational levels. This entails incorporating climate considerations into the Alliance's capabilities, training and defence planning, and ensuring their climate-resilience.

3.1. Adaptation to the changing strategic context

At the strategic level, priorities for NATO in the Arctic maritime domain are: keeping the Greenland-Iceland-UK (GIUK) gap open for reinforcements in case of conflict in Europe or in the Baltic Sea; ensuring peacetime freedom of navigation for civilian and commercial traffic; and, ensuring Allies' territorial water protection. All of these require high-end capabilities that were considerably degraded since the end of the Cold War, such as Anti-Submarine Warfare (ASW) [12]. To accomplish such tasks in a context where CC will continue to affect NATO's readiness, military mobility and deterrence and defence posture, the Alliance needs both Arctic-capable maritime forces and appropriate naval installations in strategic positions. Moreover, coastal Allies should have a number of icebreakers proportionate to the area of their Exclusive Economic Zones (EEZ) in order to ensure adequate domain awareness, and sufficient radar coverage for the protection of Critical Underwater Infrastructure (CUI), as well as for Search and Rescue (SAR) operations.

3.2. Adaptation to climate impacts at the operational level

The effectiveness of these adjustments, however, will be strictly connected to the impacts of CC. In building and deploying an Arctic-capable force, for instance, NATO should carefully balance the need for exercises and operations with the minimization of accidents at sea, particularly in light of intensifying naval traffic and more frequent at-sea interactions with Russia. In addition, Allied maritime forces will not only see the scope of their tasks and missions broaden (e.g., an increasing need for SAR capacities due to the intensifying maritime traffic), but also a changing and more challenging operating environment. Indeed, wave-heights are projected to grow significantly in the coming decades, as well as the incidence of new undersea currents, intensified storms, and radiation exposure. Moreover, we should also expect foggier seas as well as a growing number of icebergs as sea ice melts [13]. Consequently, CC is affecting military readiness, since maritime infrastructure (ships, ports, and dockyards) is facing growing risks of sea-level rise, flooding and storms, which will eventually affect the safety of sea lines of communication (SLOCs) [14]. Existing naval bases built on thawing permafrost will also be at extreme risk of inoperability and will need to be restructured or permanently closed. On the other hand, new bases will have to be built to ensure the effective logistic supply of a larger naval presence, such as the projected expansion of the port of Nome, in Alaska, to host cruise and military ships, as well as the pressing need for a deep-sea port in the Canadian Arctic to support navy operations [15]. Given NATO's priority to guarantee the integrity and protection of Allied nations, adaptation of maritime capabilities to CC is a pressing issue for maritime forces in the Arctic. This should include the proactive modernization of naval platforms, bases and other military infrastructure at sea, and the adaptation of weapon systems to extreme temperature conditions and rapid temperature changes [16]. On the human side, priorities should be on the adaptation of training, exercises and procedures (e.g., in disaster response, or in ship de-icing) including through mutually beneficial partnerships with local communities to leverage traditional expertise. Arctic training involving the Canadian Armed Forces and the local Canadian Rangers are an excellent example of best practice in cooperation that will facilitate climate adaptation [17].

4. Mitigating Climate Change

Lastly, the third pillar of NATO's CCSAP announces NATO's contribution to the mitigation of CC through the formulation of voluntary goals to reduce greenhouse gases (GHGs) emissions from the military. The Arctic and its unique ecosystems are some of the most climate-vulnerable on Earth, and world oceans are notoriously at the forefront of CC and environmental degradation. This makes the case for an extra-focus on the Arctic maritime domain in the context of NATO's mitigation efforts.

4.1. Climate and environmental footprint of naval activities in a highly vulnerable Arctic maritime domain

The fragile landscapes and unique marine ecosystems of the Arctic are rapidly changing, with the distribution of marine species shifting, the disappearance of species that are crucial to food webs, and a changing ocean primary production. The melting ice also generates destructive feedback loops further aggravating global warming: thawing permafrost releases high amounts of methane and melting sea ice exposes larger parts of a dark ocean absorbing more heat. In addition, the region's marine biodiversity is further impacted by environmental and noise pollution, and by collision hazards from increased shipping. Increasing navigation in Arctic seas, including by military forces, means higher risks of oil spill, which can persist for weeks or longer in cold seas, release of GHGs emissions and air pollutants, and damage to important marine life zones. Such negative impacts are particularly relevant for defence assets in the High North, as a result of higher levels of fuel usage for electricity and heating due to their remote locations and extreme-cold conditions. Furthermore, the development of military infrastructure can disrupt wildlife habitats. These drastic environmental and biodiversity changes also compound human risks, as they threaten the health, livelihoods, mobility, and traditional lifestyles of local, mostly indigenous, coastal communities. Finally, the use, storage and disposal of nuclear and nuclear-powered military capabilities in Arctic waters, especially along the Russian coast, pose serious risks of radioactive contamination, which can persist for extended periods and harm both local wildlife and communities [18].

4.2. Science and cooperation opportunities to advance the mitigation of NATO’s Arctic military footprint

In this context, NATO, through its nascent Climate Change and Security Centre of Excellence (CCASCOE – Montreal, Canada) and with the expertise of the Centre for Maritime Research and Experimentation (CMRE – La Spezia, Italy), can serve as a standard-setting tool and coordination platform to provide guidance for Allies and partners to operate sustainably in the region [19]. Allied expertise can be leveraged to: coordinate emissions reporting; inform investment decisions; drive innovation towards more energy-efficient and carbon-neutral technologies; and, share best practices to improve energy efficiency at sea and reduce black-carbon soot. The recent integration of Finland in NATO and Sweden’s prospective admission will bring considerable benefit to the accomplishment of this agenda. Both countries are first-line players in green energy and climate security, with excellent green innovation capacities, thus bringing important expertise in S&T inside the Alliance [20]. Moreover, their well-developed railway network can represent a viable alternative to ship transport in the case of deploying reinforcements to NATO’s north-eastern flank, merging military effectiveness and emissions curbing. Finally, the Arctic Council would be composed of seven NATO Nations out of eight members, thus ensuring a better coordination of environmental and defence policies, including when it comes to managing environmental risks linked to nuclear activity. Importantly, by acting as a standard-setting body in the new technology used (e.g., batteries and charging stations), NATO needs to ensure that interoperability remains at the forefront of its green engagement in Arctic seas.

5. Conclusion

The implications of CC in the Arctic maritime domain are complex, interconnected, and transcend the strategic, operational and human security dimensions. When operationalizing its CCSAP at the regional level, NATO’s response to these challenges will need to be holistic and factor in the specific vulnerabilities of Arctic seas. Key avenues for action include: increasing Allied awareness of the regional climate impacts by leveraging technology and by mainstreaming the climate variable into Arctic war-gaming; adapting naval capabilities, training and exercises to a changing climate, including by valuing and encouraging local knowledge; and, harnessing S&T cooperation opportunities to advance the mitigation of NATO’s environmental footprint in Arctic seas. The aim of this short paper is to set the ground for a more ambitious research project that will explore these aspects more in-depth and will provide further policy recommendations for the application of NATO’s CCSAP in the Arctic maritime domain.

6. Acknowledgements

Fabio Lissi would like to acknowledge the support and supervision received from all CMRE Research Division and administrative staff, and the funding from NATO Office of Chief Scientist.

References

[1] NATO (2022, June 29). *NATO Strategic Concept*. https://www.nato.int/cps/en/natohq/topics_210907.htm

[2] NATO (2021, June 14). *Climate Change and Security Action Plan*. https://www.nato.int/cps/en/natohq/official_texts_185174.htm

[3] NATO (2022). *Climate Change and Security Impact Assessment*. The Secretary General's Report

[4] NATO (2023). *Climate Change and Security Impact Assessment, 2nd Edition*. The Secretary General's Report

[5] Goodman, S. & Kertysova, K. (2022). NATO: An unexpected driver of climate action?, *NATO Review*. https://www.nato.int/docu/review/articles/2022/02/01/nato-an-unexpected-driver-of-climate-action/index.html

[6] Kertysova, K. (2023). Implementing NATO's Climate Security Agenda: Challenges Ahead. *NATO Review*. https://www.nato.int/docu/review/articles/2023/08/10/implementing-natos-climate-security-agenda-challenges-ahead/index.html

[7] Boulègue, M. (2019). *Russia's Military Posture in the Arctic*. Chatham House

[8] Heininen, L., & Exner-Pirot, E. (eds.) (2020). *Climate Change and Arctic Security*. Palgrave Pivot, Cham

[9] Congressional Research Service (2023). *Changes in the Arctic: Background and Issues for Congress*. CRS Report

[10] Andersson, P. Willaing Zeuthen, J., & Kalvig, P. (2018). Chinese Mining in Greenland: Arctic Access or Access to Minerals? *Arctic Yearbook 2018*, 1-15. https://arcticyearbook.com/arctic-yearbook/2018/china-the-arctic/2018-sp-scholarly-papers/265-chinese-mining-in-greenland-arctic-access-or-access-to-minerals

[11] Garcia Rico, L. (2022). *NATO and Climate Change: A Climatized Perspective on Security*. Belfer Center for Science and International Affairs

[12] Peters, J. (2021). Below the Surface: Undersea Warfare Challenges in the 21st Century. In: Pawlak, J. & Peters, J. (eds.) (2021). *From the North Atlantic to the South China Sea. Allied Maritime Strategy in the 21st Century*. The Kiel Seapower Series, 1st edition. NOMOS. http://dx.doi.org/10.5771/9783748921011

[13] Song, S. et al. (2023). Adapting to a Foggy Future along Trans-Arctic Shipping Routes. *Geophysical Research Letters*, *50*(8). https://doi.org/10.1029/2022GL102395

[14] Carniel, S. et al. (2022). *Climate Change and Military Effectiveness in the Maritime Domain: Implications for NATO*. CMRE Report

[15] Leblanc, P. (2022, March 25). *It is time to reconsider the development of Resolute Bay*. The Hill Times. https://arcticsecurity.ca/pdfs/ResoluteBay.pdf

[16] Heise, R. (2021). NATO is responding to new challenges posed by climate change. *NATO Review*. https://www.nato.int/docu/review/articles/2021/04/01/nato-is-responding-to-new-challenges-posed-by-climate-change/index.html

[17] Baudu, P. (2023, June 15). *Building a Safer North: Climate Security Risks in the Canadian Arctic*. The Maritime Executive. https://www.maritime-executive.com/editorials/building-a-safer-north-climate-security-risks-in-the-canadian-arctic

[18] Nilsen, T. (2023, September 15). *Norwegians fear radiation as Russia prolongs test-window for Burevestnik missile*. The Barents Observer. https://thebarentsobserver.com/en/nuclear-safety/2023/09/norwegians-fear-radiation-russia-prolongs-test-window-burevestnik-missile

[19] Baudu, P. (2022, July 22). *Navigating Melting Ice and Eroding Exceptionalism: Theory-Driven Policy Pathways for NATO's High North Commitment*. IRIS. https://www.iris-france.org/168952-navigating-melting-ice-and-eroding-exceptionalism-theory-driven-policy-pathways-for-natos-high-north-commitment/

[20] Khorrami, N. (2022, May 3). *By Merely Entertaining NATO Membership, Sweden Has Changed*. Wilson Center. https://www.wilsoncenter.org/article/merely-entertaining-nato-membership-sweden-has-changed

How climate change can worsen security dilemmas in the Norwegian High North

Marius Nyquist PEDERSEN[a,1] and Bjørn Olav KNUTSEN[b]
[a] *Norwegian Defence Research Establishment*
[b] *Norwegian Defence Research Establishment*
ORCiD ID Marius Nyquist PEDERSEN https://orcid.org/0009-0000-4396-2646, Olav KNUTSEN https://orcid.org/0000-0002-1878-4312

Abstract. Security dilemmas are well-known in international relations, where one state's efforts to enhance its security might provoke reactions from other states, potentially leading to decreased security for all states involved. One of Norway's security and defence policy aims in the Norwegian High North (the Norwegian Sea, Barents Sea, and Svalbard) is to maintain low tensions by cooperating with Russia in common interest areas, like fisheries and the Incidents at Sea Agreement. This aim remains valid after the Russian attack on Ukraine in 2022. In an era of growing great power rivalry, climate change might function as a threat multiplier. Sensitivity to climate change is higher in the High North because the initial warming leads to events that amplify warming, mainly due to a decreasing albedo effect, which makes Arctic warming three times faster than the global average. This article contributes to our understanding of High North security dynamics by analysing how climate change affects NATO's patterns of operations and exercises in the Norwegian High North. It specifically asks how climate change affects the way actors like NATO Nations and Russia interact in this area. We also ask how Norway's approach to security and defence changes due to the continuing warming of the High North. Our article is meant as a contribution to the growing debate within NATO on how climate change functions as a threat multiplier and as an addition to our understanding of how NATO addresses climate change as seen in the 2021 *Climate Change and Security Action Plan.*

Keywords. Climate change, Security dilemmas, Norway, High North, Arctic, NATO, Russia, Defence, Security

1. Introduction

Norwegian policy in the High North is summarised in the axiom "High North, Low tension". This includes avoiding a militarisation of great power relations in the region. However, the security situation in Europe has changed dramatically, especially since the Russian attack on Ukraine in February 2022. Avoiding any kind of escalation of the war to include NATO, including in Northern Europe, is a particular challenge. The High North is central to Norway's security concerns, especially due to the shared land and sea border with Russia [1].

The Norwegian government has stood by its traditional goal of avoiding the securitisation of the High North since the invasion of Ukraine in 2022. This has required stability and predictability in Norwegian policies towards other state actors in the area [2], particularly a dual policy of deterrence and reassurance in its relations with Russia [3]. Cooperation

---

[1] Corresponding Author: Marius Nyquist PEDERSEN, Marius-Nyquist.Pedersen@ffi.no.

continues with Russia on important policy areas, particularly fishing arrangements and search and rescue (SAR). These policies aim to prevent new security dilemmas in the High North as a consequence of great power rivalry and an emerging multipolar international order. The Norwegian Minister of Foreign Affairs stated that while "[w]e monitor and protect our own areas, but we are completely dependent on Allied help if we were to be attacked. The climate crisis means that we need more cooperation to deal with effects on ecosystems and people in the Arctic" [2].

The purpose of this article is to analyse the effects of climate change on tensions in the High North and whether climate change acts as a threat multiplier. A threat multiplier can increase the risk of conflict [4]. Climate change and security are becoming more interlinked, a phenomenon that preoccupies both policymakers and scholars alike. NATO identifies climate change as "one of the defining challenges of our times. It is a threat multiplier that impacts Allied security, both in the Euro-Atlantic area and in the Alliance's broader neighbourhood" [5].

We analyse our research question from a Norwegian perspective. Our approach is based on interviews with key personnel in the Royal Norwegian Navy, the Norwegian Coast Guard, the Norwegian Joint Headquarters (Joint HQ), and NATO HQ International Staff. In our analysis of how climate change is a threat multiplier, we give attention to which state actors are present in the Norwegian part of the High North, how these actors operate on a day-to-day basis, and how and where in the High North they conduct military exercises. Our aim is to measure the degree to which climate change is a threat multiplier in the Norwegian High North.

To answer our research question, we first discuss security dilemmas as a source of potential conflict in the High North and analyse how climate change functions as a threat multiplier. We also include a short literature review and define our position in the current research debate. Then we discuss how climate change affects operations and exercises in the Norwegian High North and how Norway's approach to security and defence is affected. This section is based on semi-structured interviews with key Norwegian personnel with extensive insights into these issues. In the final section, we discuss to what extent climate change will affect High North security in a longer-term perspective based on what we know as of today.

