Ref. Ares(2024)664813 - 29/01/2024

GROOM II

GLIDERS FOR RESEARCH, OCEAN OBSERVATION & MANAGEMENT : INFRASTRUCTURE AND INNOVATION

Project acronym: **GROOM II**

Project title: Gliders for Research, Ocean Observation & Management: Infrastructure and Innovation

Grant agreement no. 951842

D.4.3

GROOM RI CONTRIBUTION TO STATUTORY MONITORING FRAMEWORKS

Due delivery date: M36

Actual delivery date: January 2024

Organization leading for this deliverable:

NATIONAL OCEANOGRAPHY CENTRE (NOC)

Dissemination level		
PU	Public	**x**
CO	Confidential, only for members of the consortium	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951842

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Deliverable number	4.3
Deliverable responsible	NATIONAL OCEANOGRAPHY CENTRE
Work Package	WP4 - GROOM RI Integration and contribution to sustained observing efforts

Document revision history			
Version	**Date**	**Modifications introduced**	
		Change reason	**Modified by**
v0.1	06/02/2023	Initial draft	Charlotte Williams
v1.0	31/08/2023	Corrected draft	Charlotte Williams
V1.1	13/10/2023	Review	Alvaro Lorenzo Lopez, George Petihakis, Louise Biddle, Bastien Queste, Anthony Bosse, Johannes Karstensen, Evi Bourma, Rana Abu Alhaija, Carlos Barrera, Matthew Palmer, Daniel Hayes, Pierre Testor and Laurent Mortier
V2	19/10/2023	Final draft	Charlotte Williams
V3	25/10/2023	Review	Pierre Testor and Charlotte Williams
final	09/01/2024	Final document	Yves Ponçon and Clara Flack

Deliverable abstract

The GROOM II Research Infrastructure (from here onwards GROOM RI) can provide a trusted link between national glider observation, related to statutory observing and monitoring efforts, and internationally coordinated ocean observing systems. In this report an assessment of the contribution of a future GROOM RI on statutory monitoring frameworks is provided.

We outline how a GROOM RI could **benefit Marine Strategy Framework Directive** (MSFD) **monitoring** and future **assessments of 'Good Environmental Status'** (GES) in Europe, and provide a number of **recommendations** that we believe need to be adhered **to ensure optimal monitoring** of the health of European oceans.

We suggest that further Marine Autonomous System (MAS) pilot studies need to be carried out to **collect more data and evidence**, in order to better assess the scientific and economic efficiency of using MAS for MSFD monitoring and assessment of GES.

Additionally, we recommend that the **GROOM RI monitors all MSFD MAS operations** across all of Europe and act to create synergies between member states **to share MAS data**, complementing existing MSFD best practices and improving assessments of GES where sparse observations of key parameters are highlighted as the responsible factor for inconclusive GES assessments.

Furthermore, we recommend that the GROOM RI facilitates the coordination between GROOM RI partners to **assist future MSFD assessments** in the case of member states lacking resources to allow sufficient assessments of GES.

We demonstrate the use of MAS in an MSFD monitoring capacity by **providing a comprehensive review of the parameters** that MAS are capable of measuring and **how mature** these methods and technologies are currently. We link these parameters through to the **specific variables** that are **relevant to monitoring European marine ecosystem** and health in a statutory framework capacity. Sensors on MAS which measure parameters that contribute to the descriptor for assessment of hydrographical conditions are amongst the most mature (e.g. temperature and salinity). We demonstrate however that existing and emerging **technology for sensors on MAS** can in fact **contribute to assessments for 9 of the 11 MSFD descriptors**.

A **series of case studies** where MAS have been used previously to assess various MSFD indicators of ocean health across European seas is also provided. These provide **good practice examples** for 3 of the 4 MSFD marine regions: the Baltic Sea, Mediterranean Sea and North-East Atlantic where numerous MAS programmes have taken place; MAS operations have only recently started in the Black Sea. These case studies demonstrate how the implementation of MAS acted to increase our understanding of ocean health in these regions and thus may assist in current and future assessments of 'Good Environmental Status' across all 4 of the MSFD regions in Europe.

Table of Contents

Table of tables

Table of figures

List of Abbreviations

ADP	Acoustic Doppler Profilers
Argo	Scientific international programme for ocean observation using a fleet of robots
AUV	Autonomous Underwater Vehicle
BSIMAP	Black Sea Integrated Monitoring and Assessment Programme
CAMPUS	Combining Autonomous observations and Models for Predicting and Understanding Shelf seas
CMRE	Center for Maritime Research and Experimentation
CTD	Conductivity, Temperature and Depth
DBCP	Data Buoy Cooperation Panel
DYMS22	Dynamic Messenger 22
EC	European Commission
EuroArgo	European contribution to the Argo Programme
EOOS	European ocean observing systems
FAO	Food and Agriculture Organization
GEF	Global Environment Facility
GES	Good Environmental Status
GOOS	Global Ocean Observing System
GROOM RI	GROOM Research Infrastructure
ISFET	Ion-Sensitive Field-Effect Transistor
JRC	The Joint Research Centre

MAP	Mediterranean action plan
MASSMO	Marine Autonomous Systems in Support of Marine Observations
MRU	Marine Reporting Unit
MSFD	Marine Strategy Framework Directive
OSPAR	North-East Atlantic Environment Strategy and the Convention on Biological Diversity
PAH	polycyclic aromatic hydrocarbons
PAR	photosynthetically active radiation
REPMUS	Robotic Experimentation and Prototyping Augmented by Maritime Unmanned Systems)
TRL	Technology Readiness Level
UN	United Nation
UNCLOS	UN Convention on the Law of the Sea
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UVP6	The Underwater Vision Profiler 6
WP	Work Package

1. Introduction

1.1 Overview

Observations from mobile autonomous platforms and vehicles play a pivotal role in both global and European ocean observing systems (EOOS) used for statutory monitoring frameworks, such as those collected by Argo and moorings (Data Buoy Cooperation Panel). Such platforms are often reported to provide the sustainable future for such frameworks. Marine Autonomous Systems (MAS) missions offer a wide range of sensors that can provide physical to biological and ecological information to support marine legislative schemes.