2. Security Dilemmas in the High North

The research literature on security dilemmas in the High North is vast and presents widely different perspectives on the security dynamics present in the region. The literature varies from presenting the High North as an area "… that feels the burn of rising instability and competition" [6] to describing Europe's northern flank as "likely to remain stable and mostly quiet in the short and medium term" [7]. These perspectives vary according to theoretical perspectives. Neo-realists tend to view the region as an area of more intense great power rivalry, while liberal scholars and social constructivists emphasise common interests, interdependencies, changing security identities and norms [8] [9]. Neo-realists dominate popular writing and media accounts, focussing on the "race to the North Pole", but little empirical evidence is present to underpin such a claim [9].

From a Norwegian perspective, the most important current question is to what extent it is possible to maintain low tensions in the High North, particularly after February 2022. Obviously, the High North is central for Norway's security considerations with its shared land and sea border with Russia (see e.g., [10] [11]). Norway has actively pursued diplomatic efforts to ensure low tensions in the High North [12] in line with its liberal approach to international relations. The most recent research literature claims, however, that Norway's traditional reassurance policies towards Russia need some clarifications in light of Russia's attack on Ukraine as well as Finland's and Sweden's accession to NATO (Bjur, 2023). The reassurance efforts are characterised as crisis management, deterrence calibration and conciliation. They include measures like risk reduction and avoiding unintended incidents, taming the deterrence posture in order to maintain status quo of low tensions, and to transform the reassurance policies to include efforts ranging from "civilian people-to-people contact, military cooperation, and efforts to enhance disarmament and increase détente" [3].

All of these measures might become even more relevant in times of geopolitical shifts and changes in the High North due to climate change. There is a rich research literature on how global warming transforms Arctic security, which might necessitate a new military architecture in the region [13]. Keil (2014) investigates the likelihood of confrontation over resources in the High North, concluding that a geopolitical rush for resources is unlikely to occur, despite climate change [8]. Newer research introduces the Arctic Military Exercise (ArcMilEx) dataset that shows that exercises have become more frequent in the High North since 2006. These exercises act as a barometer of both Arctic and non-Arctic states' concern about regional stability and security. The number of exercises range from one or two annually to as many as four in 2019 [14]. Baudu (2022) addresses how climate change acts as a catalyst of interests in the region, concluding that the High North 'can be a test bed for NATO to advance its climate engagement' in light of climate change as a threat multiplier [15].

Nevertheless, a Norwegian perspective on how climate change can act as a threat multiplier and amplify already existing security dilemmas in the High North is missing from the research literature. With this paper, we wish to fill this gap. We will adhere to a realist approach, but we will not make unsubstantiated claims based on core realist tenets. Instead, we apply realism as a theoretical toolkit to analyse empirical insights we have collected based on qualitative interviews.

2.1. Qualitative Interviews

In this article, we rely on semi-structured interviews. In a semi-structured interview, a prepared interview guide facilitates digression and reflection on the part of the interviewee, and the interviewer may ask follow-up questions. This creates a feeling of process ownership for the interviewee, and the interview guide ensures that the research topic remains centred [16] [17].

We conducted expert interviews, a category of semi-structured interviews. For such interviews, the sample is made up of relevant experts on the chosen topic [18]. We interviewed seven subjects. Our subjects came from the Norwegian Joint HQ, the Norwegian Navy, the Norwegian Coast Guard, and NATO HQ International Staff. We have identified these departments, sections, and missions as the most relevant to the High North context.

2.2. The Security Dilemma Theory and the High North

According to security dilemma theory, actions taken by a state to enhance its own security can make other states perceive themselves as less secure and lead them to respond in kind [19] [20]. This can lead to an overall reduction in the first state's security. Robert Jervis shows that the security dilemma is particularly strong when a state finds it challenging to distinguish offensive forces from defensive forces, and when offence has the advantage over defence. Additionally, geography and military technology affects the balance between offence and defence [20]. Technology may tilt the balance in favour of either offensive or defensive strategies, while geography tends to favour defence due to barriers to manoeuvre and distance [21].

States can never be entirely sure about the current and future intentions of other states that are able to harm them [22]. Due to misperceptions about these intentions, "states with fundamentally compatible goals may nonetheless end up in competition and war" [23]. The "offence-defence" theory may explain the threat level derived from this dilemma [24]. If the nature of forces can be distinguished, a state seeking security can alleviate the security dilemma by deploying purely defensive forces [25].

The nature of forces is challenging to measure, as it is usually a subjective measurement: "What seems sufficient to one state's defence will seem, and will often be, offensive to its neighbours" [26]. For instance, Russia presents its military build-up in the Arctic as fundamentally defensive against what it considers a hostile NATO alliance. As such, an

Arctic build-up by any NATO Nation will likely be considered offensive from a Russian perspective. Thus, as Wilhelmsen and Hjerman (2022) show, other political factors may weaken factors that alleviate the security dilemma [27].

Threats usually travel more easily across short distances, especially in the military and political sectors [28]. Within these sectors, states tend to be far more concerned with the capabilities and intentions of their neighbours, rather than distant countries [29]. This makes the Arctic particularly vulnerable to security dilemmas, because Russia has four Arctic NATO countries as neighbours, only separated by the Arctic Ocean. Regional factors may however alleviate the Arctic security dilemma. For instance, the rather barren nature of the Arctic offers troops and military installations limited concealment, simplifying their detection and monitoring. Nevertheless, the fact that all other Arctic states are NATO Nations may shore up Russian fears of a four-against-one scenario. Russia's military build-up could likewise cause a security dilemma for NATO, fearing that they will be outnumbered by Russian forces in the region [30].

The nuclear age has shifted the balance considerably in favour of defence [24]. The High North is host to an important leg of the Russian nuclear triad — ballistic missile submarines (SSBNs) — which detracts considerably from other states' offensive incentives. This alleviates the security dilemma.

The Arctic region finds itself in a security dilemma closely tied to militarisation. If a state does not strengthen its military resources, other, more powerful states could more easily exploit them. On the other hand, if a state increases its military resources, neighbours may perceive this as a threat and militarise further [31]. The regional hegemon, Russia, has spent years increasing its military forces and infrastructure in the Arctic, particularly on the Kola Peninsula. These forces have, however, been severely depleted by the war in Ukraine. Nonetheless, the strategic weapon systems remain.

Climate change acts as a *threat multiplier*. According to Goodman and Baudu (2023), threat multipliers refer to the "tendency of climate change to multiply existing threats to security" [32]. The impact and magnitude of climate change varies by region, and the threat multiplying effect of climate change in the Arctic will be unique. In particular, climate change will increase the risk of competition and confrontation in the High North due to new resources becoming accessible [8]. As such, the security risks of climate change in the High North are closely tied to territory. In the Arctic security dilemma context, tensions rise when states move to secure their territory and assert sovereignty over it [33].

3. Analysis

The Norwegian Coast Guard, operating in the maritime domain, already observes an effect of climate change in the High North: increased accessibility, which has resulted in increased traffic. This leads to a higher SAR workload of the Coast Guard. The Norwegian Joint HQ, on the other hand, does not observe any major immediate impacts of climate change on Norwegian security in the High North. According to our interviewee, the High North is currently in a state of *competition*, rather than peace, due to higher tensions.

Climate change acts as a *threat multiplier*. According to the Joint HQ, the current most-noticeable threat multiplier in the High North is the war in Ukraine. In the long term, however, the Joint HQ views climate change as a salient threat multiplier, especially in terms of the status of and operations on the Svalbard archipelago. Our Coast Guard interviewees emphasised the effect on fishing activities. Ocean warming will likely precipitate the migration of fish towards the High North, accompanied by less favourable conditions in other oceans. This will increase interest in fishing in the High North.

In addition to the impact on SAR, increased commercial activity from additional states will lead to an increase in military activity. In such a situation, the Coast Guard aims to be a neutral and apolitical actor: "The Coast Guard is a de-escalating actor in the High North. We act according to law, no matter who is fishing up there". It is not merely the number of ships and actors present in the High North that will challenge the Coast Guard, but also the cold weather experience of the ships and personnel: “If you do not have experience with sailing in the High North, you have no business being there”.

The interviews revealed that new state actors are expected to enter the High North in the future, primarily to exploit resources such as fish. China has already defined itself as a “near-Arctic state” [34], and interest from the UK and France is expected to increase. According to representatives of the Coast Guard, German interest in the High North has increased after imports of Russian gas plummeted after the Russian invasion of Ukraine. Our subjects cited two primary motivations for the increasing interest in the High North: the increasing accessibility to resources such as fish, minerals, and oil, and the increasing accessibility of the Northeast Passage.

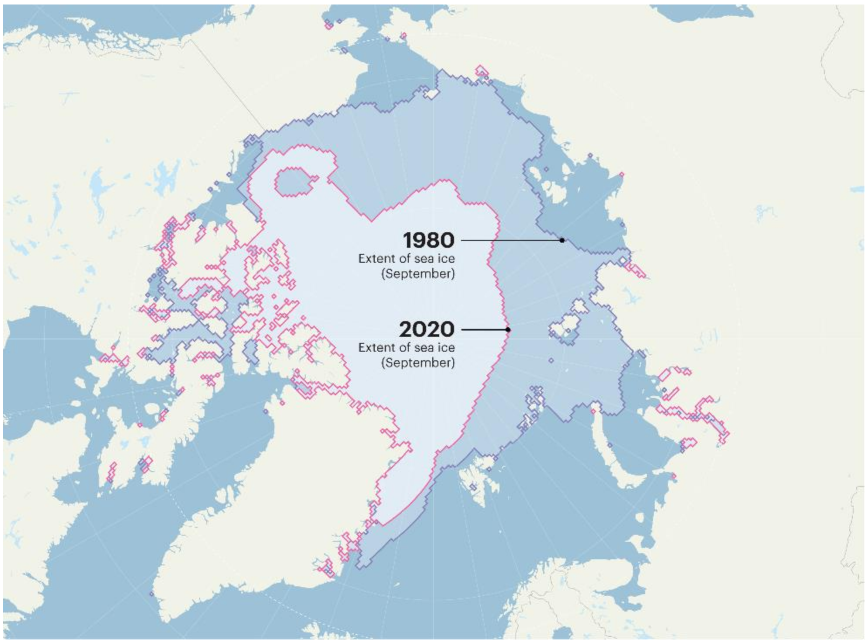


Figure 1. The extent of sea ice in the Arctic is at its lowest in September. Due to climate change, the extent of sea ice in September has shrunk considerably during the past decades. This figure was retrieved from the report of the Norwegian Defence Commission of 2021 (Defence Commission of 2021, 2023).

The High North has benefitted from the stability and pragmatism of *Arctic exceptionalism* for decades. Our Coast Guard interviewees asserted that this situation is unlikely to change dramatically. Although the war in Ukraine has certainly affected states’ views on one another on the international stage—also in the High North, this is unlikely to spill over to the High North in a considerable way. According to the Coast Guard, it is in the interest of Norway that the High North remains accessible to everyone.

The above issues are closely related to the global trend of increasing great power rivalry. According to the Norwegian Armed Forces, the great power rivalry itself does not have a strong current impact. Rather, tensions arising from the war in Ukraine cause friction, even in the High North. As the Coast Guard pointed out, this has led to more military exercises and a visit from the world’s largest aircraft carrier, the USS *Gerald R. Ford*. Moreover, the Coast Guard assesses the Russian maritime capabilities in the High North as limited and outdated, which should incentivise Russia to pursue stable conditions in the High North. Increasing regional tensions between China and Western states are strongly against Russian interests.

Norwegian daily operations in the High North principally comprise SAR, assertion of sovereignty, oil-spill preparedness, and inspection of fishing vessels. According to the Coast Guard, SAR will be affected the most. Climate change will render new maritime areas accessible to commercial, research, and military activity. Moreover, the areas tend to be poorly charted, or even uncharted. The increased traffic in these areas will likely increase SAR-related incidents. In anticipation of this increased accessibility, Russia has expanded its network of bases and its military infrastructure in the High North, as noted by our interviewees. According to the Coast Guard, this involves both the construction of new bases and the reopening of decommissioned bases.

Until recently, Norway had the sole NATO land-border with Russia in the High North. Norway hosts two important multinational exercises: *Cold Response*, a biennial NATO exercise focused on cold weather operations, and *Joint Viking*, a biennial exercise to which several NATO and Partnership for Peace nations are invited. Since 2013, Norway, Sweden, and Finland have conducted the biennial aerial exercise *Arctic Challenge Exercise* as a part of the *Nordic Defence Cooperation* (NORDEFCO). Norway also participates in the bilateral SAR exercise *Barents* with Russia. However, *Barents 2022* was cancelled, likely because of the Russian invasion of Ukraine. No *Barents 2023* has been announced.

Interestingly, our Joint HQ interviewee claimed that the issue of payment to host nations will be the most significant factor when it comes to Allied exercises in the Norwegian High North because Norway charges a fee to host NATO exercises. Conversely, especially due to particularly strong public support for anything NATO related, Sweden and Finland are unlikely to charge such fees. They are more interested in attracting a NATO presence, as new members. Thus, NATO may elect to opt for the lower-cost recent NATO additions, rather than Norway, when planning exercises in the High North. Indeed, Norwegian winters are likely to become shorter and less cold due to climate change, but the impact of this on Allied military exercises would pale next to the exercises being moved to other countries altogether.

4. Discussion

NATO operates a 360-degree security approach. The Strategic Concept from June 2022 emphasises that NATO "… will retain a global perspective and work closely with our partners, other countries and international organisations, such as the European Union and the United Nations, to contribute to international peace and security" [35].

Our analysis shows how Arctic climate change establishes new frameworks for security regarding state actors, day-to-day operations, and military exercises in the Norwegian High North. Based on our chosen realist approach, the main question remains how climate change in its capacity as a threat multiplier affects the character and extent of security dilemmas in the High North. Another important question is whether climate change favours offensive or defensive strategies by relevant state actors, the members of the Arctic Council, and the non-Arctic states France, Germany, the United Kingdom, and China. China has defined itself as a "near-Arctic state".

The offence-defence balance theory states that the security dilemma is at its most intense when offensive strategies are favoured [20]. Climate change acts as a threat multiplier when it strengthens offensive strategies. And if climate change acts as a threat multiplier, a state's reaction to aggravated international tension increases the chances of war. This will undermine the long-standing Norwegian aim of maintaining low tensions in the High North.

Several factors suggest that climate change acts as a threat multiplier in the High North. The most important factor is the receding ice cap. For Russia, this is a major challenge because Russia will lose its icy buffer against the United States. Furthermore, climate change affects the thickness of the ice. The thickness is not uniformly distributed around the North Pole: due to the Gulf Stream, the ice is thinner towards Russia, making the country vulnerable as other state actors may reach Russia's northern shores by sea. On the Norwegian side, the islands in the Svalbard archipelago as well as the Norwegian islands of Bear Island, Hopen, and Jan Mayen will be surrounded by an increasingly navigable sea. As mentioned in our interviews, these islands have had their "backs against the ice". The receding ice will influence day-to-day operations in the High North and the areas in which military exercises can take place, especially in light of the principle "train where you expect to fight" [36]. The most recent example is when the US Navy's newest supercarrier, the USS *Gerald R. Ford*, arrived in Oslo in May 2023 and participated in enhanced US-Norwegian military cooperation activities amid increased Russian activity “in the Arctic circle” [37].

Other factors point in the opposite direction, contributing to mitigating climate change as a conflict multiplier. One of them is, somewhat unexpectedly, the war in Ukraine. As one of our respondents emphasised: “Russia aims to keep the war in Ukraine as isolated as possible. They have not taken steps that would have provoked increased Western activity in the vicinity of the Russian naval bases on the Kola Peninsula”. Another respondent stated: “We have not changed our operational pattern. In the future, though, we will have to look at the islands in a different way, but we are not planning for climate change”.

But climate change is indeed taking place. The Norwegian Defence Commission of 2021 devotes a chapter to the security consequences of climate change in their report. They assert that the warming taking place on Svalbard is six times higher than the global average temperature rise [38]. Consequently, the glaciers are melting faster than before, and this will lead to a sea-level rise. Furthermore, the report states that the permafrost is thawing at a high rate and snow and landslides will increase. This will present the Norwegian authorities with many demanding issues in the future.

Our interviewees agreed with the findings of the Defence Commission but added that increased traffic in the area will challenge SAR and oil spill preparedness. As one interviewee said, the area north of Svalbard is “the last frontier” but will become increasingly accessible. This will make the area even more vulnerable. The cancellation of the bilateral *Barents* exercise is an example of how climate change acts like a threat multiplier, making all parties more vulnerable. The war in Ukraine makes cooperation with Russia in the High North impossible on several issues. And in turn, fewer meeting points between state parties might make offensive strategies more favourable. What will mitigate the prevalence of offensive strategies is the Nordic countries’ long experience in dealing with Russia — as seen under the Cold War and after, and experience with the risks in dealing with Russian military activity in the area [7]. However, we do not underestimate the possibilities for climate change to become an important threat multiplier. Long experience with handling Russian activities on a day-to-day basis is an important mitigation strategy in this regard.

5. Conclusions

Until today, Arctic exceptionalism has protected the Norwegian High North from being detrimentally affected by global tensions. Despite these tensions increasing, local cooperation in the region has continued. There is currently no traditional security dilemma in force in the Norwegian High North that may be exacerbated by climate change. Rather, climate change acts as a threat multiplier which erodes Arctic exceptionalism and in turn paves the way for an emergent security dilemma in the Norwegian High North. Rather than exacerbating a regional security dilemma, climate change will likely *precipitate* one.

References

[1] Østhagen, A. (2021). Norway’s Arctic policy: still high North, low tension? *The Polar Journal*, *11*, 75-94

[2] Huitfeldt, A. (2023). *Foreign policy statement to the Norwegian parliament*. The Government of Norway

[3] Bjur, I. N. (2023). Enduring Principles, Changing Practices? Norway’s Reassurance Policy towards Russia in the Face of NATO’s Nordic Enlargement. In: Holtsmark, S. G., Labrosse, D. & Ball, C. (eds.), *NATO’s Northern Enlargement: How Did It Happen, Where Will It Lead?* (II-4). H-Diplo|RJISSF Policy Roundtable

[4] Ide, T. (2023). Rise or Recede? How Climate Disasters Affect Armed Conflict Intensity. *International Security*, *47*, 50-78

[5] NATO (2021, June 14). Climate Change and Security Action Plan

[6] Ciolan, I. (2022, April 11). *The EU’s geopolitical awakening in the Arctic*. European Policy Centre. https://www.epc.eu/en/Publications/The-EUs-geopolitical-awakening-in-the-Arctic~47c318

[7] Bekkevold, J. I. & Hilde, P. S. (2023, July 28). *Europe's Northern Flank Is More Stable Than You Think*. Foreign Policy. https://foreignpolicy.com/2023/07/28/arctic-nato-russia-china-finland-sweden-norway-northern-europe-defense-security-geopolitics-energy/

[8] Keil, K. (2014). The Arctic: A New Region of Conflict? The Case of Oil and Gas. *Cooperation and conflict*, *49*, 162-190

[9] Steinveg, B. (2023). *Arctic Governance through Conferencing. Actors, Agendas and Arenas*. Springer.

[10] Heier, T. & Kjølberg, A. (eds.) (2015). *Norge og Russland. Sikkerhetspolitiske utfordringer i nordområdene*. Universitetsforlaget

[11] Olsen, J. A. (eds.) (2018). Security in Northern Europe. *Deterrence, Defence and Dialogue*. Royal United Services Institute

[12] Østhagen, A. (2023). Ine Eriksen Søreide: nordområdene, USA og balansekunst. *Internasjonal Politikk*, *81*, 60-76

[13] Boulègue, M. & Depledge, D. (2021, May 4). New military security architecture needed in the Arctic. Chatham House. https://www.chathamhouse.org/2021/05/new-military-security-architecture-needed-arctic

[14] Depledge, D. (2022). Train Where You Expect to Fight: Why Military Exercises Have Increased in the High North. *Scandinavian Journal of Military Studies*, *3*, 288-301

[15] Baudu, P. (2022, July 22). *Navigating Melting Ice and Eroding Exceptionalism: Theory-Driven Policy Pathways for NATO’s High North Commitment*. IRIS. https://www.iris-france.org/168952-navigating-melting-ice-and-eroding-exceptionalism-theory-driven-policy-pathways-for-natos-high-north-commitment/

[16] Drageset, S. & Ellingsen, S. (2010). Å Skape Data Fra Kvalitativt Forskningsintervju. *Sykepleien forskning*, *5*, 332-335.

[17] Roulston, K. & Choi, M. (2018). Qualitative Interviews. In: Flick, U. (eds.) *The Sage Handbook of Qualitative Data Collection*. Thousand Oaks, CA: SAGE Publications Ltd

[18] Muskat, M., Blackman, D. & Muskat, B. (2012). Mixed Methods: Combining Expert Interviews, Cross-Impact Analysis and Scenario Development. *The Electronic Journal of Business Research Methods*, *10*, 9-21

[19] Walt, S. M. (2022, July 26). *Does Anyone Still Understand the ‘Security Dilemma’?*. Foreign Policy. https://foreignpolicy.com/2022/07/26/misperception-security-dilemma-ir-theory-russia-ukraine

[20] Jervis, R. (1978). Cooperation under the Security Dilemma. *World Politics*, *30*, 167-214

[21] Glaser, C. L. (1998). What is the Offense-Defense Balance and Can We Measure it? *International Security*, *22*, 44-82

[22] Booth, K. & Wheeler, N. (2008). Rethinking the Security Dilemma. In: Williams, P. D. (eds.) *Security Studies: An Introduction*. Taylor & Francis

[23] Jones, S. G. (2003). The European Union and the Security Dilemma. *Security Studies*, *12*, 114-156.

[24] Lynn-Jones, S. M. (1995). Offence-Defence Theory and its Critics. *Security Studies*, *4*, 660-691.

[25] Glaser, C. L. (1997). The Security Dilemma Revisited. *World Politics*, *50*, 171-201

[26] Posen, B. A. (1993). The security dilemma and ethnic conflict. *Survival*, *35*, 27-47

[27] Wilhelmsen, J. & Hjerman, A. R. (2022). Russian Certainty of NATO Hostility: Repercussions in the Arctic. *Arctic Review on Law and Politics*, *13*, 114-142

[28] Buzan, B. & Wæver, O. (2003). *Regions and Powers: The Structure of International Security*. Cambridge University Press

[29] Friedberg, A. L. (1993). Ripe for Rivalry: Prospects for Peace in a Multipolar Asia. *International Security*, *18*, 5-33

[30] Byers, M. & Covey, N. (2019). Arctic SAR and the “security dilemma”. *International Journal*, *74*, 499-517

[31] Åtland, K. (2014). Interstate Relations in the Arctic: An Emerging Security Dilemma? *Comparative Strategy*, *33*, 145-166

[32] Goodman, S. & Baudu, P. (2023). Climate Change as a "Threat Multiplier": History, Uses and Future of the Concept. *Briefer*. Center of Climate & Security

[33] Dyer, H. C. (2017). Security Politics and Climate Change: the new security dilemma. In: Corry, O. & Stevenson, H. (eds.) *Traditions and Trends in Global Environmental Politics: International Relations and the Earth*. Routledge

[34] Kossa, M. (2020). China’s Arctic engagement: domestic actors and foreign policy. *Global Change, Peace & Security*, *32*, 19-38

[35] NATO (2022, June 29). *NATO Strategic Concept*. https://www.nato.int/cps/en/natohq/topics_210907.htm

[36] Depledge, D. (2022). Train Where You Expect to Fight: Why Military Exercises Have Increased in the High North. *Scandinavian Journal of Military Studies*, *3*, 288-301

[37] Parken, O. (2023, May 24). *USS Gerald R. Ford Makes Historic Visit To Norway On Its Inaugural Cruise*. The Drive. https://www.thedrive.com/the-war-zone/uss-gerald-r-ford-makes-historic-visit-to-norway-on-its-inaugural-cruise

[38] Defence Commission of 2021 (2023). *Forsvarskommisjonen av 2021*. For fred og frihet

The connection of Atlantic and Arctic oceans in the 21st century: challenges of maritime and human securities. Portugal in the Arctic. Scenario thinking (2023-2035)

Céline RODRIGUES [a,1]
[a] *Universidade Nova de Lisboa, FCSH, Lisboa, Portugal*
ORCiD ID: Céline RODRIGUES https://orcid.org/0009-0002-2924-4984

Abstract. This research intends to evaluate how the Arctic region can be an opportunity for Portugal to add to its foreign policy as well as defence and maritime strategies, using the prospective analysis by presenting scenarios in the 2023-2035 timeline. Portugal finds itself at the crossroad between climate change, oceans and the closeness of the Arctic due to the possible expansion of the continental shelf and the melting of the Arctic Ocean that opens new maritime routes connecting Atlantic and Arctic regions. A trinity of topics represented by the theoretical and conceptual framework that includes: Green Theory, maritime security and human security. The two oceans already meet through the Atlantification process that is accelerating the melting ice and placing challenges to non-traditional security: maritime security and human security by confirming the crossroad of securities and oceans, Portugal needs to reposition at a geopolitical level as a global coproducer of maritime security by preventing human security. Thus, challenges transform in opportunities for Portugal by being in the Arctic in the 21st century, or at least looking closely at this region.

Keywords. Arctic, Atlantic, human security, maritime security, Oceans, Portugal

1. Introduction

According to the European Union in 2008, the General Secretariat of the Council of the European Union (EU) (6125/18) sharing its "Conclusions on Climate Diplomacy," and the United Nations (UN) in the report of the Secretary-General Climate change (A/64/350) on September 11, 2009, climate change is considered a *threat multiplier*, assuming and assimilating Sherri Goodman´s expression.

In order to live up to its claims of being a pioneer in ocean governance and a co-developer of global maritime security as stated in the National Ocean Strategy 2021–2030, Portugal has a responsibility to protect and secure the Atlantic region. This responsibility extends beyond just preserving Portugal's sovereignty as a maritime nation and as a founding member of NATO and a member state of the EU.

The goal of this research is for Portugal's telescope to be able to look north — as it did in the 15th century when Portuguese explorers reached Greenland, Newfoundland and Labrador — by acknowledging new challenges in the 21st century for maritime security and Portugal and understanding the need for coordinated actions among political, diplomatic, and military actors in various international fora, presenting different scenarios,

---

[1] Corresponding author: Céline Rodrigues, celineceli@hotmail.com

within the period 2023-2035. The development of the prospective analysis will formulate an answer to the question defined for this research: which are the challenges of maritime and human securities in North-Atlantic and Arctic Oceans, respectively, that place Portugal in the Arctic in the 21st century? Secondary questions are: what is the contribution of Portugal in the Arctic; what does it mean to be in the Arctic; and, how to be in the Arctic [1]?

The framework Green Theory – Human Security – Maritime security is of relevance, as the assimilation of nature and climate in international relations (IR) considering the transboundary, globalization and interdependence of such topics aside the growing importance of nature and climate change in this century [2]. The foundational knowledge for the development of this investigation provides a lens to look at challenges and opportunities arising north, which are Portugal´s concern in a first place, as well as for the European Union, NATO and the rest of world. Portugal, by looking at: i) – globalisation of climate change that affects the Arctic region, Arctic Ocean and consequently the country; and ii)- a new ocean that is opening, considering the extension of globalisation moving North, getting closer to Portuguese sea territory, (in case the Portuguese request for the extension of the continental shelf is accepted); then, I consider relevant that Portugal: 1) looks North, acknowledging the fusion between the two oceans and the extension of globalisation in the Arctic region, in the words of Sörlin becoming a Meta-Geographical Space (2017) [19]; 2) assimilates climate change, nature and oceans in IR, defence and foreign affairs; 3) brings together social and natural sciences in a cooperative way by assuming vulnerabilities in climate threat context; and, 4) assumes its huge water territory as the extension of land territory.

Another area is now being affected by globalization. Portugal can have a significant and leading role in the various sectors, including ocean and maritime security, as a result of the Arctic region's melting ice creating a new navigable Ocean that is already influencing geopolitics at a global level with regional implications.

Oceans are among the crucial issues in this new century, along with climate change and the Arctic. The turning point for maritime security occurred in 1998. As a result, as the millennium drew near, the UN proclaimed that year the International Year of the Oceans. Tiago Pitta e Cunha credits Portuguese diplomacy and policy for this accomplishment in his book Portugal e o Mar (2004). The Independent World Commission on the Oceans (IWCO) Report, written by Mário Soares, was released that same year and lists both military and non-military threats that could lead to global disorder at sea. As the year of Portugal's reconnection to the Atlantic, 1998 is also remembered as the year that brought about the world exposition on oceans in Lisbon, known as Expo98.

It may be observed that in the twenty-first century *IR is no longer just a sub-discipline of political science and economics, but is also subordinate to the geophysical sciences* as mentioned by Harrington as cited by Corry [7].

This study aims to fill a gap in the interdisciplinarity of those topics in IR within Portuguese academia by opening cooperative relations between natural and social sciences, an idea already advocated in 1998 by the Independent National Commission on the Oceans with the goal of increasing literacy in the ocean and climate change as well as producing new and relevant information about those topics within Portuguese research. This means that this way of thinking is not brand new in Portugal. However, it doesn't seem as though this concept of scientific collaboration is being properly applied in the Portuguese context and academic environment.

Therefore, it is anticipated that this research will contribute to: closing the gap in the interrelation of sciences and reintegrating nature into the field of study of IR; starting the conversation in Portugal about including the Arctic region in foreign, defence, maritime, and environmental policies; rethinking and repositioning the nation in light of the changes to come in the Arctic region also connected to the possibility of the extension of the continental shelf; and, preparing and acting in a preventive way, reconstructing a new narrative based on a new relation with the Atlantic that uses correctly ancestral and intergenerational knowledge about the ocean as well as for the Arctic countries to recognise Portugal as a probable and plausible actor.

2. The Arctic region and Portugal in the midst of Environment – Oceans – Security nexus

Emilian Kavalski and Magdalena Zolkos (2016) assert that, in contrast to other branches of social sciences, IR has excluded and distanced itself from nature. Along the way, IR have grown to forget about nature. Somehow, at its inception, IR had made the assumption that people and nature coexisted, that they were both essential components of the ecosystem (as acknowledged by the Convention on Biological Diversity in 1992 and Darwisnist vision), and that people should respect the environment in which they live and upon which their survival and existence depend [13].

The Second World War marked a turning point in this vision and will continue to do so because it excluded nature from the study of international relations (Corry, 2020a) [7]. With the Westphalian construction of the world based on a state-centric perspective no longer being applicable in the actual context, climate change and nature have moved from the boarder to the centre of International Relations. According to Steve Mentz (2009), there has been a shift from land to sea in this century, or the *New Thalasso,* which acknowledges the importance of the climate-ocean nexus for the stability of the earth and, consequently, for the survival of human life [14]. The interconnectedness that extends far beyond just trade and economics, jurisdiction, and state sovereignty has been reinforced by the fact that environmental issues (which include climate change and global warming) have an impact on every nation and have been a major topic in international relations in the 21st century. It moves into the realm of security.

The early modern era that introduced the world to new worlds is also referred to as the Age of Discoveries, *Age of Errors* (meaning *arriving unexpectedly at a place that's not the one you were trying to reach*, Steve Mentz, 2019, p. 52) [15], *First Globalization* (Cristina Brito cit. Costa, Rodrigues & Oliveira, 2014) [3] or *Wet Globalization* (Steve Mentz, 2022) [16]. Regardless of the phrase, it is a period that was started by Portuguese navigators, the ocean serving as a highway for evolution, and connection that was limited to littoral connections. The Industrialization period, the period that corresponds to the Anthropocene from Crutzen's perspective and the Great Acceleration, that influenced human activity beginning in the 1950s of the previous century, made possible the beginning of the modern world system.