In line with the global initiatives such as those set forward during the G7 summit in May 2016, the G7 science and technology ministers issued the "Tsukuba" communiqué regarding the future of the seas and the oceans (G7 FSOI). That document included a recommendation to support the development of a global initiative for an enhanced, global, sustained sea and ocean observing system. MAS were highlighted as a platform to enhance observational capability in two key areas and/or parameter space that are currently not well sampled by Argo, the global research vessel fleet, and fixed-point stations. Additionally, in 2016 the OceanGliders program was launched in order to support active coordination and enhancement of global glider (a ~2m long, buoyancy driven MAS) activity. The OceanGliders program is distributed across regional and national observing systems, sharing best practices and scientific knowledge needed for glider operations, data collection and analysis [1].

One of the key oceanographic areas emphasised as being under-sampled in the G7 summit was the highly productive coastal and shelf seas, which represent the transition region between the open-ocean and coastal area. The Global Ocean Observing System (GOOS) also highlighted the needs for improved sampling of coastal areas, an example being within the framework of the UN decade for ocean science for sustainable development (UN Decade) in its "Ocean observing Co-design" and CoastPredict programs. The OceanGliders program already contributes to the international efforts of the GOOS, thus glider, and other MAS, show potential implementation for coastal and shelf monitoring. How GROOM RI will contribute to the GOOS and OceanGliders is described in 'D4.1: Report on plans for an EU contribution to OceanGliders, the GOOS/GCOS and EOOS, and data delivery on a sustained basis'.

The shelf seas include productive upwelling regions with diverse and rich ecosystems that support a significant proportion of national fisheries. The shelf seas host intense boundary currents that play a key role in climatically important meridional transports of heat and freshwater, nutrients, oxygen and matter. Due to their proximity to populated coastlines and associated anthropogenic impacts (including pollution, marine litter, fisheries), as well as their disproportionate impact on the global ocean climate and biogeochemistry, it is vital that the states and rates of change in coastal and shelf seas are appropriately monitored to guide policies set in place to protect and sustainably manage these areas.

In this report we will demonstrate how the GROOM II Research Infrastructure (from here onwards GROOM RI) could benefit statutory monitoring frameworks by providing a trusted link between national MAS observation efforts and internationally coordinated ocean observing systems. Section 1 will outline European statutory monitoring frameworks and briefly cover details for the specific marine areas. Section 2 will describe monitoring indicator variables and provide evidence of the capability of

MAS to meet statutory requirements, together with a recommendation on their technology readiness level (TRL). Section 3 provides glider case studies for each of the 4 marine areas defined by the Marine Strategy Framework Directive. Section 4 of this report will assess the current best practices for marine monitoring. Finally, at the end of the report in section 5 we will provide future recommendations for the monitoring of ocean ecosystems and health in terms of European sustained monitoring frameworks and outline how a GROOM RI would benefit these.

1.2 European statutory monitoring frameworks

To effectively protect the marine environment across Europe, the European Union has put in place the Marine Strategy Framework Directive (MSFD) in 2008. EU member states are required to take actions and measures in order to achieve and maintain Good Environmental Status (GES) in the marine environment. GES is a qualitative description defined as 'ecologically diverse and dynamic ocean and seas which are clean, healthy and productive'. To help EU countries achieve GES, the directive sets out 11 illustrative qualitative descriptors as well as criteria and methodological standards () and obliges the member states to monitor, achieve and maintain GES of their marine waters and to take measures to meet the established targets [2]:

D1) Biodiversity is maintained;

D2) Non-indigenous species do not adversely alter the ecosystem;

D3) Population of commercial fish species is healthy;

D4) Elements of food webs ensure long-term abundance and reproduction;

D5) Eutrophication is minimised;

D6) The sea floor integrity ensures functioning of the ecosystem;

D7) Permanent alteration of hydrographical conditions does not adversely affect the ecosystem;

D8) Concentrations of contaminants give no effects;

D9) Contaminants in seafood are below safe levels;

D10) Marine litter does not cause harm;

D11) Introduction of energy (including underwater noise) does not adversely affect the ecosystem.

Each descriptor is further expounded through a comprehensive list of indicators. The implementation (and updates) of the marine strategies follows a 6-year cycle, which started in 2012 and is currently in its second phase. Articles 8, 9 and 10 are implemented during the 1st year of the cycle (2012, 2018), Article 11 is implemented during the 3rd year (2014, 2020) and Articles 13 and 14 during the 4th year (2015, 2022). The 3rd cycle of implementation will start in 2024.

Member states are required to provide every six years documents describing the initial environmental status (submitted by 2012), the GES to be achieved and what targets will be set to achieve it. According to Article 4, the MSFD is applicable to the four marine regions of Europe, namely the Baltic Sea, the

Black Sea, the Mediterranean Sea and the North-East Atlantic Ocean, where the last two are divided in four subregions each. Member States may implement the Directive in subdivisions of their marine waters. The 23 member states responsible for these 4 areas are:

- Belgium
- Bulgaria
- Croatia
- Cyprus
- Denmark
- Estonia
- Finland
- France
- Germany
- Greece
- Ireland
- Italy
- Latvia
- Lithuania
- Malta
- Netherlands
- Poland
- Portugal
- Romania
- Slovenia
- Spain
- Sweden
- United Kingdom (up to 2021, upon which the UK MSFD framework was adopted)

Each member state has an obligation and national requirements for statutory monitoring of the region(s) relevant to it. As an essential step to achieve or maintain GES, the member states must establish monitoring programmes with various activities for the assessment of the 11 descriptors, carried out at the relevant scale by laboratories operating within the appropriate quality control systems using internationally agreed methods. Member state submissions for the 4 appropriate marine areas listed above are coordinated via regional seas conventions.