2.1. Portugal and the Atlantic Ocean

Portugal's relationship with the Atlantic has a complicated past. According to Professor Nuno Severiano Teixeira (2010)[18], this complexity differs in three periods that correspond to Portugal's international inclusion. The first period, starting in the middle ages until the 15th century, is when Portugal looked to Spain, and its world was the Iberian Peninsula, land. The second moment, which is the longest, from the 15th century until the end of the dictatorship, is when the country forgot about the hinterland and defies what structural theorists called water barrier instead of looking at sea as a vector of political development. The third and final period is the moment that began with democracy in the country, in which Portugal is working on its balance between land – sea/ocean that is truly happening in this new century, in a new familiarity to the Atlantic Ocean. This period gave Portugal the opportunity to become a thalassocracy by taking advantage of its maritime geography (Geoffrey Till, 2009)[20].

The second-largest ocean, the Atlantic, has been studied by historians, including David Armitage (2002; 2018) who distinguished three types of Atlantic history: *1) circum-Atlantic history, that is the transnational history; 2) trans-Atlantic history, the international history; and, 3) cis-Atlantic history national or level history within an Atlantic context* (2002, p. 15). In 2018, the author believes that three additional concepts can be added to understand better the evolution of oceanic history in the context of the Atlantic: *4)- Infra - Atlantic history: related to the subregional history of the Atlantic world; 5)- Sub - Atlantic history: that looks at the submarine history of the Atlantic world; and, 6)- Extra - Atlantic history: the supraregional history of the Atlantic world that links* *to other oceans* (p.95). According to Mahan's six conditions listed in chapter 1 of his book *The influence of sea power upon history*, Portugal can be considered a sea power because of its Atlantic history, which is a component of Portuguese history.

The Atlantic Ocean is bordered by North and South America on the west and Europe and Africa on the east. The Atlantic connects to the Arctic Ocean and to the Southern Ocean to the south.

2.2. The Arctic Ocean

When compared with all other seas and oceans that have been the site of battles and discoveries, the Arctic Ocean is an exception. An exceptionality that is changing. An ocean navigated by Pytheas (325 b.c), Vikings in the 10th century, was also navigated by Portuguese explorers in the 15th century, who were able to reach Labrador and Newfoundland 20 years before Colombus. Arctic and Atlantic Oceans are assimilating as a result of those negative effects. According to Admiral James Stavridis (2017), the maritime domain dispute will likely continue to play a significant role in geopolitics. The Arctic Ocean is mentioned in European literature, primarily in Jules Verne's *Les aventures du Capitaine Hatteras* (1867) and Arthur Conan Doyle's *The Captain of the Pole Star* (1883), where the difficulty of the adventures is characterized, captured and described as an inhospitable, white, harsh, and frightening location. By integrating globalization, unity, and exchange that already exists under the waters between the Atlantic and Arctic Oceans (the *Atlantification* process), the Arctic will lose, is losing, its isolation. Nowadays, the Arctic Ocean is *gaining space within spatial and political significance* (Sverker Sörlin, 2017, p. 270)[19]. The same author highlights a distinction between the frozen sea and the Atlantic, namely that it belongs to transnational history rather than world history. The disappearance of the Arctic sea ice means that interests and claims are unlikely to be solved through the United Nations Convention on the Law of the Sea (UNCLOS).

3. Conceptual and Theoretical Framework

A theory that frames environmental issues in a political way (Hugh Dyer, 2018)[8] is required to address the growing awareness and consciousness that emerged in the 1960s of the previous century. Hugh Dyer believes that while IR only see the state and its national interests, green theory aids in understanding in terms of long-term ecological values. Because of this, the author claims that this theory helps IR to reconsider how the state, the economy, and the environment are related (idem, 2018). Given that the established paradigm in international relations has ignored nature for 100 years, it is a theory that challenges the status quo.

3.1. Green Theory

The author John Barry (2014) [2] recognises in his chapter titled "Green political theory" three periods, or waves, that are to be considered in the evolution of the term green political theory. The first moment begins in the 1990´s by identifying “ecologism” as an ideology and green political theory as a “distinctive approach”. The second wave is the moment in which other schools of thought are developing, such as feminism, liberalism and critical theory, which allows the expansion of debates between those schools and green political theory. It is during this wave that Green theory is recognized within IR with the transnationalism question of problems caused by climate change. The third and ~~mos~~ recent generation, designated as *third generation* of green theory due to its interdisciplinary ~~nature~~, is integrated with practical and empirical research of a *range of disciplines and knowledge outside politics, political science and political theory* (John Barry, 2014, p. 4) [2]. Scholars have been clarifying the difference between green politics, as the ones who consider that the structure can be challenged, and environmentalists as the ones who accept the framework and pursue the solution within the structures.

For the survival of humankind, it is expected that governments will place a greater emphasis on the individual, particularly when climate change is viewed as a threat, and understand the interdependence between human, nature, and the need for an equilibrium to be able to survive with sustainable development. The Green Theory, whose authors use the terms cooperation, multilateralism, and participatory democracy rather than the word security, challenges this construct (John Barry, 1999; 2014) [1], [2]. Weapons cannot stop climate change, and it entered the policy sphere once defined as a security issue.

As advocated by Green Theory, the end of the Cold War presents an opportunity for a fresh start and a shift from traditional security, which is state-centric, towards human security (non-traditional security) (Barbora Padrtova 2020) [17]. Perceiving that environmental issues go beyond national states borders leads to a differentiation in the evolution of security concept, which implies the integrated discernment of relevance, putting a person-centred emphasis on the individual, and being a person-centred idea and concept. The disruption with traditionalist vision from the Copenhagen School occurs when economic, military, political, environmental and social topics are considered sectors of security when associated to different sources of threats (Barbora Padrtova 2020) [17].

3.2. Human security

Kamrul Hossain (2017) goes back to the Illuminisme era, when the concept of human security was defined by Hobbes, Locke, and Rousseau. At that time, the idea was to establish standards for a shared security to protect people and ensure their freedom from fear, freedom from want, and freedom to live in dignity. However, Muhab ul Haq's 1994 Human Development Report introduced a new concept called "human security" that he claimed would "revolutionize the 21st century" (1994, p. 3) with four characteristics: 1)- it is a universal concern; 2)- the components of human security are interdependent; 3)- human security is easier to ensure through early prevention; 4)- human security is people-centred (idem, pp. 22-23). As a result, the meanings of security and human rights are expanded, as can be read in the report by the UN Commission on Human Security (2003). The broader definition of security emphasises the shift from nations to people/individuals. Human security takes a people-centred approach, and emphasises the need to protect individuals from a wide range of threats, such as economic deprivation, environmental degradation, poverty, disease and political violence. The interdisciplinarity of this concept is identified by the following seven dimensions: i)- Economic security; ii)- Food security; iii)- Health security; iv)- Environmental security; v)- Personal security; vi)- Community security; and, vii)- Political security (1994, pp. 24-25). The 2009 (Human Security in Theory and Practice) and 2016 (Human Security Handbook) reports also consider as principles of this approach: i)- People-centred; ii)- Multi-sectoral / comprehensive; iii) Context-specific; and, iv)- Prevention-oriented (2009, 2016). The following phases are to be followed in order to put in practice the human security approach/policy: Phase 1: Analysis, mapping and planning; Phase 2: Implementation; Phase 3: Impact assessment (2009) / Rapid assessment (2016).

In contrast to academics, who frequently *intersect* (Hossain, 2013) and *interlink* (Fukuda-Parr and Messineo, 2011) [9] human security and Responsibility to Protect (R2P), it is important to emphasize that ul Haq had a distinct understanding of the gap between R2P and that concept. Scholars view it as ambiguous and lacking in a clear definition (Sakiko Fukuda-Parr and Carol Messineo, 2011).

This approach has been criticized as being too broad and lacking in a clear definition. The UN General Assembly's 66th session, A/66/763, clarifies that *human security is an approach to assist Member States in identifying and addressing widespread and cross-cutting challenges to the survival, livelihood, and dignity of their people* (number 3, p. 1). The 2022 report and the 2016 handbook both highlight the usefulness and importance of this approach in programme design and policy recommendations.

According to Ul Haq, the concept of human security can change depending on where and how it is applied.

3.3. Maritime security

Maritime security is the third line that closes the tripartite of the conceptual and theoretical framework for this study.

The authors Basil Germond (2015)[12], Christian Bueger, and Timothy Edmunds (2017)[5] claim that maritime security is a recent concept, one of the most recent words to be added to the vocabulary of international security, and a new area of international policy that is of high priority (Bueger, Edmunds, and McCabe, 2019). Until the end of the Cold War, the phrase was not used, and when it was, it was more commonly understood as naval power. The term *maritime security* was coined following that historical event, which represents a change in many international aspects and visions, and when used, it was more closely associated with preventive measures to address illegal activities on or from the sea. As the new millennium approached, maritime security was getting more attention as a result of maritime terrorism.

The buzzword of maritime security (Christian Bueger, 2015)[4] has been added to the security agendas of both states and other actors, who have been incorporating it as a major global issue. Although the focus of IR and security studies is uneven and frequently linked to Great Power Politics, Christian Bueger and Timothy Edmunds (2017) argue that this is not the case. According to the authors, this not particularly novel idea, and was only recently developed as a branch of security thinking and has been attracting academics whose research focuses on maritime law in the age of globalization. The discussion of maritime security has historically tended to take a more realist or liberalist stance, but more recently, it has begun to shift toward a constructivist or even critical security studies perspective (Christian Bueger, and Timothy Edmunds, 2017) [5]. The same authors affirm that the focus was primarily on the maintenance of the good order as developed by Geoffrey Till (2009) [20]and less on the bottom-up types of cooperation and conflict that are interfering with the maintenance of the good order.

Since the concept of maritime security can mean different things to different people, there is no agreed-upon definition for it or agreement on how to apply it. The term *maritime security* has only recently been used in official documents including those from NATO and the International Maritime Organization (IMO) Maritime Safety Committee, as well as in national policies, particularly following the 9/11 attacks. The classification of an object as a security concern is defended by the Copenhagen School, and the speech act permits this assumption. Regarding maritime security, Cristian Bueger argues for the same position. The maritime security concept assumes that the reference objects are a security concern once they are recognized as threats as a part of grammar, discourse, or speech acts (2015).

According to Christian Bueger, and Timothy Edmunds (2017), maritime security has four domains: human security; economic development; marine environment; and, national security. Similar to human security, it has four characteristics, the first of which, interconnection, is comparable to Mahub ul Haq; cross-jurisdictional, transnational environment, and liminality are the remaining three. These domains and characteristics illustrate the complexity of the idea and the all-encompassing approach, just like human security. The term and concept of maritime security, in the opinion of both Andres Thomashausen (2014) [21] and Christian Bueger (2015)[4], are related to human security.

4. Scenario thinking – regional prospective

According to futurist authors, *looking at the future can disturb the present* (Berger cited by Godet, 2011, p. 21) [10]. Acting with the appropriate knowledge that enables one to foresee potential outcomes is what scenario thinking is all about.

The hypotheses must be defined taking variables into account and then transformed into scenarios from a regional perspective. The observations, analyses, and qualitative research in the following reports serve as the foundation for the selection of the variables: Security in uncertain times - The Military Advice of the Chief of Defence 2023 (Norway, 2023); Arctic Security Under Threat: Urgent needs in a changing geopolitical and environmental landscape (Canada, 2023); Global Strategic Trends the Future Starts Today (2022); Arctic 2050 Mapping the Future of the Arctic (2020); Foresight Portugal 2030 (2021); Global Trends 2040 - a more contested world (2021); NATO 2030: United for a New Era (2020); Strategic Trends Programme Global Strategic Trends - Out to 2045 (2018); and, Maritime Futures 2035: The Arctic Region (2018). The evidence from this literature strengthens the connections between far-off places so that it is accepted that local events are influenced by those taking place thousands of miles away and vice versa.

In *Creating Futures Scenario Planning as a Strategic Management Tool*, Michel Godet (2006) [11] explains that the regional prospective indicates that the subject is a specific geographic area. Regional prospective, despite being a recent phenomenon, was developed between the years 1955 and 1975, primarily with the help of French academics. According to Michel Godet (2011) [10], the term prospective takes into account long-term trends and risks that alter the present and necessitates strategy to make decisions that are feasible so that anticipation drives action. According to the definition of the term *scenario*, it is a description of a potential future in which important key events occur between the time the situation exists and the time the scenario is established.

Four scenarios are anticipated to be created, with the aim of lowering the level of uncertainty, as only a few scenarios are required to account for the majority of likely futures (Michel Godet, 2011) [10]. The following four scenarios will be noted and named: Scenario 1: Portugal in the Arctic; Scenario 2: Alienation; Scenario 3: In the midst of confusion; Scenario 4: Losing control.

The Delphi exercise, a method created by Olaf Hemer in the 1950s and 1960s to serve the needs of the United States Army, will enable the collection of many expert opinions on proposed scenarios. The following people/entities shall receive the questionnaires to be answered in an anonymous way: diplomats, scholars, scientists, ministers (from the ministries of defence, economy and maritime affairs, environment, and foreign affairs), and the chiefs and commanding officers of the Army and Navy.

5. Early conclusions

Only when the importance and role of the Arctic in the Earth system and as a region with global impact is assimilated and accepted will Portugal be in condition to include the Arctic and other poles in its various strategies and policies, defending cooperation and science diplomacy. Though, it shall be added that the cognizance of the new maritime routes, as a consequence of the melting ice provoked by climate change, replace geopolitically the country and the Azores Island in the Atlantic Basin in the 21st century, aware of the presence of the Republic of China and the Federation of Russia in the Arctic and North Atlantic. The new Portuguese national defence strategy and new lines for maritime security are expected to express this awareness and responsibility of protecting its sovereignty and its allies at sea. Portugal can also be the bridge between South and North (Global/Atlantic).