OSPAR started in 1972 and works as the mechanism in which the EU and 15 governments cooperate to protect the North-East Atlantic marine ecosystem. In October 2021 the North-East Atlantic Environment Strategy (NEAES) 2030 was adopted after being supported by a high-level review of OSPAR's previous strategy (2010-2020). The monitoring framework for the Baltic Sea MSFD marine area is HELCOMS, which is the Convention on the Protection of the Marine Environment of the Baltic Sea Area – also known as the . The Black Sea Convention has developed the Black Sea Integrated Monitoring and Assessment Programme (BSIMAP), within which each country is obliged to carry out ecological monitoring on marine stations, with particular emphasis given to eutrophication. BSIMAP is based on national monitoring programs financed by the Black Sea states (Romania, Bulgaria and Turkey). The Mediterranean action plan (MAP) – Barcelona Convention System works with contracting parties and partners to fulfil the vision of a healthy Mediterranean Sea and Coast that underpin sustainable development in the region. Outside of national monitoring programs, thematic scientific surveys related to various environmental problems are carried out in the frames of different projects, financed by national authorities and/or donors (UNEP, UNDP/GEF, EC, UN FAO and others). The United Kingdom (no longer a part of the EU) have transposed the framework into UK environmental law but is not obliged to report to the EU. The UK Marine Strategy helps to deliver against key international obligations and commitments to protect and preserve the marine environment in the NE Atlantic marine region under the UN Convention on the Law of the Sea (UNCLOS), the UN Sustainable Development Goal 14 (to conserve and sustainably use the ocean, seas and marine resources for sustainable development), the OSPAR North-East Atlantic Environment Strategy and the Convention on Biological Diversity. The UK Marine Strategy outlines how the UK is both currently performing and how GES status can be achieved in the future via a number of existing and planned marine monitoring programmes.

All articles produced by OSPAR, HELCOMS, BSIMAP and MAP are reported to a specific Marine Reporting Unit (MRU), thereby linking the reported information to a specified part of the countries' marine waters. The Joint Research Centre (JRC) acts as the European Commission's science and knowledge service by supporting EU policies with independent scientific evidence. The JRC carries out in-depth assessments of the member states submissions for the MSFD as well as also identifying methods to set thresholds for the GES assessments. WISE-Marine provides a platform displaying all member states reports at national, regional and European levels, as well providing the assessment of the MSFD GES status.

We will provide evidence that the monitoring programs for each marine area mentioned above could be improved using glider and other MAS observations via highlighting evidence of past operations that may have complemented these programs in section 3.

2. MAS contribution to the assessment of Good Environmental Status

MAS are capable of measuring a wide suite of ocean variables, many of which are relevant in a MSFD monitoring capacity. In the following section we provide an overview of what MSFD variables MAS can measure, and how competently through the current technology at time of writing this report.

2.1 Table of MAS variables and related MSFD indicators

Table 1 List of variables that MAS are currently capable of measuring, together with the MSFD descriptor this variable is relevant to, the method involved, technology readiness level (TRL), and the peer-reviewed evidence appropriate to this.

Variable measured by glider	MSFD Descriptor (D) relevant to	Method	TRL	Evidence
Temperature	D7	Thermistor	9-10	[3] Schmitt et al., 2006
Salinity	D7	Conductivity cell	8-9	[3] Schmitt et al., 2006
Topography	D6, D7	Altimeter and pressure sensor	2-6	[4] Zhou et al., 2014
Dissolved Oxygen	D5C5, D7	Electrochemical optode	5-8	[5] Bittig et al., 2018
Chlorophyll	D5C2, D4	Fluorometer	4-8	[6] Thomalla et al., 2017
Nitrate	D5C1, D7	Microfluidics, UV sensor	3-7	[7] Vincent et al., 2018 ; [8] Beaton et al., 2022
Phosphate	D5C1, D7	Microfluidics	4-7	[9] Birchill et al., 2021
Silicate	D5C1, D7	Microfluidics	2-4	[10] Mowlem et al., 2021
Zooplankton abundance/ distribution	D1, D2, D4	Echosounder	4-6	[11] Benoit-Bird et al., 2018 ; [12] Guihen et al., 2014
		Camera-based particle counter	1-4	[13] Picheral et al., 2021
Marine mammal abundance/ distribution	D1, D2, D4	Hydrophones/Passive Acoustic Monitor	4-6	[14] Cauchy et al., 2020 ; [15] Haxel et al., 2019
Sediments/ turbidity	D6, D7	Optical backscatter (fluorometer)	4-7	[16] Miles et al., 2021
		UVP camera-based particle counter	2-4	[13] Picheral et al., 2021;
Fish abundance/	D1, D2, D3, D4,	Echosounder	2-5	[11] Benoit-Bird et al., 2018 ; [17] Wall et al., 2012

distribution		Acoustic Doppler Profilers	2-5	[18] Powell & Ohman, 2015
Primary production	D1, D4, D5,	Chlorophyll fluorometer combined with PAR, CTG muSTAF	2-4	[19] Hemsley et al., 2015; [20] Loveday et al., 2021
Iron	D7, D5	Sensor	2-4	[10] Mowlem et al., 2021
		Microfluidics	1-4	[10] Mowlem et al., 2021
Turbulence	D7, D11	Velocity shear probes	6-9	[21] Fer et al., 2014 ; [22] Palmer et al., 2015
Phytoplankton abundance and composition	D1, D2, D4, D5	Fluorometry	2-5	[6] Thomalla et al., 2017
		Camera-based particle counter	2-5	[13] Picheral et al., 2021;
Marine noise	D11	Hydrophone	3-6	[15] Haxel et al., 2019 ; [24] Sun & Zhou, 2022
Ocean currents	D7	Acoustic Doppler Current Profiler Depth-Average Currents	2-6	[26] Merkelbach et al., 2008 [27] Rudnick et al.,2018
Hydrocarbons	D7, D8	Impedance cytometer	1-3	[28] Cyr et al., 2019
pH	D7	Sensor	2-6	[29] Johnson et al., 2016 ; [30] Hemming et al., 2017
pCO2	D7	Sensor	2-5	[31] Atamanchuk et al., 2014 ; [32] Oppeln-Bronikowski et al., 2012

2.2 Hydrographic conditions

In order to achieve GES for MSFD Descriptor 7, evidence needs to be provided that ‘permanent alteration of hydrographical conditions does not adversely affect the ecosystem’. The indicators relating to D7 are fairly broad but also probably the most developed ocean variables that can be measured. These include temperature, salinity, bathymetry, measurements and modelling of currents and waves, and pH. Interestingly, no specific monitoring and assessment methods have been established/agreed for Descriptor 7 on hydrographical conditions under the MSFD. Table 1 shows that MAS are capable of measuring all of these variables with commercially available instruments with high accuracy and precision. Temperature, salinity and water depth are generally standard measurements on small autonomous vehicles called gliders using a CTD (conductivity, temperature and depth) either pumped or unpumped and provide an accuracy suitable for reliably monitoring changes at time scales of days, weeks, months and years (± 0.01 PSU for salinity, $\pm 0.01°C$ for temperature).

Ocean pH is listed as an indicator within Descriptor 7, and a number of commercially available ion-sensitive field-effect transistor (ISFET) to measure pH are available and have already been deployed with reasonable success on gliders [29, 30]. During the REP14-MED experiment in June 2014 an ISFET was deployed in the north-western Mediterranean [30].

Glider based CO2 measurements using novel optode sensors [31] have also been carried out [32], although pCO2 is not currently listed as a descriptor in D7 or anywhere else despite it being highlighted as a gap in the recent (2020) MSFD implementation report: "Despite its relevance, the link between the MSFD and climate change, both at monitoring and policy development levels, is not obvious. Member States have highlighted the impacts caused by climate change and ocean acidification as important transboundary issues that are directly or indirectly addressed through MSFD monitoring programmes. Still, key topics such as the monitoring of ocean acidification in European seas and the impacts of marine heatwaves on marine biodiversity are not well established." Sensors for both pCO_2 and pCH_4 (methane) measurements have also been implemented on Seagliders.

2.3 Dissolved oxygen

Dissolved oxygen is a key indicator of ocean health, and the risk of deoxygenation in the productive coastal and shelf sea regions is increasing [33]. Dissolved oxygen is among the most mature of oceanographic measurements, it was measured on the H.M.S Challenger expedition in 1873-1876 and later Winkler (1888) developed a precise, but time consuming wet-chemical method for discrete measurements. Electrochemical optodes have revolutionised how we can monitor oceanic oxygen, increasing sampling temporally and spatially as demonstrated by the bio-argo program (biogeochemical-argo.org). Oxygen optodes are also fairly standard instruments deployed on gliders, they are low power and capable of measuring oxygen concentration for months at a time, with commercially available optodes providing minimal drift [5]. Combined with standard glider CTD measurements of temperature the oxygen saturation (%) can also be measured, which is a useful measure of the state of ocean oxygen for assessing marine health.

2.4 Chlorophyll, phytoplankton and primary production

Chlorophyll concentrations in marine waters relate to MSFD descriptors relating to eutrophication (D5C2) as well as food webs (D4). Phytoplankton abundance and composition relates to biodiversity being maintained (D1) and marine food webs (D4). Primary production via autotrophic phytoplankton also informs the marine food web descriptor.

Fluorometers for estimating chlorophyll biomass are also generally part of the standard glider sensor set-up as they are reliable and low power with a high TRL (8/9). This has resulted in the temporal and spatial resolution of phytoplankton measurements being dramatically increased since with increasing glider deployments. Productivity and phytoplankton biomass on large scales largely relies on ocean colour measurements derived from satellites. However, satellite derived ocean colour products do not penetrate further than the surface of the water column where much of the production in the coastal and shelf sea regions occurs [34], and thus this data is spatially limited. Other MAS (such as surface vehicles) can be used for surface calibration of satellite derived Chl-a. Glider mounted fluorometers can be used to measure phytoplankton abundance throughout the entire water column, additionally multiple wavelengths can be used to differentiate between different pigments found within various species of phytoplankton. Furthermore, as this data is available in near real time, glider missions and sampling strategies can be updated to track and monitor phytoplankton blooms. An example of this was proven recently to be successful in the CAMPUS project () in the English Channel, where the UK Met Office numerical forecasting model successfully predicted where the spring phytoplankton bloom was likely to develop. The model fed waypoints of the bloom location to an active glider, which in turn measured chlorophyll and provided NRT data to be assimilated into the model for further validation [35]. Gliders have been used to measure and estimate phytoplankton abundance and biomass via chlorophyll fluorescence measurements as described previously. However, as the carbon to chlorophyll ratio is highly variable both spatially and temporally, the estimation of phytoplankton biomass via this method is not always accurate [36].

Primary production is the rate at which energy is converted to organic substances via photosynthesis by phytoplankton. Direct measurements of primary production in the ocean are a relatively time-consuming process and thus they are sparse. Furthermore, fixed point observations may not allow spatial extrapolation due to high spatial variability of phytoplankton [19]. The quantification of primary production has recently been successfully measured in the North Sea using glider-based observations of photosynthetically active radiation (PAR) combined with chlorophyll fluorescence [20], this is based on an algorithm of primary production based on satellite data [19].

Despite fluorometers being widely deployed as a standard sensor on gliders to measure chlorophyll-a, factory calibrations can differ widely from the natural environment as they are typically based on the chlorophyll-a concentration of one phytoplankton species. Instruments signals can fluctuate and drift due to power and temperature oscillations Furthermore physical damage and biofouling to the sensors can occur during long-term deployments, especially in coastal areas [37]. Best practice is typically to carry out in situ calibrations in close proximity to the MAS fluorometer at the beginning and end of deployment, although remote sensing data from satellites can also be used [38].

2.5 Nutrients

Oceanic nutrient concentrations inform D5, as enhanced nutrients (such as nitrate and phosphate) from anthropogenic sources can result in enhanced primary production leading to eutrophication. As with dissolved oxygen, measurements of inorganic nutrients such as nitrate, phosphate and silicate have been historically monitored using wet-chemistry performed on discrete water samples which are relatively expensive and limited both spatially and temporally.

The last decade has seen the development of commercially available 'lab on a chip' sensors that are successfully able to perform the wet chemistry autonomously on MAS to measure nitrate [7,8] and phosphate [9]. Furthermore, nitrite, silicate and iron sensors are also commercially developed [9] but yet to be deployed on gliders and other MAS. These sensors use microfluidics and optics in an optofluidic chip with electromechanical valves and pumps mounted upon it to mix water samples with reagents and measure the optical response [10]. Additionally, optical (direct spectrophotometry of seawater) sensors can provide reagent free, high frequency and low energy measurements of nitrate with for many applications sufficient accuracy (e.g., deep SUNA, Seabird Scientific, United States), which have proven to be robust and deployable on small platforms [10,29]. Mowlem et al. (2021) offers a useful comprehensive review of these chemical sensors for ocean observations and their level of readiness for glider-based observations. Furthermore, we need much more nutrient data, i.e. using gliders and other MAS, to collect T, S and nutrient data and train neural network algorithms in regions of high nutrient variability such as the coastal zone.