References

[1] Barry, J. (1999). *Rethinking green politics: Nature, virtue and progress*. SAGE Publications https://doi.org/10.4135/9781446279311

[2] Barry, J. (2014). Green Political Theory. In: Geoghegan, V., & Wilford, R. (Eds.), *Political Ideologies: An Introduction*, 153-178

[3] Brito, C. et al. (2022). O oceano histórico e ecológico: Narrativas e contextos da época moderna. Publicação do Instituto Diplomático, Ministério dos Negócios Estrangeiros, *Revista Negócios Estrangeiros, Oceanos.* 22, Edição Digital, 21-40. https://idi.mne.gov.pt/images/Revista_NE/PDF/n%C2%BA22_Oceanos/Revista_Neg%C3%B3cios_Estrangeiros_n%C2%BA_22_julho_2022.pdf

[4] Bueger, C. (2015). What is maritime security? *Marine Policy.* Vol. 53. 159-164. http://dx.doi.org/10.1016/j.marpol.2014.12.005

[5] Bueger, C., & Edmunds, T. (2017). Beyond Sea-Blindness: A New Agenda for Maritime Security Studies. *International Affairs*. 93, 1293-1294. https://doi.org/10.1093/ia/iix174

[6] Corry, O. (2020). The Planetary Is Not the End of the International, In Castro Pereira, J., & Saramago, A. *Non-human Nature in World Politics*. Forthcoming Springer

[7] Corry, O. (2020). Nature and the international: towards a materialist understanding of societal multiplicity. *Globalizations*, Vol. 17(3). 419-435. https://doi.org/10.1080/14747731.2019.1676587

[8] Dyer, H. (2018). *Introducing Green Theory in International Relations*. https://www.e-ir.info/2018/01/07/green-theory-in-international-relations/

[9] Fukuda-Parr, S., & Messineo, C. (2011). *Human Security: A critical review of the literature.* CRPD Working Paper No. https://soc.kuleuven.be/crpd/files/working-papers/wp11.pdf

[10] Godet, M. (2011). *Strategic Foresight, La Prospective, Use and Misuse of Scenario Building.* http://en.laprospective.fr/dyn/anglais/ouvrages/sr10veng.pdf

[11] Godet, M., (2006). Creating Futures, Scenario Planning as a Strategic Management Tool. *Economica*. http://en.laprospective.fr/dyn/anglais/ouvrages/sr10veng.pdf

[12] Germond, B. (2015). The geopolitical dimension of maritime security. *Marine Policy*. 54, 137-142. http://dx.doi.org/10.1016/j.marpol.2014.12.013

[13] Kavalski, E., & Zolkos, M. (2016). The Recognition of Nature in International Relations. Hayden, P., & Schick, K. (Ed.) In *Recognition and Global Politics*. 139-155. https://www.manchesteropenhive.com/display/9781526101037/9781526101037.xml

[14] Mentz, S. (2009). Toward a Blue Cultural Studies: The Sea, Maritime Culture, and Early Modern English Literature. *Literature Compass*. 6, 997-1013. https://doi.org/10.1111/j.1741-4113.2009.00655.x

[15] Mentz, S. (2019). Breaking up the Anthropocene. University of Minnesota Press

[16] Mentz, S. (2022). *Shipwreck, Wet Globalization, and the Blue Humanities*. Routledge. https://doi.org/10.4324/9780367347093-RERW7-1

[17] Padrtova, B. (2020). Applying conventional theoretical approaches to the Arctic. In Routledge *Handbook of Arctic Security*. https://www.routledgehandbooks.com/doi/10.4324/9781315265797-3

[18] Severiano Teixeira, N. (2010). Breve ensaio sobre a política externa portuguesa. *Relações Internacionais.* https://research.unl.pt/ws/portalfiles/portal/4272000/NST_n28a04_2010.pdf

[19] Sörlin, S. (2017). The Arctic Ocean. In Armitage, D., Bashford, A., & Sivasundaram, S. (Eds.), In *Oceanic Histories*, (Cambridge Oceanic Histories). Cambridge: Cambridge University Press, 269-295

[20] Till, G. (2009). *Seapower: a guide for the twenty-first century*. 2nd ed. Routledge

[21] Thomashausen, A. (2014). A segurança marítima no atlântico: uma perspectiva do sul lusófono. In: Graça, P. Martins, T. *Mar no Futuro de Portugal. Uma Abordagem Estratégica.* Centro de Estudos Estratégicos do Atlântico: Etigrafe, Lda

Securitization or Arctic militarization: the best way to preserve NATO's strategic dominance in the Arctic

Vismay BUCH[a,1]
[a] *University of Toronto*
ORCiD ID: Vismay BUCH https://orcid.org/0009-0005-8937-8476

Abstract. The Arctic Circle, encompassing a vast landmass in Northern Canada and Eurasia, is a region with vast ice fields and permafrost. The region is rich in mineral and oil and gas deposits. On top of its economic importance, the region also has immense geopolitical importance for NATO and its potential adversaries. The Arctic is one of the most impacted regions by climate change because the latter exacerbates current geopolitical issues shaping global security policies. Rising sea levels, ill-defined Exclusive Economic Zones (EEZs) and increased commercial shipping through the Arctic could lead to heightened aggressive confrontation between NATO and its potential adversaries, including Russia and China. In this paper, I intend to analyze NATO and Sino-Russian Arctic policies through the securitization lens first introduced by Barry Buzan [1]. I argue that the Arctic states are militarizing the Arctic instead of securitizing climate change i.e., considering climate change as a threat to national security which limits their ability to address the issue effectively. Realistically, all Arctic states need to collaborate on securitizing climate change and protecting the ice cover of the Arctic region and therefore protecting coastal military and civilian infrastructure around the world. To maintain NATO's strategic dominance, it will require a gargantuan effort both on civilian and military fronts.

Keywords. Arctic, Securitization, National security, great power, conflict, climate change, NATO, Russia, China, oil, gas, exploration

1. Introduction

Climate change is one of the most consequential factors determining the geopolitical stability in the Arctic. Objectively speaking, melting Arctic sea ice has both significant drawbacks and benefits for the global community. To begin with, the Arctic sea ice covers roughly 5 to 6 million km^2 in summer and 14 million km^2 in the winter of the northern reaches of the Earth. Due to the warming climate, this sea ice and glacier coverage is decreasing year on year, which is affecting the sea levels across the globe, which is in turn threatening coastal cities [2]. Furthermore, rising average global temperatures have also led to the thawing of the permafrost in the Arctic, which can affect the stability of the infrastructure whether it be military or civilian.

Climate change poses major challenges to the safety and security of all nations, but in the Arctic, melting sea ice provides numerous opportunities for the Arctic states [3]. According to the United States Geological Survey (USGS), the Arctic region has about 90 million barrels of oil and 1.67 trillion ft^3 of natural gas, and melting sea ice would make

---

[1] Vismay Buch, vismay.buch@mail.utoronto.ca

those reserves even more accessible to nations, and will be open for investments in oil and gas extraction by all states and all oil and gas corporations. Melting sea ice is also making the Arctic Sea routes increasingly accessible; the newly evolving Arctic shipping routes include the Northwest Passage (NWP), which passes through the northern territories of Canada, and the Northern Sea Route (NSR), crossing through northern Russia. **Figure 1** shows the Trans Polar Sea Route passing through the geographic North Pole of the Earth. To achieve this transit, there cannot be any Arctic Sea ice in the summer. The rise of the Arctic shipping routes would make the Suez and Panama canals less of a strategic chokepoint and would allow ships to avoid the possibly dangerous Strait of Malacca and the Gulf of Aden [4]. These advantages of melting sea ice to states have the potential to create competition for natural resources and global shipping shortcuts. Climate change will play a huge role in shaping the national security narrative of all Arctic and near Arctic states. According to Buzan, states in the Arctic periphery are trying to securitize their threatened coastlines and melting sea ice and to an extent climate change in the hope of mitigating the problem. In the context of the Arctic states, securitization involves considering climate change as a security threat to all nations. It also means that the Arctic states would need to eliminate or at least minimize their production of fossil fuels.

On the other hand, the post-Cold War discovery of oil and gas in the Arctic has led to a morphed definition of securitization and recently there has been a mass deployment of military infrastructure in the region from all stakeholders for them to effectively exercise their rightful claim to the Arctic. As noted by Greaves [5], the Arctic region can be defined as a Regional Security Complex (RSC) which encompasses all the current Arctic stakeholders such as the Arctic states, the Arctic Council and NATO, just to name a few. The Arctic states are only partially securitizing climate change because even while facing the consequences of climate change, they keep on producing fossil fuels to enrich their economies. Furthermore, Russia has been increasing its production of oil and gas for the past years and all the Arctic states except Iceland have some conflict of interest in fully securitizing climate change and denoting it as one of the main threats to national security. All the Arctic states are building up their military capabilities around the Arctic in order to project power and maintain influence over the Arctic. Militarizing rather than securitizing climate change for the Arctic stakeholders translates simply into an overarching control of future shipping lanes as well as undisputed control over 90 million barrels of oil and 1.9 trillion cubic meters of natural gas [6]. By vetoing, the climate securitization bid at the UN Security Council cleared the way for Russia to reap more benefits from the melting sea ice. Furthermore, an ice-free Arctic would play an indispensable role in augmenting the Russian ambitions of controlling the Arctic. However, the regional climate and defence policies of all the Arctic nations affect their willingness and capability to securitize climate change in a meaningful way. Intergovernmental organizations such as the Arctic Council and the United Nations Security Council also play a major role in building the required diplomatic channels for peaceful discussions and cooperation in the Arctic. The Arctic Council, an Intergovernmental organization facilitating Arctic cooperation, consists of Canada, the US, Iceland, Norway, Sweden, Finland, Denmark, and the Russian Federation. Some of the common features of the Arctic policies of all Arctic states include conservation of marine biodiversity, Arctic logistics, sustainable economic growth, protection of indigenous cultures, and climate mitigation. However, at the juncture of the aforementioned policies, all nations diverge into their passive-aggressive rhetoric of peaceful control of the Arctic. Collaboration between the Arctic states at multilateral venues like the Arctic Council is hard to come by as Russia along with its economic, political and military ally China have not much to gain from securitizing climate change and preserving the Arctic; it is because the Arctic region is rich in oil and gas resources and, with increasingly ice-free Arctic Ocean Region (AOR), it could be easily accessible and can be extremely beneficial for Russia. Moreover, an ice-free Arctic also provides an excellent shipping route which can effectively shorten the shipping times by days. Potential NATO adversaries like Russian and China are already strategically benefitting from such heightened mobility in the Arctic [7]. Therefore, I believe that it is of utmost importance that NATO and its current and future Arctic and non-Arctic member Nations present a unified stance in militarizing the

AOR. In this paper, I will outline the ways the great power conflict between NATO and the Sino-Russian bloc is plunging the AOR into militarization and how NATO can maintain operational readiness in the High North, while at the same time building a strong and climate-resilient unified Arctic Command.

2. Climate Securitization or a lack thereof

As alluded to in the introduction, securitization can be defined as the consideration of an object or a phenomenon as a security threat. In this case, climate change and a resulting rise in sea level can be considered a threat to national security. Securitization of climate change cannot be a unilateral or even a limited multilateral effort, it has to be a broader global effort on all fronts which requires broad multilateral backing. Such efforts have not gained major support at many global forums. Various Arctic states such as Norway have announced time and again that if it comes to preserving the Arctic region or maintaining the operational readiness of the Norwegian Armed Forces, operational readiness will take precedence over securitizing climate change as in this renewed threat environment protecting Norwegian sovereignty is far more critical than preserving the AOR from climate change [8]. UN Security Council Resolution 14732 to securitize climate change failed with 12 in favour, one abstention (China), and two votes (Russian Federation and India) against it. When it comes to climate collaboration specifically in the Arctic region, the Arctic Council has been the premiere venue for diplomatic efforts on negotiations to collaborate on climate-related issues in the Arctic. However, gains from securitizing climate change are not equally distributed around the Arctic Circle.

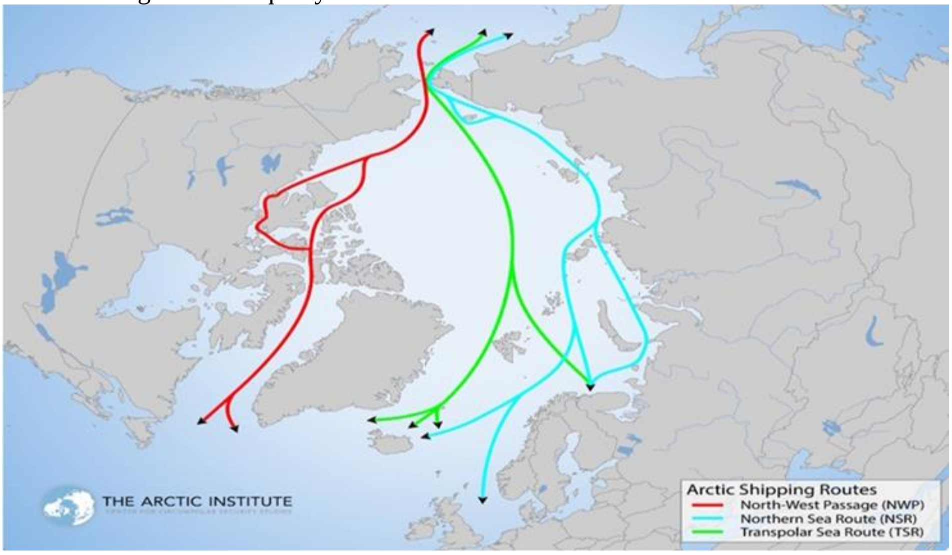


Figure 1: Map of the Arctic Shipping Routes, most notably the Northern Sea Route (NSR) which mainly passes through the Exclusive Economic Zone of Russia whereas the North-West Passage passes through the territorial waters of Canada. When the ice melts, these routes could become flashpoints for the geopolitical conflict between NATO and the Sino-Russian bloc. Credit. The Arctic Institute.

Among the 13 Arctic Council observer states the roles of India, China, and Japan are noteworthy. In 2013, at the Kiruna ministerial meetings of the Arctic Council, India, China, and Japan were recognized as observer near-Arctic states, but their involvement in the Arctic started a long time before they were officially recognized as such [9][9]. Instead of securitizing climate change, all three nations have adapted their Arctic policy to reflect the ice-free Arctic Ocean with tremendous economic potential. Throughout the years, India has maintained a scientific approach to the AOR. Since 2008, India has set up a research station in Svalbard, Norway named Himadri to study the effects of climate change on global sea levels and temperature [10]. In 2022, India released its official Arctic policy mainly focusing on climate research in the Arctic and improved transportation and connectivity in the region. This policy also professes the need for international good governance and cooperation and states India’s intent to expand its research capabilities in the Arctic by installing two climate observatories in Kongsfjorden and Ny Alesund in northern Norway. During a similar period, China started as an *ad hoc* observer state at the Arctic Council meetings [11]. Japan on the other hand received its first freight shipment through the Northern Sea Route in 2012, which sparked the need for a comprehensive Japanese Arctic policy. Obtaining observer state status allows having a say in the matters of Arctic and climate change. Japan’s security policy highlights its role as a force, promoting cooperation and safe passage of all commercial vessels. Moreover, Japan also maintains their commitment to sustainable research practices in the Arctic through dedicated funding for research projects like the Arctic Challenge for Sustainability Projects (ArCS) [12].

3. Sino-Russian Nexus Vs NATO – An Emerging Great Power Rivalry in the Arctic

Russian Arctic policy focuses mainly on the increased investment in developing ports and other shipping capabilities. Russian Arctic policy seeks to develop the Russian Arctic region into a strategic resource base and to utilize the natural resources in the Arctic to strengthen the Russian economy. Russia remains steadfast in its claims that “some countries obstruct economic or other activities by the Russian Federation in the Arctic”. Russia has also maintained that its extended claim of the Arctic is legitimate and is completely able and willing to challenge any contradicting statements issued by any other Arctic nation. In February 2020, on the 100th Anniversary of the Spitsbergen (Svalbard) Treaty with Norway, the Russian Foreign Minister sent an open letter questioning the nonbinding Norwegian fisheries protection zones around the Svalbard Islands that play a major role in Norwegian claims of the Arctic seabed under the UN Convention on the Law of the Sea (UNCLOS).

China released a white paper on its first official Arctic policy in 2018 which outlines increased cooperation between China and the other Arctic states in developing new methods to harvest the green energy potential including geothermal, wind and tidal [13][14][15]. The Chinese government and firms plan to forge trade relationships with the Arctic states to extract oil and other natural resources in the region; the Sino-Russian partnership in the Arctic goes way beyond joint research facilities. The biggest boost to the Russian-Chinese relationship came after the Western sanctions were imposed on Russia after its illegal invasion of Ukraine, and, because of this, almost all the Western partnerships with Russia for Arctic oil and gas exploration were suspended. China now sees a “window of opportunity” for Chinese state-owned enterprises and other private companies to aid Russia and its oil giants financially and technologically. In 2013, Russian oil and gas giant Rosneft and China commenced a joint venture in Eastern Siberia to develop an oil field. Increased cooperation between China and Russia poses huge security challenges to the West [16]. Since 2012, Russian and Chinese navies have conducted yearly military drills near the Bering Strait to showcase a unified front against perceived Western aggression. China has also not been as vocal as the other Arctic states and NATO member Nations over Russia’s increased militarization of the Arctic. For search and rescue capabilities, and securing the Northern Sea Route, Russia has reactivated many of the Cold War-era Soviet Arctic military bases and built some new ones along the NSR. To continue to further exploit oil and gas in the Arctic, China and Russia have forged strategic relationships to fund and develop the Northern Sea Route.

Effective Russian militarization of the Arctic begins with the mutual economic partnership with China when it comes to Arctic oil and gas exploration and other important civilian infrastructure that can be used by ships transiting through the NSR. In addition, Sino-Russian NSR cooperation dates back to at least 2017 when both nations signed an agreement to start the construction of the “Polar Silk Road” connecting Asia to Europe via the Russian Arctic. Russian and Chinese teams have been investigating the feasibility of a one-of-a-kind oil terminal in the Yamal peninsula as an extension to the joint Chinese and Russian project which can transport oil and gas to both Asia and Europe via pipelines and can be easily upgraded to include a pier for loading sea-based oil tankers in the future.

As the NSR remains increasingly ice-free, Russia's Arctic Strategy aims to increase shipping through the NSR to 80 million tons in 2024 and to more than 130 million tons by 2030. **Figure 2** below shows the number of deep-water ports and the extent of the Exclusive Economic Zone (EEZ) of Russia in its Arctic region [17]. As the Ukraine war progresses, Russia is not able to find a reliable trade partner and a nation able and willing to support Russian oil and gas activities in the AOR and Siberia other than China.

During his recent visit to Moscow, Chinese President Xi Jinping reiterated China's unwavering support for Russia in expanding the Yamal and Arctic Liquefied Natural Gas (LNG) projects in the Russian Arctic Circle. In addition to the LNG projects, China also pledged to expand the role of the Chinese army in the Arctic for search and rescue (SAR) operations along with the Russian Navy [18]. After the much-celebrated success of the Yamal project apparent in 2020, Novatec — a Russian oil and gas firm — aims to start a new LNG plant named Arctic-2 with a 30% stake from Chinese State-owned enterprises and an intent of starting one of three production lines by the end of 2023.

Figure 2: Map of Russian and American military installations around the AOR. The map portrays the overall strategic posture of US/Canada (in blue) and Russia (in red). The Russian side shows 4 Arctic Brigades, 14 Operational Airfields and 16 deep-water ports. Credit. Dan Sullivan, US Senator of Alaska via Robbie Gramer of Foreign Affairs [19].

4. Effective Solutions

As a solution to this conundrum of climate securitization and the rampant militarization of the AOR, I believe that widespread public awareness regarding the Arctic and its stakeholders is crucial, which would result in having greater public support for an attempt to securitize climate change all while constantly upping NATO's military posturing in the Arctic to combat Sino-Russian advances in the region. To gain effective situational awareness on both climate securitization and Arctic militarization front, NATO and its member Nations will have to first achieve sufficient public/national awareness about the effects of climate change to at least attempt to securitize climate change, especially in the AOR, and secondly reach consensus over the role of Allied armed forces.

Within the civilian fora, it is crucial to increase awareness of the impending security consequences of climate change specifically in the AOR. To achieve such awareness among the public and nations, I believe that NATO should create a Climate Resiliency Centre of Excellence (CoE) which can help NATO members and partners across the world to develop climate-resilient civilian and military infrastructure. This CoE along with NATO's Public Diplomacy Division can conduct broad outreach about the importance of the AOR and the need to militarize it, specifically targeting the public in NATO member states. When it comes to preparing for an ice-free Arctic soon, NATO policy would need to adapt to the race for resource extraction and consequent aggressive militarization in the Arctic and prepare NATO member states especially the Arctic states to maintain effective situational awareness of their sovereign territories in the High North. To exert effective control over their sovereign territories, NATO member states may need to update their military infrastructure threatened by rising sea levels.

One of my recommendations to the Canadian Department of National Defence, when it came to preserving Canadian sovereignty in the face of repeated Russian air patrols in the Canadian Air Defence Identification Zone (ADIZ), was to improve the Cold War Era Distant Early Warning (DEW) line of early warning radar sites. Once detected, intruders must be engaged following the proper rules of engagement. Therefore, I recommended stationing a permanent squadron of the Royal Canadian Air Force (RCAF) fighter and support aircraft in its northernmost Forward Operating Location (FOL) in Inuvik, Northwest Territories, which would also help to intercept effectively any foreign encroachment into Canadian sovereign airspace. All in all, I believe that such strategy could be extrapolated across NATO and implemented around the Arctic Circle to deter Sino-Russian aggression in the AOR in the future.

A reason why Russia is better at militarizing the AOR is because of its Arctic Command as described above. The current American Arctic strategy professes the need for better communication between the US Northern Command (USNORTHCOM) and the US European Command (USEUCOM) which would enable allies to partner up in the Arctic and effectively deter the Russian build-up. Along with maintaining strategic partnerships with its European allies, the US also aims to increase cooperation between stakeholders of the Arctic region to improve multilateral engagement through institutions such as the Arctic Council. Moreover, experts at the Arctic Institute note that as "NATO's Strategic Concept 2022" emphasizes climate resilient and green defence initiatives, many of NATO's Arctic members would face the security consequences of climate change. The Working Group at the Arctic Institute proposes that NATO create a Joint Arctic Command (ARCOM) to lead the efforts on militarizing the Arctic and securitizing climate change to protect NATO nations against climate change [20]. NATO needs to have a separate regional command specifically for the Arctic because it is a region of great geopolitical importance for the alliance. Moreover, in the past, NATO's northern flank was protected by vast icefields but now the northern flank is threatened by military activities by Russia and China and therefore, NATO must maintain increased domain awareness in the region and an AOR regional command will be able to effectively marshal and coordinate allied assets in the north. Overall, the Russian Arctic Command is a game changer for Russian influence in the AOR ranging from its extended EEZ claim to strengthening its nuclear deterrence. Russia has indeed better militarized the Arctic than NATO.

In conclusion, Arctic nations are taking part in initiatives to securitize climate change meanwhile attempting to militarize the AOR as it is one of the most impacted regions by climate change. Hence, it is probable that soon the shipping routes and the resource-rich areas in the AOR will be ice-free and teeming with economic opportunities. Along with these economic opportunities come militarization and potentially great power competition between NATO and the Sino-Russian bloc. The Arctic region in general is usually neglected in normal public discussion channels as it is overshadowed by other major news stories, but the region once considered impenetrable now is vulnerable to attacks and could end up being a means to attack Western Europe and North America. Therefore, I propose to increase public awareness about the effects of climate change on the AOR and for

NATO to effectively militarize the AOR all while trying to securitize it to protect NATO’s coastal communities and military infrastructure. Hence, adapting the British Special Air Services motto “Who Dares Wins”, it can be said for the Arctic that “Who Militarizes Wins.”

References

[1] Buzan, B., Waever, O., & de Wilde, J. (1998). Security: A New Framework. *American Political Science Review*, *93*(4)

[2] Congressional Research Service (2021). *Changes in the Arctic: Background and Issues for Congress*. CRS

[3] Arctic Oil & Gas. (n.d.). *National Ocean Economics Program*. https://www.oceaneconomics.org/arctic/extractive/

[4] Humpert, M. (2011, September 15). *The Future of the Northern Sea Route - A "Golden Waterway" or a Niche Trade Route*. The Arctic Institute.

[5] Greaves, W. (2019). Arctic break up: Climate change, geopolitics, and the fragmenting Arctic security region. *Arctic Yearbook*

[6] US Energy Information Administration. (2021). *Frequently Asked Questions (FAQs) - US Energy Information Administration*. EIA. https://www.eia.gov/tools/faqs/faq.php?id=709&t=6

[7] Sorensen, C., & Klimenko, E. (2017). *Emerging Chinese–Russian Cooperation in the Arctic: Possibilities and Constraints*. SIPRI, 10-60. https://www.sipri.org/sites/default/files/2017-06/emerging-chinese-russian-cooperation-arctic.pdf

[8] Halvorsen, A., & Andre, A. E. (2023). *Norwegian Defence Commission of 2021*. https://files.nettsteder.regjeringen.no/wpuploads01/sites/495/2023/06/forsvarskommisjonen_kortversjon-1.7_singel.pdf

[9] United Nations Security Council (2021). *Security Council Fails to Adopt Resolution Integrating Climate-Related Security Risk into Conflict-Prevention Strategies*. United Nations. https://www.un.org/press/en/2021/sc14732.doc.htm

[10] Ramesh, Rashmi. (2021, May 18). *India's Role in the Arctic: Reviving the Momentum Through a Policy*. The Arctic Institute. https://www.thearcticinstitute.org/india-role-arctic- reviving-momentum-through-policy/

[11] Kopra, S. (2013). *China's Arctic Interests. Arctic Yearbook,* 10-25. https://arcticyearbook.com/images/yearbook/2013/Scholarly_Papers/5.KOPRA.pdf

[12] The Headquarters for Ocean Policy (2015). *Japan's Arctic Policy*. https://www8.cao.go.jp/ocean/english/arctic/pdf/japans_ap_e.pdf

[13] Government of India, (2022). *India's Arctic Policy – Building a Partnership for Sustainable Development*. https://www.moes.gov.in/sites/default/files/2022- 03/compressed-SINGLE-PAGE-ENGLISH.pdf

[14] Ministry of Foreign Affairs, Russian Federation (2020). *Press release on Foreign Minister Sergey Lavrov's message to Norwegian Foreign Minister Ine Eriksen Soreide on the occasion of the 100th anniversary of the Spitsbergen Treaty*

[15] The State Council Information Office of the People's Republic of China. (2018). In: *China's Arctic Policy*. http://www.scio.gov.cn/zfbps/32832/Document/1618243/1618243.htm

[16] Sorensen, C., & Klimenko, E. (2017). *Emerging Chinese–Russian Cooperation in the Arctic: Possibilities and Constraints*. SIPRI, 10-60. https://www.sipri.org/sites/default/files/2017-06/emerging-chinese-russian-cooperation-arctic.pdf

[17] Staalesen, S. (2023, March 21). *Arctic shipping and energy on Putin's agenda with Xi Jinping*. The Independent Barents Observer

[18] Zhang, K., Maixiu H., & Dang, C.N. (2022). *The Potential of Sino–Russian Energy Cooperation in the Arctic Region and Its Impact on China's Energy Security*. Hindawi. https://www.hindawi.com/journals/sp/2022/8943314/

[19] Gramer, R. (2017, January 25). *Here's What Russia's Military Build-Up in the Arctic Looks Like*. Foreign Policy. https://foreignpolicy.com/2017/01/25/heres-what-russias-military-build-up-in-the-arctic-looks-like-trump-oil-military-high-north-infographic-map/

[20] Zhang, K., Maixiu H., & Dang, C.N. (2022). The Potential of Sino–Russian Energy Cooperation in the Arctic Region and Its Impact on China's Energy Security. *Hindawi*. https://www.hindawi.com/journals/sp/2022/8943314/

Improving Copernicus forecasts of Arctic sea ice and icebergs with the ACCIBERG project

Laurent BERTINO[a,1], Catherine DOWNY[a], Thomas LAVERGNE[b], Steffen TIETSCHE[c], and Andrea STORTO[d]
[a] *Nansen Center, Bergen, Norway*
[b] *MET Norway, Oslo, Norway*
[c] *ECMWF, Bonn, Germany*
[d] *CNR, Rome, Italy*
ORCiD ID: Laurent BERTINO https://orcid.org/0000-0002-1220-7207, Catherine DOWNY https://orcid.org/0000-0001-9484-966X, Thomas LAVERGNE https://orcid.org/0000-0002-9498-4551, Steffen TIETSCHE https://orcid.org/0000-0002-2961-0289, Andrea STORTO https://orcid.org/0000-0003-3856-8905

Abstract. The Arctic Ocean will always be treacherous in spite of its rapid warming. Sea ice and icebergs remain major risks for navigation in Arctic waters; therefore, monitoring and forecasting them is crucial. While the Copernicus Marine and Climate Change Services can provide the necessary information, users may not benefit from it as intended due to both a lack of consistency and missing uncertainty estimates. The EU-funded ACCIBERG project will address these issues. It will develop a new iceberg forecast service using remote sensing algorithms, data assimilation and cloud computing to consistently offer probabilistic sea ice and iceberg forecasts based on Copernicus data. The new forecasts will be automated and used by various groups navigating in the Arctic – from fisheries to cruise tourism.

Keywords. Sea ice, iceberg, probabilistic, forecasting, data assimilation, Copernicus Services.

1. Introduction

Sea ice and icebergs are a major security risk for navigation and fisheries in Arctic waters. Both will remain a significant threat even in a warmer Arctic, where maritime traffic is expected to increase. Sea Ice Services are needed more and more to support less experienced captains with automated high quality forecasts and new information about icebergs that are not available today.

To monitor and forecast sea-ice types and icebergs, adequate forecasts of sea ice, ocean, wind, and wave conditions for the whole Arctic are crucial. The Copernicus Marine and Climate Change Services provide such information products. However, their uncertainties are not provided in a consistent and user-friendly manner. Reliable uncertainty estimates can however be based on forecast ensembles across the two Copernicus Services.

ACCIBERG will improve the quality of sea ice and ocean nowcast and forecast products and their uncertainty estimates in both Copernicus Services. It will also extend the spatial coverage of the satellite detection of icebergs and develop a completely new iceberg forecast service. ACCIBERG will build upon state-of-the-art sea-ice and ocean models,

---

[1] Corresponding Author: Laurent Bertino, laurent.bertino@nersc.no.

remote sensing algorithms, data assimilation and cloud computing to offer consistent probabilistic sea-ice and iceberg forecasts based on Copernicus data. National or commercial sea-ice services are limited to smaller regions and will benefit from the increased accuracy and consistency across the Copernicus products.

The new forecasts will be demonstrated in ACCIBERG by European Ice Services and ships of opportunity. The new iceberg forecasts will be automated and validated, and benefit a wide range of user groups navigating in the Arctic, from fisheries to cruise tourism, including maritime surveillance under the Copernicus Security Service. We will provide prototype products ready to be implemented in the Copernicus services and accessible from a single entry point: its inherent cloud computing solution WeKEO.

2. Calibration of probabilistic sea-ice forecasts

2.1. Sub-seasonal to seasonal forecasts

These types of forecasts are routinely provided by the Copernicus Climate Change Service (C3S) and the European Centre for Medium-Range Weather Forecasts (ECMWF). To improve user uptake of these forecasts, ACCIBERG is developing prototypes of forecast products that are calibrated and include uncertainty estimates. We have developed an initial version of a sea-Ice Calibration, vErifiCAtion and Products software (ICECAP), which we tested using ECMWF sub-seasonal ensemble forecasts on the dramatic case of the rapid freeze-up of the Siberian Shelf in October/November 2021. This rapid freeze-up event took the shipping industry by surprise, leading to more than 20 ships becoming stuck in the ice. Figure 1, below, shows promising preliminary results from ICECAP: after a simple calibration for known mean errors in the forecast, a much earlier freeze-up than in previous years is correctly predicted several weeks in advance.

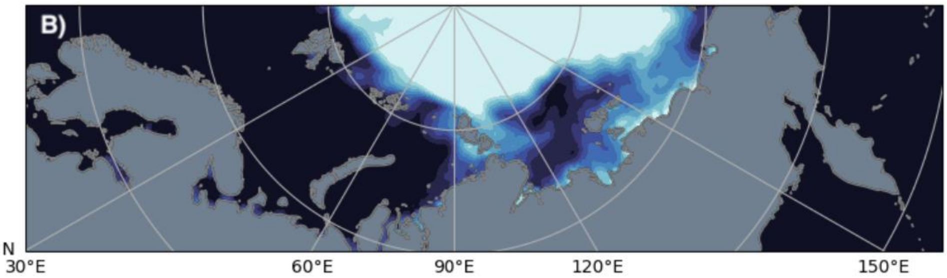


Figure 1: Sea-ice concentration on the Siberian Shelf for 22/10/2021 predicted 16 days in advance by the ECMWF ensemble forecast. After calibration, this forecast would have warned users of a high probability of a freeze-up happening much earlier than in previous years.