2.6 Zooplankton, fish and marine mammal abundance/distribution

Zooplankton, fish and marine mammal abundance and distribution informs the MSFD descriptors relating to both biodiversity being maintained (D1) and marine food webs (D4). Sensors commonly used in autonomous platforms leave large gaps in our understanding between primary producers and large predators, a relationship that relates to D4, ‘Elements of food webs ensure long-term abundance and reproduction’. Echosounders have the potential to fill this gap [11]. Descriptor 4 is made up of a number of indicators and is perhaps the most challenging to implement. Assessing highly dynamic and complex interactions between marine food webs is non-trivial [39]. This descriptor addresses the functional aspects of marine food webs, particularly the rates of energy transfer within the system and levels of productivity in key components, and ecosystem structure in terms of size and abundance of individuals [39].

Echosounders have been widely deployed on gliders and other MAS (TRL 2-6) and used for estimating zooplankton and fish biomass for many reasons, including the use of multiple frequencies, ease of calibration and well-defined instrument parameters [11,40,41]. Echosounders on MAS have already proven successful in monitoring fish abundance [17,42] and zooplankton [12]. Studies have also shown that Acoustic Doppler profilers (ADP) deployed on MAS also provide accurate measurements of zooplankton biomass [18].

The implementation of gliders for bioacoustics recordings combined with other in-situ sensors mentioned above has been proven to provide insights for behavioural studies of low frequency baleen whales, high frequency beaked whales, tracking of sperm whales and other odontocetes [14], as well as acoustically active fish [15].

The Underwater Vision Profiler 6 (UVP6) is capable of collecting data on aquatic particles as well as plankton from gliders [13], thus useful in providing information on zooplankton (and phytoplankton) abundance and distribution.

For the non-trivial descriptor 1, it is evident that MAS measurements can significantly improve monitoring of many marine biodiversity indicators in European waters for MSFD, and the sensors employed and described above have a reasonably high TRL.

2.7 Sediments/turbidity

Turbidity of the water column informs us about the amount of suspended particulate matter, and relates to the descriptor D7, 'permanent alteration of hydrographical conditions does not adversely affect the ecosystem'. Turbidity sensors work by measuring optical radiation that is backscattered by particles in the water from a transmitted light pulse. Turbidity is normally measured on gliders as part of the standard commercially available fluorometry set up (e.g. the ECO Puck, Sea-bird Scientific). Many measurements of backscatter from previous glider missions in EU seas are already publicly available via national marine data facilities but are still to be fully exploited.

2.8 Turbulence and mixing

The measurement of marine turbulence in shelf and coastal seas informs descriptor 7 relating to monitoring hydrographical conditions. Oceanic turbulence is sampled using shear probes, which measure small scale fluctuations in velocity and temperature. Commercially available turbulence probes have been successfully deployed on gliders over the past decade [21,22]. A shear probe instrument package developed by Rockland Scientific called the Ocean Microrider sits on top of the glider, and stores turbulence data internally that is downloaded on recovery of the glider. Further methods to estimate turbulence and mixing have used the large-eddy method, derived from vertical velocities derived from a glider flight model [23], although these methods are not a direct measure but are instead derived from scaling arguments that are not relevant in shallow (coastal) ocean environments. The Microrider may also be deployed on larger MAS such as the Autosub Long Range [25], however are not suitable for autonomous surface vehicles.

2.9 Marine noise

The monitoring of underwater noise involves the use of sound maps which are generated via a combination of acoustic modelling techniques and observations of marine sound. Despite the onset use of underwater gliders for acoustics around 2006, minimal research has focused around underwater ambient noise level conditions. This has been recently developed however by gliders equipped with a hydrophone [15], and gliders have been highlighted as a new, effective platform for sound level measurements across regional spatial scales [24].

2.10 Hydrocarbons

The monitoring of hydrocarbons using glider can be performed using either the mini-fluo, SeaOwl (SBE) or Cyclops (Turner), which are MAS-compatible fluorescence sensors that target the detection of polycyclic aromatic hydrocarbons (PAHs) in the marine environment [28].

3. Case studies of good practice MAS operations for monitoring in EU seas

In the previous section, we provided evidence and the TRL of MSFD indicators that MAS, in particular gliders, are capable of measuring. In this section we provide case studies for each of the designated MSFD areas of various EU monitoring and maritime/naval operations that have benefited from the use of MAS, and outline how the use of MAS has improved monitoring in these areas.

3.1 North-East Atlantic Sea

The North-East Atlantic sea region is divided into 4 subregions for the purpose of MSFD monitoring; Greater North Sea, Celtic Seas, Bay of Biscay and the Iberian Coast, and Macronesia. Evidently these are expansive regions covering various physical and biogeochemical conditions spatially and temporally. As mentioned in section 1, OSPAR coordinates monitoring programs for this MSFD area.

The UK project AlterECO (an Alternative framework to assess the marine ECOsystem) took part in the North Sea between 2017 – 2019 with the aim to demonstrate the suitability of solely using AUVs for monitoring ecosystem health and functioning. As part of this project 19 gliders were deployed providing measurements of temperature, salinity, chlorophyll, turbulence, dissolved oxygen, primary production [20], nitrate [43], phosphate [9] and turbidity. The project maintained a continuous 100km transect over an area in the North Sea prone to seasonal oxygen depletion [44] for 18 months. The Marine Autonomous Robotic Systems centre at the National Oceanography Centre (Southampton, UK) was responsible for deploying, piloting and recovering many of the gliders, with a user interface so that scientists were able to monitor the data in real-time and alter missions accordingly.

The MASSMO project (Marine Autonomous Systems in Support of Marine Observations) is a pioneering multi-partner series of trials and demonstrator missions that aim to explore the UK seas using a fleet of MAS. So far, the project is in its 4th phase and has monitored both the marine environment (D7) marine life (D1, D4) and marine noise (D11) [45] around both the North Sea and Celtic Seas. The project has provided valuable information on marine mammals and fish, and uses weather information from the Met Office and the Royal Navy, satellite data from Plymouth Marine Laboratory and tidal information from the National Oceanography Centre to inform piloting the MAS.

3.2 Mediterranean Sea

REPMUS (Robotic Experimentation and Prototyping Augmented by Maritime Unmanned Systems) is the largest annual robotics exercise in Portugal. It serves as a platform for international navies, academic institutions, and industrial research organizations to collaborate and test technologies and concepts that enhance operational efficiency.

The inaugural edition of the REP exercise took place in 2010 through a partnership between the Faculty of Engineering at the University of Porto (through the LSTS) and the Portuguese Navy. In 2015, the NATO Science and Technology Organization Center for Maritime Research and Experimentation (CMRE) joined as a co-organizer, followed by the NATO Maritime Unmanned Systems Initiative (NATO MUSI) in 2019. Currently, the four institutions collaborate as co-organizers of the REPMUS exercise.

The REPMUS22 and DYMS22 (Dynamic Messenger 22) exercises provide valuable opportunities to assess the interoperability of new maritime unmanned systems. These exercises aim to ensure that Allies can effectively cooperate in countering future security challenges. REPMUS primarily focuses on testing and training, while DYMS emphasizes practical operations training with new marine technologies and readiness.

Dynamic Messenger represents the first comprehensive NATO operational experimentation exercise dedicated to integrating unmanned systems into the maritime domain. It specifically targets NATO Task Groups at sea and involves the participation of 16 NATO nations, with over 18 ships, 48 unmanned assets, and 1500 personnel. The exercise utilizes a CATL message protocol to facilitate status reporting among unmanned vehicles from different institutions and nations. It also enables mission synchronization across various nodes and enhances situational awareness for all operators involved.

Several national monitoring programs around the Mediterranean Sea use gliders such as MOOSE (France), SOCIB (Spain) and POSEIDON (Greece). As part of the French MOOSE program, two endurance lines are active since 2010: T00 between Nice and Corsica, T02 between Marseille and Menorca [43]. The objective of these two lines is to be able to monitor the full seasonal cycle of deep convection (Jan-March) and the subsequent spring phytoplankton bloom (March-April). The core measurements include temperature, salinity, oxygen, fluorescence and turbidity.

Poseidon System has integrated two SeaExplorer gliders in its observing network for the Greek Seas (Fig. 1). One of them can reach 700 m while the other belongs to the next generation SeaExplorer X2 gliders designed to dive up to 1000 m depth. Both of them carry the payload of a CTD (conductivity, temperature, depth) and a dissolved oxygen sensor (GPCTD + DO sensor of SEABIRD ELECTRONICS).

Since 2017, HCMR conducts missions in the north Cretan Sea. An endurance line has been established in this area, in order to monitor the physical and biochemical parameters of the seawater (e.g. temperature, salinity, oxygen concentration), study the seasonal variability of the flow field, and collect evidence for the intermediate or deep water formation events that are known to occur in the area. During its mission the glider performs profile measurements following a trajectory parallel to the island of Crete, which has a length of approximately 220 km (fig. 1). The missions have a duration of 30 to 47 days, while the glider is able to repeat this trajectory 2 to 3 times during each mission. Its horizontal velocity (SOG – speed over ground) fluctuates between 0.15 and 0.4 m/s (depending on the direction and the magnitude of the sea currents) while its vertical velocity has values between 0.1 and 0.2 m/s.

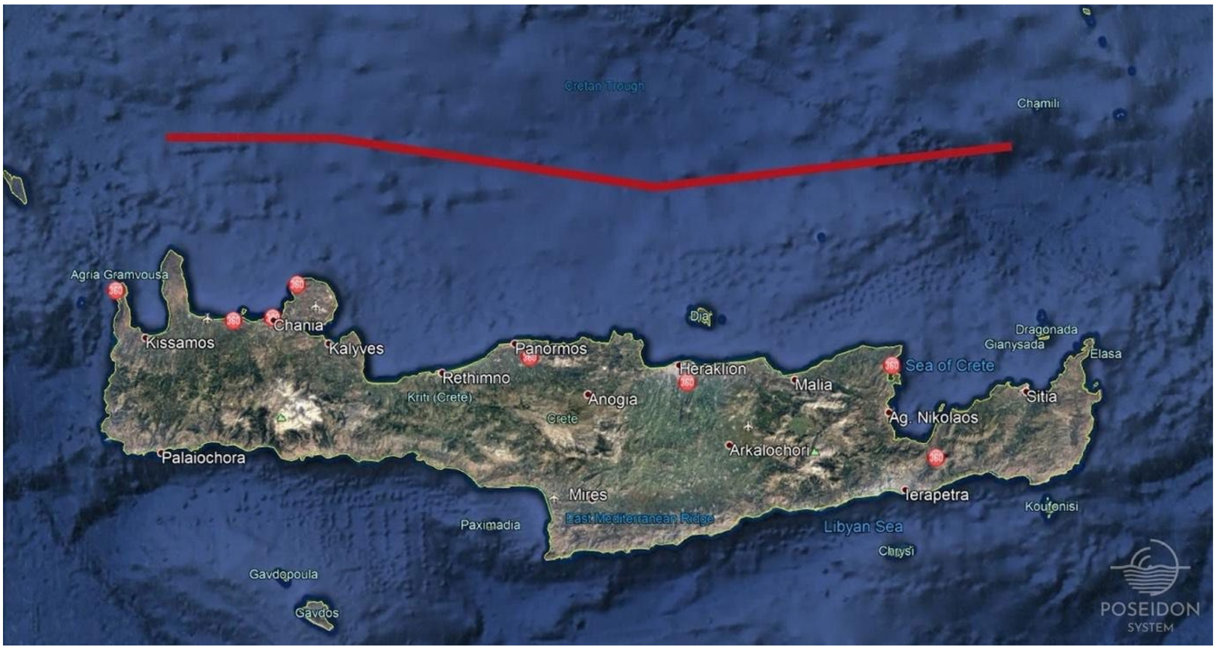

Figure 1 – The trajectory of the glider in the Cretan Sea

Cyprus has had glider missions providing a large amount of data within the Mediterranean since 2009, which ceased in 2021 due to lack of funding and loss of one glider.