Moreover, to further improve sea-ice forecasts, ACCIBERG partners are developing stochastic modeling techniques for the ocean model NEMO [2]. In particular, uncertainties in sea-ice dynamics and ocean-sea-ice interaction are known to be large and can potentially affect sub-seasonal to seasonal predictions. At the moment, these predictions do not account for the uncertainty associated with the sea-ice modeling component. ACCIBERG will formulate and provide optimal solutions to account for the sea-ice uncertainty, with targeted application in the NEMO-SI^3 modeling framework for the ECMWF seasonal prediction system, and potentially in the Copernicus Marine Service (CMEMS) systems that rely on the NEMO ocean numerical model, such as the 30-day forecasting capability that is currently under development by the CMEMS Global Monitoring and Forecasting Center. The stochastic modulation of sea-ice parametrizations will increase the reliability of the sea-ice forecast uncertainty estimates, with potential benefits to the forecast skill scores.

2.2. *Short-range and medium-range forecasts*

The CMEMS Arctic Monitoring and Forecasting Center focuses on forecasts out to 10 days only, using both the HYCOM-CICE model [7] and the stand-alone neXtSIM-F sea-ice model [6]. ACCIBERG partners are also developing ensemble perturbation techniques targeted to short-term ice-ocean forecasting. These efforts concentrate on the representation of uncertainties in the winds, using the ECMWF ensemble forecasts as input, but also combining random perturbations based on a spectral method. Tests are ongoing to evaluate which spatial scales are most effective at exciting the relevant modes of variability of the ice-ocean system. Improved ensemble simulation techniques can also be beneficial for ensemble data assimilation techniques.

3. Assimilation of raw satellite passive microwave sea-ice data

Obtaining sea-ice concentration (SIC) from raw Passive Microwave (PMW) satellite data involves a complex suite of algorithms to transform the brightness temperatures (TB) measured by the satellite at several microwave frequencies (Level-1B) into SIC values first in satellite projection (Level-2) and finally in daily gridded formats (Level-3/Level-4). In this processing, some information is lost, either due to truncation of the retrievals between the zero and 100% concentrations, or because of the temporal averaging of all the inputs to an assumed daily average.

3.1. *From daily maps to individual orbits*

Recently, the assimilation of individual satellite orbit data of SIC (vs. the standard assimilation of daily maps) was developed and tested in the NFR SIRANO project (2019-2024). Parallel experiments within a regional ice-ocean forecasting system of the Barents Sea and Svalbard region revealed that the assimilation of individual SIC orbit data generally resulted in a better analysis and a better short-range forecast of the sea-ice cover, although the impact depended on the background state [1].

3.2. *From ice concentrations to brightness temperatures*

We plan to continue this work by directly assimilating Level-1B (TB) data rather than SIC. To do so requires “flying the satellite in the model” [3] and using an observation operator adapted to the satellite missions at hand (in our case, the Advanced Microwave Scanning Radiometer - 2, AMSR2). We will use a modified version of the “Wentz” parametric ocean Radiative Transfer Model (RTM) [4] to simulate AMSR2 TBs at key microwave frequencies (Ku- and Ka-band) from the geophysical input of the CMEMS models (for the SIC and sea-ice type) and of the ECMWF numerical weather prediction (NWP) system (the atmosphere that lies between the surface and the satellite). The first step is to improve the way sea-ice emissivity values are entered in the model, and make this emissivity dependent on sea-ice type, which will borrow from the dynamic tie-point methodology of the OSI SAF and CCI SIC algorithms [5]. The observation operator will then be interfaced to the Ensemble Kalman-Filter (EnKF) data assimilation (DA) system of the CMEMS Arctic Marine Forecasting Center, and DA experiments subsequently performed to assess the impact of TB assimilation on SIC and sea-ice type analysis and forecast.

4. Iceberg forecasting

More accurate sea ice edge and ensemble forecasts of ocean currents will be beneficial to iceberg forecasting. As a first step, an iceberg drift simulation module is being included in the OpenDrift package that can use the latest Copernicus forecasts of all the forces driving the drift of an iceberg: ocean currents, tides, winds, sea ice and waves [8]. The

OpenDrift software is containerized, meaning that it can be used on cloud solutions such as WeKEO, the data access system where different Copernicus products are efficiently accessible, thus removing intensive downloading operations.

Near real-time remote sensing of icebergs will also be expanded spatially from the Greenland Sea out to the Barents Sea using Synthetic Aperture Radar (SAR) from the Sentinel-1 satellite series as well as several Copernicus Contributing Missions from international sources. The numerical model will be used to fast forward the map of possible iceberg targets from the satellite images and provide an iceberg-risk forecast map. Individual iceberg forecasts will also be provided on demand for users in the field using the IceWatch mobile app. Once an iceberg is spotted, the picture location and time can be fed into the forecast model and a number of possible trajectories sent back to the user. Experienced users familiar with safety protocols in the vicinity of icebergs [9] can receive a free GPS-tracking buoy from ACCIBERG and contribute to the calibration of the forecast model.

5. Conclusion

ACCIBERG is developing improved capabilities for the Copernicus Services through enhanced remote sensing and forecasting techniques. These Copernicus data services are all freely available and open. Users of the Copernicus Services will thus be able to consult forecasts of sea ice accompanied by their uncertainties from short-range to seasonal scale. The demonstration period for iceberg forecasting is planned for Summer 2024 and we are welcoming beta-testers willing to take part in iceberg tagging activities to join our advisory team. The work is paving the way towards the optimal exploitation of future Copernicus Sentinel Expansion missions: Copernicus Imaging Microwave Radiometer (CIMR) for PMW imaging of sea ice, and Copernicus L-band SAR (ROSE-L) with an improved iceberg detection capacity.

6. Acknowledgements

The work is supported by the EC through grant number 101081568 (ACCIBERG) https://acciberg.nersc.no/. The authors are grateful to John Redmayne for the careful revision of the manuscript.

References

[1] Durán Moro, M. et al. (2023). *Assimilation of satellite swaths versus daily means of sea ice concentration in a regional coupled ocean-sea ice model*. The Cryosphere Discuss. [preprint]. https://doi.org/10.5194/tc-2023-115

[2] Storto, A., & Andriopoulos P. (2021). A new stochastic ocean physics package and its application to hybrid-covariance data assimilation. *Quarterly Journal of the Royal Meteorological Society*, *147*, 1691–1725. https://doi.org/10.1002/qj.3990

[3] Kaminski, T., & Mathieu, P. P. (2017). Reviews and syntheses: Flying the satellite into your model: on the role of observation operators in constraining models of the Earth system and the carbon cycle. *Biogeosciences*, *14*, 2343-2357. https://doi.org/10.5194/bg-14-2343-2017

[4] Meissner, T., & Wentz, F.J. (2012). The Emissivity of the Ocean Surface Between 6 and 90 GHz Over a Large Range of Wind Speeds and Earth Incidence Angles. In: *IEEE Transactions on Geoscience and Remote Sensing* (vol. 50, no. 8, pp. 3004-3026). https://doi.org/10.1109/TGRS.2011.2179662

[5] Lavergne, T. et al. (2019). Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records. *The Cryosphere*, *13*, 49-78. https://doi.org/10.5194/tc-13-49-2019

[6] Williams, T., Korosov, A., Rampal, P., & Ólason, E. (2021). Presentation and evaluation of the Arctic sea ice forecasting system neXtSIM-F. *The Cryosphere*, *15*, 3207–3227. https://doi.org/10.5194/tc-15-3207-2021

[7] Xie, J. et al. (2017). Quality assessment of the TOPAZ4 reanalysis in the Arctic over the period 1991–2013. *Ocean Science*, *13*(1), 123-144. https://doi.org/10.5194/os-13-123-2017

[8] Keghouche, I., Bertino, L., & Lisæter, K. A. (2009). Parameterization of an iceberg drift model in the Barents Sea. *Journal of Atmospheric and Oceanic Technology*, *26*(10), 2216-2227. https://doi.org/10.1175/2009JTECHO678.1

[9] Hughes, N.E. (2023). D4.1 Safety Protocols for Citizen Science Demonstrations. Deliverable report of Project HEUR ACCIBERG (grant 101081568)

Increasing climate literacy to meet climate security demands

Kristen FLETCHER[a,1], Rebecca GRIPPO[b] and Marina LESSE[c]
[a] *Naval Postgraduate School*
[b] *Roger Williams University School of Law*
[c] *Naval Postgraduate School*
ORCiD ID: Kristen FLETCHER: https://orcid.org/0009-0003-4925-313X

Abstract. Climate literacy includes an understanding of fundamental elements of climate science, impacts of climate change, and approaches to adaptation or mitigation. Specifically, a climate literate military force understands how climate change can and will affect mission, operations, installations and outcomes. This paper presents evolving efforts in climate literacy in the United States focusing on climate security education and training. Recent climate education and training efforts in the national security sector include climate-focused tabletop exercises and wargaming and curricular changes at military educational institutions. To evolve, these efforts must be integrated into current curricula and training and put into the context of the impact of climate change on operations and installations, and consideration of vulnerable populations.

Keywords. Climate security, climate literacy, education, training, national security

1. Introduction

Climate literacy includes an understanding of fundamental elements of climate science, impacts of climate change, and approaches to adaptation or mitigation. Specifically, a climate literate force understands how climate change can and will affect mission, operations and outcomes. It is well-established that climate change can magnify existing conflicts, induce migration, and exacerbate other critical and volatile factors in a community and region. As the U.S. Department of Defense (DoD) and other agencies develop climate literacy programs, it is crucial that military leaders and first responders tasked with fostering and protecting human security around the globe acquire an understanding of the impacts of climate change and how it links to conflict at both national and international levels [1]. It is also essential to include how climate change impacts affect operations, installations and disproportionately affects migration and vulnerable communities.

2. Evolution of Climate Literacy in the U.S. Department of Defense

2.1. Key DoD Documents and Service Climate Strategies

Shortly after his inauguration in January 2021, U.S. President Biden issued several Executive Orders addressing the climate crisis and including climate considerations as an essential element of U.S. foreign policy and national security. Over the next few years, DoD issued the *DoD Climate Assessment Tool* (April 2021) [2], *DoD Climate Adaptation*

---

[1] Corresponding Author: Kristen Fletcher, kristen.fletcher@nps.edu.

Plan (September 2021) [3], and *DoD Climate Risk Analysis* (October 2021)[8]. The Climate Risk Analysis stated that "DoD will integrate the security implications of climate change into key strategic documents, programs, and international partner engagements. DoD will also consider how to integrate climate considerations into DoD educational institution curriculums." The integration is illustrated in Figure 1; education and training are included in Lines of Effort (LOEs) 1 and 2, while Climate Literacy is one of four "enablers" that crosscuts all LOEs.

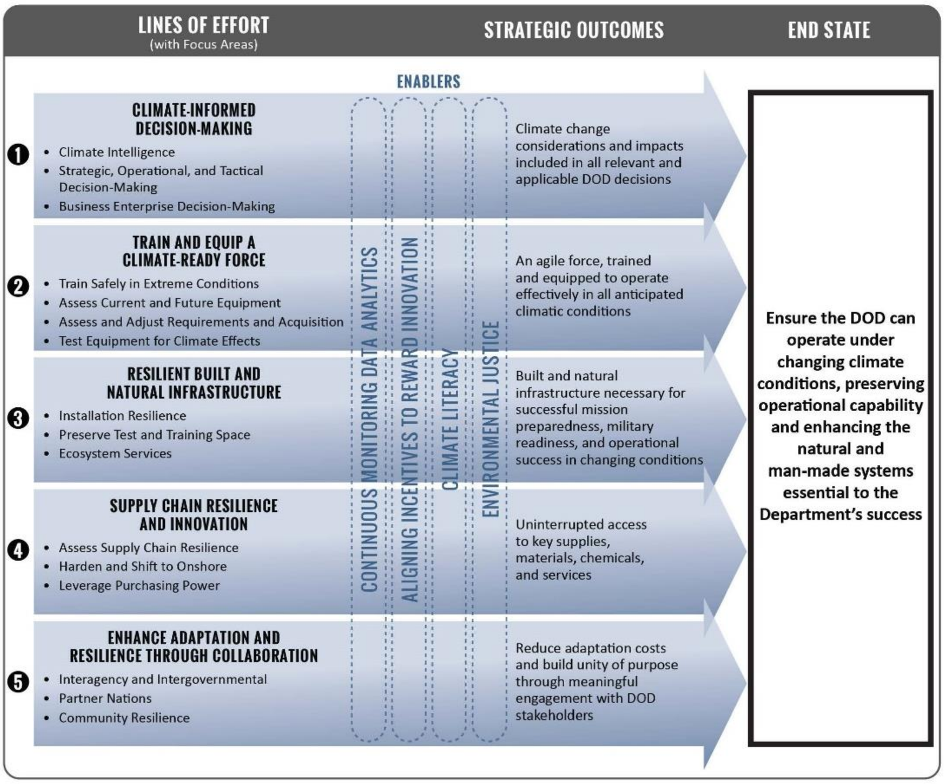


Figure 1. Lines of Effort in the U.S. Department of Defense Climate Adaptation Plan [3].

Incorporating climate literacy depends upon its definition. The U.S. Global Change Research Program notes that a climate-literate person:

1. understands the essential principles of the Earth's climate system;
2. knows how to assess scientifically credible information about climate;
3. communicates about climate and climate change in a meaningful way; and,
4. can make informed and responsible decisions regarding actions that may affect climate.

Although the DoD does not explicitly define climate literacy, the individual Services have incorporated the concept into their climate strategies. The *2022 Army Climate Strategy* [5] notes that the Army has already started building climate literacy into current training, including the Army Materiel Command's "Climate 101" Course which focuses on climate implications for lands, energy, water, soil and other installation issues. The Navy's strategy, *Climate Action 2030*, [9] states that the Department will "incorporate meaningful climate related training and education curricula tied to mission objectives into the continuum of learning for the entire force, from enlisted personnel to senior officers and civilians." Finally, the *Air Force Climate Action Plan* calls for climate considerations to be integrated into department professional military education curriculum and technical and continuing education curriculum by FY24[7].

In August 2023, the Assistant Secretary of Defense for Readiness issued a memorandum calling for all intermediate- and senior-level Professional Military Education [6] programs will "consider adjusting their existing climate security instruction" with particular learning outcomes. These learning outcomes lend themselves to an informal definition of climate literacy from DoD which may include:

1. understanding how climate change affects strategic, operational and tactical environments;
2. understanding the basic elements of climate change science;
3. knowing where to access the best available, validated, and actionable information about climate change;
4. communicating effectively about the national security implications of climate change; and
5. recognizing when and how to apply climate considerations when making national security decisions or when providing best military advice, in ways appropriate for their mission, function, and role.

The above list presents learning outcomes for intermediate-level education. For senior leaders, the memorandum also called for them to understand (1) how climate change affects the geostrategic environment for the U.S., Allies, and partners to include risk assessments, adaptation, mitigation, and the energy transition and (2) how potential adversaries leverage climate change in their bilateral/multilateral engagements with other countries in competition with the U.S.

Importantly, the memorandum notes that each institution "has the latitude to develop an approach to incorporate the outcomes that are best suited" for its programs. As noted in the Army Climate Strategy[5], "For some audiences, there will be purpose-built courses. For others, the next evolution means making smart decisions to integrate climate topics into existing instruction and associated educational exercises." The next two sections present a few existing models for advancing climate literacy[15].

2.2. Climate Literacy and the U.S. Naval Education Institutions

Even prior to the issuance of the Navy Climate Strategy but acknowledging the impact of climate change on security, the Naval Education Enterprise Climate Collaboration (Climate Collaboration) launched in April 2021 with the Naval Postgraduate School (NPS), Naval War College (NWC) and U.S. Naval Academy (USNA) as initial participants. Over time, the Marine Corps University and U.S. Naval Community College joined to fill out the group with all five Naval Education Institutions. The purpose of the Climate Collaboration is for the institution to join regularly (usually monthly) to collaborate on climate security issues, share research and educational resources, and host cooperative events.