3.3 Baltic Sea

The Baltic Sea has four countries actively utilising gliders in the region (Finland, Estonia, Sweden and Germany). Of these, the Voice of the Ocean Foundation Ocean Observatories (VOTO OO) are the most active. The Voice of the Ocean Foundation is a Swedish non-governmental organisation that aims to increase knowledge and understanding of the marine environment. One aspect of this is their establishment of Ocean Observatories around the Baltic Sea, at known sites of water mass exchange. These observatories are targeted to be continuously occupied by at least one glider and since March 2021 there has been one glider in the water at least 98% of the time (87% occupancy on the western side of Sweden, 93% in the Baltic Proper).

The gliders are equipped with temperature, salinity and dissolved oxygen sensors as standard, with most also carrying ADCP and chlorophyll sensors. One glider is equipped with a microfluidics sensor to collect nitrates. However, bathymetric information must be removed for any profiles taken within Swedish territorial waters, if a surveying-type pattern has been established, due to national law unless specific permissions are applied for.

The data has been used by researchers In the EuroSea project, which focused on integrating and improving European Ocean Observing and Forecasting systems. By including the VOTO OO data, the improved reanalysis product had better results at forecasting eutrophication events (compared to the existing CMEMS reanalysis products). As well as being immediately available through the VOTO ERDDAP server, the data is shared directly with the Swedish Navy.

FMI in Finland performs yearly deployments in the Bothnian Bay. TalTech in Estonia has participated in large scale experiments supported by VOTO to map broad scale circulation in the Eastern Gotland Basin. Hereon in Germany has worked extensively in the Gotland Basin as well.

3.4 Black sea

The first glider deployment in the Black Sea recently took place as part of DOORS–-''Developing Optimal and Open Research Support for the Black Sea, which is a new €9m EU research project linking science, policy and industry for critical Black Sea regeneration. This first DOORS' glider deployment took place on the 6th of May on the Romanian shelf break, and performed repeatable perpendicular sections of 70 km length from the shelf to the open waters. The DOORS project brings together expertise and technology from 35 institutions from the Black Sea region and other European countries to address the human and climate change impacts on damaged ecosystems. DOORS provides an excellent example of EU collaboration to support and contribute to a healthy, productive, and resilient Black Sea.

4. Consideration of GROOM RI in maritime/naval information systems

Unmanned maritime vehicles (UMS) include unmanned air, surface, and underwater vehicles of different sizes and capabilities.

The UMS market is projected to grow at a significant CAGR for the next decade. This is in part because advances in sensors, computation, energy storage/harvesting, and materials are now making it possible to design and deploy advanced vehicles with high levels of reliability and performance. The market pull used to come primarily from the military, but this is changing because of new requirements coming from the oil & gas industry, as well as from offshore wind farms, to name just a few examples.

The UMS segment of military unmanned underwater vehicles (UUV), in particular gliders, is especially relevant to GROOM II vision and methods. There are several reasons for this:

1. A significant number of missions are about Remote Environmental Assessment (REA), in which gliders are tasked to sample a given area with the purpose of providing measurements of key ocean variables for assimilation and operational model development. Observe that REA missions are not significantly different from oceanographic missions undertaken by several oceanographic institutions worldwide.
2. REA missions are now evolving into more complex coordination patterns aimed at maximizing the performance of an ensemble of gliders for a given operational vignette.
3. There is a growing need to minimize the number of operators per glider, even if gliders come from different manufacturers.
4. In relation to the previous point, there is now an incentive for manufacturers to provide some level of interoperability for their products to enable integration into a system of systems, while minimizing operating costs (CAPEX). This is done by reducing the number of operators and the skill set required to operate heterogenous gliders.

5. Interoperability, interchangeability, and heterogeneity (in terms of MAS and payloads) will lead to new concepts of operation aimed at taking the most out of a combination of gliders. In fact, in some concepts of operation, and underlying AI-powered command and control strategies, an ensemble of N gliders provides capabilities that were not present in each glider. In fact, the capabilities of the ensemble are more than N times the capabilities of each glider.
6. MAS are now being considered for other times of military missions, namely Anti-Submarine Warfare, protection of critical infrastructures, key routes, etc. These demanding missions pose new challenges to glider and payload design that will certainly impact the global glider market, thus extending the mission portfolio for MAS. Examples include hybrid vehicles, that may use additional propellers for additional speed when needed, or vehicles towing acoustic arrays for underwater acoustic detection.
7. There is a new trend in development models for unmanned vehicles: experimental evaluation and testing in operational environments. In fact, the traditional development cycles for complex systems are now being revised and updated to account for the speed of technological innovation. This is done with the help of incremental development strategies and periodic operational experimentation which is targeted at evaluating and testing new components or subsystems as they become available and at incorporating lessons learned in new versions of a system or new versions of a component. Otherwise, it would not be possible for system developers to accompany the exponential growth in some technological areas.

The relevance of military operations with gliders for GROOM II provided the motivation to establish strategic synergies with the REPMUS exercise. REPMUS is a 2-week duration annual exercise, co-organized by the Portuguese Navy, the Porto University through LSTS-FEUP (partner of GROOM II), the Centre for Maritime Research and Experimentation from NATO, and the Maritime Unmanned Systems initiative from NATO. REPMUS brings together the elements of the triple helix (academia, industry, and the armed forces) to evaluate and test unmanned vehicle systems in an operational environment. The synergies with GROOM II are of the utmost importance because GROOM seeks to develop a framework infrastructure to support, in a uniform manner, the operation of heterogeneous MAS thus paving the way to assist MAS operators and smaller institutions in planning and execution control, as well as to enable synergies among these operators that were not possible before.

In 2023 there has been a secure network infrastructure providing access points to vehicles and control stations. Vehicles and control stations sent periodic updates, including status and position, to the network. This information was ingested by control centres for situational awareness and tasking (some vehicles were also enabled for remote tasking). This network and software infrastructure provided an unprecedented framework for coordination and control of such many assets. These assets include several heterogeneous MAS from different manufacturers. GROOM II participation in the REPMUS 23 edition included contributions to experiment planning, as well as analysis of the lessons learned.

5. Best practices and recommendations for the implementation for a GROOM RI for monitoring

5.1 Overview and gap analysis

In the previous sections we have provided evidence of how MAS can be utilised for marine monitoring of specific variables, and the descriptors which these are relevant to. We also provided good practice examples (case studies) of glider based marine monitoring in each of the 4 MSFD regions. Here we will briefly highlight where MSFD monitoring and GES assessments demonstrate that they are lacking information, and surmise where glider-based monitoring could improve this.

It is imperative to note that the frameworks for GES were designed when we had specific platforms (e.g. ships) and thus have needed updating and will need to continue to be updated in the future according to advancing ocean observing technology. The MSFD Annex [2] carried out an assessment on how well monitoring programmes at the regional level cohered with one another for each descriptor (omitting D4 and D6) in terms of a high, medium and low level of coherence (Table 2).

Of the 13 descriptors listed in this table for all four MSFD regions, only 37% are listed as having high coherence of monitoring programmes of the EU member states at regional level. Descriptor 7 (hydrographic conditions) only shows high coherence at regional levels within the Black sea region, yet we have highlighted how capable glider measurements can be for monitoring D7 indicators. Furthermore, we have provided good practice examples for the Baltic Sea, Mediterranean Sea and North-East Atlantic where numerous glider programmes have taken place, which could have contributed across the regional levels to support MSFD assessments. Of the assessments highlighted in Table 2, glider measurements have been taken in each MSFD region for many of these. Efforts to achieve good environmental status are mainly – or even exclusively – effective when they are the result of international cooperation and coordination. A GROOM research infrastructure that could support cohesion between member states therefore could assist with GES assessments at regional, and European level.

Descriptor	D1,4 Birds	D1,4 Mammals	D1,4 Fish	D1,4 Water column	D1,4,6 Seabed	D2	D3	D5	D7	D8	D9	D10	D11
Baltic Sea region	M	H	M	H	M	H	M	H	M	M	M	L	M
NE Atlantic Ocean region	M	H	M	M	M	M	H	H	M	H	H	H	M
Mediterranean Sea region	M	M	H	M	M	L	H	M	M	M	H	H	M
Black Sea region	H	H	M	H	H	H	H	H	H	M	M	M	H

Figure 2–- From EU MSFD Annex these are assessments of coherence of the monitoring programmes of EU member states at regional level. Where Green (H) = high coherence, orange (M) = medium, red (L) = low.

Additionally, it was highlighted by Zampoukas et al. [47] more than a decade ago how useful glider and MAS based measurements could potentially be compared to other standard marine monitoring equipment for MSFD indicator monitoring. Since then sensor technology has evolved in such a way that gliders and other MAS are capable of measuring an entire suite of extra variables since this assessment. On the other hand, Zampoukas et al. also emphasise that the operation of gliders in an MSFD capacity requires considerable technical expertise, which is not necessarily available for all member states. A GROOM RI could facilitate coordination between member states for MAS operations with the expertise needed.

5.2 Data Quality

Observing operations for statutory purposes often address the creation of data products that have legal implications, forming also the base for decision making. An agreed-on set of Standard Operating Procedures (SOPs) is required that defines sensor and data handling and outlines the way uncertainties of the data are estimated. These documents will enable making data interoperable and allow comparison of quantities and indicators and also tracking e.g. temporal evolution of a signal crossing various national waters.

It is in particular a specification of uncertainty estimates of data which cannot be (in almost all cases) estimated from sensor uncertainty provided by the manufacturer alone but requires agreed on protocols for estimation. Use of community agreed or even certified reference material is key as this way traceability of data towards a common standard is enabled.

In September 2021 OceanGliders moved to GitHub. Four SOPs have been moved online now for community review:

- Salinity: Community review finished, received GOOS endorsement. Preparation of v1.0.0 to be released on OBPS

- Depth Average Currents: In preparation for community review,
- Oxygen: Publication of v1.0.0 which is deposited on OBPS with doi: http://dx.doi.org/10.25607/OBP-1756 (López-García et al. 2022). Received GOOS endorsement,
- Nitrate: Community review finished, GOOS endorsement. Preparation of v1.0.0 to be released on OBPS,
- Chlorophyll a: Initiated by the community. Writing started at the end of June 2022.

The GROOM RI community already works closely with OceanGliders community, and will apply SOPs in future operations to ensure EU and internationally recognised data quality procedures for MSFD data collected from MAS operations. The role of GROOM RI for the Best Practices is described in D6.3 : *Best Practices for Data Management, Operations, Maintenance and Fault Reporting*.

5.3 Recommendations for GROOM RI

We provide the following recommendations for the GROOM RI:

- The GROOM RI must monitor MSFD MAS operations to create synergies between member states to share data and operations in order to improve quality of GES assessments.
- We recommend that further MAS pilot studies are carried out to collect more data and evidence, in order to better assess the scientific and economic efficiency of using MAS for MSFD monitoring and assessment of GES.
- For member states lacking resources (cost or expertise) to enable effective MSFD assessment of GES, we recommend the GROOM RI facilitate coordination with other GROOM RI partners who are able to facilitate this for GES assessments. The GROOM RI access policy (D2.1) will play a key role here.
- The GROOM RI will facilitate operations across Economic Exclusion Zones (EEZ) across member states.
- For MSFD indicators that MAS are not yet capable of measuring, the GROOM RI will work with partners to help provide the adequate information on developing MAS sensor technology, and how these technologies can contribute to the assessment of specific MSFD indicators.
- The GROOM RI will complement existing MSFD best practices and marine observation systems.
- Through the above recommendations, the GROOM RI will support the coherence of monitoring programmes of EU member states at regional level, as this has been highlighted as a shortfall in the MSFD assessments of GES.

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7. Acknowledgements

Valuable reviews and contributions to this document were provided by Alvaro Lorenzo Lopez, George Petihakis, Louise Biddle, Bastien Queste, Anthony Bosse, Johannes Karstensen, Evi Bourma, Rana Abu Alhaija, Carlos Barrera, Matthew Palmer, Daniel Hayes, Pierre Testor and Laurent Mortier.