The Combined Naval Address on Climate, Energy and Environment is the group's primary event with a high-level speaker followed by questions from students at the institutions. Following most events, there is a Faculty Roundtable in which faculty from institutions can engage with the speaker in a small group format. Speakers have included Dr. Saul Griffith (led by NWC), Dr. Marshall Shepherd (led by NPS), the Honorable Meredith Berger (led by USNA), and Dr. Neta Crawford (led by NPS)[4]. Another Combined Naval Address is scheduled for October 2023 (led by NWC).

The Climate Collaboration is now working with the Department of the Navy Climate Team (Energy, Installations and Environment or EI&E) to develop climate literacy for the Navy[9]. Members of the EI&E Climate Team participate in the monthly calls to discuss the best way for the institutions to contribute to increased awareness of climate change, climate security issues and links to mission and operations. Each institution teaches different students (officers, civilians, cadets, enlisted) at different points in their career and each institution can offer research relevant to climate security issues. In addition, each institution has different processes for establishing and updating curriculum; some processes can advance climate literacy but others can hinder.[17] The Climate Collaboration can provide a model for understanding the hurdles at different institutions and how climate literacy can best be accomplished in educational and training settings.

2.3. Tabletop Exercises, Wargaming and Coursework

All three Services call for climate considerations to be incorporated into wargames and tabletop exercises. The Army Strategy specifies that wargames that “stress test” a supply chain will be particularly useful. The Air Force Climate Action Plan calls for climate considerations to be incorporated into Department wargames starting in FY23. The Navy, led by its EI&E Climate Team, has held two Climate Tabletop Exercises (TTX) and has plans for a Caribbean-focused TTX in 2024. As noted by wargaming experts, the games can play a valuable role in “helping national security actors anticipate strategic surprise and understand a changing threat landscape.” But to effectively use these tools to evolve climate literacy, they must address certain challenges.

First, climate change is an immensely complex topic and can present design challenges related to isolating specific questions for inquiry. Second, as climate change and climate security are inherently interdisciplinary, having the right mix of individuals in exercise design and execution is key to success. Third, many wargaming experts are not climate change experts and vice versa; as a result, the design of a wargame, whether focused on climate change or using climate change impacts as exacerbating circumstances, will require understanding of a variety of geophysical and human systems.

Although the format and length generally are different from wargames and TTXs, courses at educational institutions can run into similar challenges. As noted above, the Navy Education Institutions teach students at different stages of their careers and in different disciplines. At some institutions, it is a straightforward process to add electives, such as a climate course, into curriculum while at others, the question becomes what may be pulled out of a curriculum to insert a climate-related course. One model underway is to establish a resource bank of material, speakers, videos, and interactive exercises related to climate security so that professors can select what is most relevant to their class and students. On a larger scale, Brown University hosts a Syllabus Bank on climate change from a variety of disciplines, that is accessible to military and non-military institutions. An approach like this can overcome the lack of demand signal from leaders to create climate security curricula and the competition with other long-standing priorities in education and training. This integration approach may also withstand the scrutiny resulting from political or administration shifts.

In addition, NPS and the NATO Centre for Maritime Research and Experimentation are collaborating on a Climate Change and National Security course. This course is designed as a one- or multiple-week course to present the science, policy and regional considerations relevant to climate change and national security, incorporating current issues and concepts in both Climate Security and Environmental Security. The course provides an overview of the major climate change threats impacting the globe, with a particular focus on climate change impacts to national security and energy systems. It includes an overview of relevant science, legal, and policy issues related to climate change using scenario-based learning and facilitated discussion on how security leaders can prepare to address these challenges. Modules include: the science of climate change; climate change impacts to national security; the nexus of energy and climate change; climate law; and, governance and financial considerations. The course can be adapted to location and audience by incorporating regional priorities and case studies.

2.4. Literacy in the Context of Impacts on Operations

A persistent challenge faced in climate security is accurately identifying and understanding the true impacts of climate change on military operations. Understanding, projecting, and predicting climate change impacts are not only important for planning at the strategic and operational levels, but also for tactical-level planning. France, for example, has formally recognized the need for climate adaptation in their military and set forth efforts to integrate climate change impacts and preparedness into their respective force structures. The UK House of Commons recently released a report, entitled *Defense and Climate Change*, noting that [22]: “The Armed Forces, defence acquisition and the defence estate — both at home and abroad — will also need to adapt to respond to the impacts of climate change over the coming decades, with consequences for geostrategy, defence readiness, resilience and the effective delivery of military effect.”

Working climate change impacts into education and training requires intergovernmental climatology data and analysis.[13] Fortunately, that information is more readily available than ever before; however, access to the data in a format that benefits servicemen and women with analysis that is relevant to military platforms, installations and missions is what is truly needed. Recent formats include tools such as stop light charts to understand where the greatest impacts are expected. More work is necessary to hone such tools and identify commonalities among regions, platforms and systems. Because the body of research and analysis on climate change impacts is growing, education and training must adapt to new information, making it applicable to the force and mission.

3. Consideration of Climate-Induced Migration and Vulnerable Populations

Climate change has exacerbated natural disasters on a global scale, such as droughts and rising sea levels and temperatures, which have forced the migration of approximately 21.5 million people, and this is estimated to grow to 143 million in the next 30 years according to the Intergovernmental Panel on Climate Change (IPCC) [10]. Countries already vulnerable because of economic, governance or other issues are less able to recover from climate change disasters. These climate change impacts also have disproportionate effects on the women in those countries. According to the Council on Foreign Relations, the Northern Triangle states, made up of El Salvador, Guatemala, and Honduras, are “among the poorest in the Western Hemisphere” with intrastate conflict and lack of economic stability, making this region particularly vulnerable to climate-induced migration[14].

Women in these areas are particularly hard-hit; women in agriculture, for example, “face persistent inequities in access to land and extension services that can make recovery from extreme weather events particularly challenging.”[16] The U.N. Environment Programme estimates that about 80% of the people displaced by climate change disasters are female, and the United Nations Development Programme [16]finds that women are fourteen times more likely to die in a climate catastrophe than men. Climate change-induced environmental degradation “diminishes access to food, drinking water, sanitation and education more for women than men,” and the IPCC’s sixth assessment [10] found that “women are among populations most at risk of heat related mortality at 1.5 degrees Celsius of warming.”

These inequities stem from the lack of investment in reproductive health, prominent gender-based violence, and other policies that deny women’s rights. Reporter Zoha Tunio provides a compelling example that when a culture does not allow women to learn how to swim, it puts them at a greater risk of drowning which is one of the highest causes of death in water-related climate disasters. Thus, because climate-induced migration more heavily affects impoverished communities and women, there is a human security issue that needs attention and understanding [21].

Understanding the risks that a community faces is key to protecting human security in vulnerable communities and carrying out the military’s mission there [1] [19]. According to a series on Gender and Conflict by the International Committee of the Red Cross and the University of Vermont, awareness of the disproportionate issues involving climate-induced migration is essential to gaining a full picture of human security in a region or community.[18] Currently, there is a lack of overarching theory on how gender is important and relevant to military operations, but there is a demand signal to create one given the relevance of disproportionate effects to international human rights law and international humanitarian law [19].

Gender inequality can be an indicator of deeper, more underlying conflict. A 2005 study on the role of gender inequality in predicting conflict indicates that states with higher levels of gender inequality are more likely to experience intrastate conflict. A similar 2020 study by Tobia Ide on climate-related disasters found that the link between gender inequality and intrastate conflict is "highly context-dependent and that countries with large populations, political exclusion of ethnic groups, and a low level of human development are particularly vulnerable." Thus, gender inequality existing in the community, where military personnel are often stationed, is indicative of greater issues in the area which affect operations and mission success [15].

4. Conclusion

A climate-literate force can more readily integrate climate considerations into its operations if its planning, policy and doctrine includes tailored learning outcomes and understanding of climate change impacts [13][21]. Training and education are one piece of this equation, with educational institutions and other tools like wargaming playing an important role. In addition, military leaders and personnel are an important part of establishing a climate-literate force, because they are on the ground in vulnerable communities and often at the decision-making table. DoD climate literacy curricula must draw on best practices — not only within educational institutions but also from research — to communicate the compounded risks from climate change and give decision makers a better understanding of climate impacts to operations, installations, and how vulnerable communities are especially affected.

References

[1] Burke, S., & Cameron, A. (2022). Wargaming Climate Change: Who Plays for the Red Team?, *War on the Rocks*. https://warontherocks.com/2022/11/wargaming-climate-change-who-plays-for-the-red-team/

[2] Lopez, C.T. (2021). DOD Makes Climate Assessment Tool Available to Partner Nations. *U.S. Department of Defense*, https://www.defense.gov/News/News-Stories/Article/Article/3370578/dod-makes-climate-assessment-tool-available-to-partner-nations/

[3] US Department of Defense. (2021). *Climate Adaptation Plan*. https://www.sustainability.gov/pdfs/dod-2021-cap.pdf

[4] Crawford, C. N. (2023, April 17). *The US Navy and Climate Change*. MRonline. https://mronline.org/2023/04/17/the-u-s-navy-and-climate-change/#ednref_1

[5] Department of the Army, Office of the Assistant Secretary of the Army for Installations, Energy and Environment. (2021). *United States Army Climate Strategy*, https://www.army.mil/e2/downloads/rv7/about/ 2022_army_climate_strategy.pdf

[6] Department of Defense, Office of the Assistant Secretary of Defense for Readiness. (2023). *Memorandum for Assistant Secretaries of the Military Departments for Manpower and Reserve Affairs*

[7] Department of the Air Force, Office of the Assistant Secretary for Energy. (2022). *Installations and Environment, Department of the Air Force Climate Action Plan*. https://www.safie.hq.af.mil/Portals/78/documents/Climate/DAF%20Climate%20Action%20Plan.pdf?ver=YcQAZsGM_Xom3DkNP_fL3g%3d%3d

[8] Department of Defense, Office of the Undersecretary for Policy (Strategy, Plans and Capabilities). (2021). *Department of Defense Climate Risk Analysis*, https://media.defense.gov/2021/Oct/21/2002877353/-1/-1/0/DOD-CLIMATE-RISK-ANALYSIS-FINAL.PDF

[9] Department of the Navy, Office of the Assistant Secretary of the Navy for Energy. (2022). *Installations, and Environment, Department of the Navy Climate Action 2030*

[10] Intergovernmental Panel on Climate Change. (2023). *IPCC Sixth Assessment Report (AR6) Synthesis Report*, https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

[11] Kareko, R. T. (2019). Female Engagement Teams. *NCO Journal*, https://www.armyupress.army.mil/Portals/7/nco-journal/images/2019/October/FET/FET.pdf

[12] Ide, T., Brzoska, M., Donges, J., & Schleussner, C. (2020). Multi-method evidence for when and how climate-related disasters contribute to armed conflict risk, *Global Environmental Change*. 62, https://www.sciencedirect.com/science/article/pii/S0959378019307307?via%3Dihub

[13] Minitere Des Armees. (2022). *Climate & Defence Strategy*.

[14] Mogelgaard, K. (2022). *Investing in Women and Girls is Central to Addressing Root Causes of Migration from Guatemala*, New Security Beat, https://www.newsecuritybeat.org/2022/11/investing-women-girls-central-addressing-root-migration-guatemala/

[15] NOAA Global Change Research Program. (2023). *NOAA, Smithsonian and fed partners seeking suggestions to update key climate literacy guide*, https://research.noaa.gov/2023/03/23/noaa-smithsonian-and-fed-partners-seeking-suggestions-to-update-key-climate-literacy-guide/

[16] Okai, A. (2022). Women are hit hardest in disasters, so why are responses too often gender-blind?, *United Nations Development Programme*, https://www.undp.org/blog/women-are-hit-hardest-disasters-so-why-are-responses-too-often-gender-blind

[17] Population Institute. (2022). *Invisible Threads: Addressing the root causes of migration from Guatemala by investing in women and girls*, https://www.populationinstitute.org/wp-content/uploads/2022/10/PI-3059-Guatemala-Migration-Report-WEB-Updated.pdf

[18] Prescott, J. M. (2022). Why militaries need a theory of gender's operational relevance. *Humanitarian Law & Policy*, https://blogs.icrc.org/law-and-policy/2022/07/07/militaries-theory-gender-operational-relevance/

[19] Prescott, Jody M., & Lovell, R. (2022). Gender inequality, armed conflict and climate change: why militaries can and should map compounded risk. *Humanitarian Law & Policy*, https://blogs.icrc.org/law-and-policy/2022/09/29/gender-inequality-armed-conflict-climate-change-militaries-map-compounded-risk/

[20] Roy, D., & Cheatham, A. (2023). Central America's Turbulent Northern Triangle, *Council on Foreign Relations*, https://www.cfr.org/backgrounder/central-americas-turbulent-northern-triangle

[21] Tunio, Z. (2022). Leaders and Activists at COP27 Say the Gender Gap in Climate Action is Being Bridged Too Slowly. *Inside Climate News*, https://insideclimatenews.org/news/18112022/leaders-and-activists-at-cop27-say-the-gender-gap-in-climate-action-is-being-bridged-too-slowly/

[22] United Kingdom House of Commons. (2023). *Defence and Climate Change*, https://committees.parliament.uk /publications/41129/documents/200843/default/

[23] U.S. Global Change Research Program. (2009). *Climate Literacy: The Essential Principles of Climate Science*, https://downloads.globalchange.gov/Literacy/climate_literacy_highres_english.pdf

[24] Watson, J. (2022, July 28). *Climate change is already fueling global migration. The world isn't ready to meet people's changing needs, experts say*. PBS News Hour, https://www.pbs.org/newshour/world/climate-change-is-already-fueling-global-migration-the-world-isnt-ready-to-meet-peoples-needs-experts-say

List of Authors

Document Data Sheet

Security Classification		*Project No.*
PUBLIC RELEASE		OCS000EF50
Document Serial No.	*Date of Issue*	*Total Pages*
CMRE-CP-2024-001	March 2024	x + 148 pp.

Author(s)

Sandro Carniel, Aniello Russo, Fabio Lissi (*eds.*)

Title

Climate Change and Security Workshop Proceedings

Abstract

Building on NATO Climate Change and Security Action Plan (CCSAP) and NATO 2030 initiative, NATO Science and Technology Organization (STO) is committed to deepen research on the climate-induced security challenges and to find innovative solutions. Within the Climate Change and Security (CC&S) Programme committed by the Office of the Chief Scientist (OCS), the Centre for Maritime Research and Experimentation (CMRE) hosted a dynamic and multidisciplinary workshop on the critical intersection between CC&S, uniting an array of distinguished experts. The Climate Change and Security Workshop was held in Lerici, Italy 3 – 5 October 2023, at Villa Marigola.

The event was attended by 112 participants and featured 5 keynote speakers and 39 presenters. This gathering facilitated in-depth discussions on the multifaceted climate-induced security challenges and innovative solutions within the maritime domain. Spearheaded by CMRE, in collaboration with OCS, the workshop collected contributions spanning from scientific, political, and military areas of expertise, in accordance with the four pillars of the NATO CCSAP: awareness, adaptation, mitigation, and outreach. The workshop strengthened CMRE's network of partners in the CC&S field and effectively outlined the new CMRE Climate Change and Security Analysis (CCSA) Project.

During the three days, 5 keynotes, 21 papers presentation, 24 poster pitches, and 2 panels were offered to the audience. This document collects the 17 papers accepted for publication.

Keywords

Climate Change, Security, Maritime Domain, Workshop

Issuing Organization

NATO Science and Technology Organization
Centre for Maritime Research and Experimentation

Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
STO CMRE
Unit 31318, Box 19, APO AE 09613-1318]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@cmre.nato.int