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Abstract

The ocean is an important pathway to a low-carbon and climate resilient society, e.g. in areas of blue carbon, green shipping, offshore renewable energy, aquaculture, fishery and coastal adaptation. Currently, 26 EU member states have made their National Adaptation Strategy (NAS) and/or National Strategy Plan (NAP) which needs a strong climate information service. European Global Ocean Observing System (EuroGOOS) has a strategy to expand existing operational marine service to climate change in 2020-2030. As focal points of national marine, climate and/or weather services, ROOS (Regional Sea Operational Oceanographic System) members have extensive experiences in working with citizens, stakeholders and decision-makers at national, regional and municipality levels. This paper will review current marine climate service capacity in ROOS members, identify gaps in modelling, products and service, and propose a seamless earth system approach for developing EuroGOOS and ROOS marine climate service capacities.

Keywords: marine climate service, climate change adaptation, earth system, EuroGOOS, Green Deal

1. User needs, current service capacities and inadequacies

Ocean plays a key role in tackling challenges of climate change to ensure sustainable development (Hoegh-Guldberg *et al.*, 2019). Major ocean pathways for climate change adaptation includes, but is not limited to, enhancing carbon storage by benthic vegetation in the ocean (blue carbon), reducing emissions of shipping (green shipping), enhancing off-shore wind, solar and wave energy production (blue energy) and utilization of marine resources in a sustainable manner. Ongoing climate change is already calling society now to consider also how to adapt to global sea level rise, increased erosion, marine heat waves and other marine extreme events which impact on coastal infrastructures and livelihood. Marine climate information service is essential for supporting the implementation of the ocean pathways for climate change adaptation and mitigation. Citizens, stakeholders and decision-makers will have different needs on marine information and related adaptation options and solutions when they adapt to the low-carbon and climate resilient future. The required information also evolves in the planning and implementation phases of the adaptation measures. In the planning phase, for improving the resilience, governmental and inter-governmental decision-makers at EU, regional sea, national and municipal levels, will need to know in their geographic areas the evolution, the diagnostic, the forecast, and projections of the environmental and ecosystem variables. Some of the questions that need to be addressed are: what is the impact of the change? What are the most affected (high risk) areas? What are the potential solutions in terms of reducing risks and improving resilience? For decarbonisation, the decision-makers will need to implement Marine Spatial Planning (MSP) to know which spatial areas are feasible for different low-carbon solutions in terms of cost and benefit. The information provided from the climate service has to address relevant geographic scales with wide temporal spectra (physical, biogeochemical, biological and socioeconomic) with the required resolution to resolve local response. Citizens, on the other hand, will need to know: how the future climate will affect their daily life, for example, flooding risks and coastal erosion in the local areas. For the implementation phase, the governmental bodies, mainly at the municipality, region and sectoral level, will need climate information on detailed indicators, e.g. for building a dam, extreme sea level statistics with different return period is needed; the sector operators and citizens need to have information to support their daily actions, e.g. to reduce fuel consumption and greenhouse gas (GHG) emission, ship owners want to know the best sailing route according to daily meteo-ocean conditions, citizens need forecasts on a hazardous meteo-ocean state to avoid multi-risks for their houses and working places. They will also have to react to climate change and risks in the coming months to decades.

EuroGOOS community aims to expand the marine service from the current operational scale to the climate scale, as defined in EuroGOOS 2030 strategy (EuroGOOS, 2021). Currently, some member states (Denmark, Germany, Spain etc.) have initiated national marine climate service programs (Lange *et al.*, 2020). High-resolution marine climate projections have been developed by some ROOS members (Table I). At regional level, research projects have been funded to investigate future climate change and impacts on the marine environment and ecosystems, e.g., in the Baltic Sea, HELCOM (Helsinki Committee on Protecting Baltic Sea Environment) and Baltic Earth community are preparing a climate indicator service for member countries. At the EU level, EURO-CORDEX has provided atmospheric scenario projections for European Seas; Copernicus Marine Environmental Monitoring Service (CMEMS) has supplied regional sea reanalysis products for physical and biogeochemical (BGC) parameters; several C3S (Copernicus Climate Change Service) marine and coastal sectoral service projects have been carried out. The European Environmental Agency (EEA) Climate-Adapt Platform provides pan-European marine climate service for a few indicators (https://climate-adapt.eea.europa.eu/).

Table I. Existing high resolution marine climate projections produced by EuroGOOS partners.

	WAVES	OCEAN(-ICE)	BGC	HIGH TROPHIC
EU Arctic	MET.No (Nordic Seas)	IMR (Barents Sea)		
Baltic-North Sea	HZG	DMI, HZG, SMHI, BSH	SMHI, HZG	
North-East Atlantic	HZG, MET.no, MI (SW Ireland),	HZG, IEO (NW Iberia) and MI (SW Ireland)	HZG	
Mediterranean	CSIC	CSIC, OGS	OGS	

However, the existing information service capacity is far from the required by the member states, with several major inadequacies. **The first** is the lack of ensemble datasets of high-resolution (sub-km to km grid) marine system projections covering Essential Ocean Variables (EOVs) for ocean-ice, wave, biogeochemistry (BGC) and biology. As shown in Table I, the number of high-resolution marine projections available is still quite limited. Until now, there are no coordinated efforts at the European level to produce downscaled marine projections. Without such datasets, many of the marine climate service developments will be hampered and the existing best practices from national, regional and EU projects cannot be integrated and scaled up to pan-European seas. **The second** inadequacy is that the uncertainties in existing ocean projections have not been sufficiently evaluated and minimized, partly due to lack of enough ensembles and partly because the projections were made mainly for national purposes, thus the models are calibrated mainly for the national waters. As a consequence, uncertainties in the projections should be quantified before they are used for other countries. **The third** is the lack of a critical mass of research and coordination for developing a European marine climate service. Individual member states only have a small team working on a national marine climate service project, which is far from sufficient to address the entire value chain of marine climate change adaptation, ranging from end user needs, model and product development to service delivery and evaluation. **The fourth** is that current best practices on marine adaptation are local and fragmented, which require integration and upscaling to address the challenge across the scales.

2. Solutions: Concept and Methodology

A seamless, pan-European marine climate information service is needed to support end users (i.e. citizens, stakeholders and decision-makers) in all scales to address the above issues when planning and implementing the marine climate adaptation measures. Such a service must be robust, quality assured and developed through the following steps: (i) generating ocean climate projections with sufficient resolution and uncertainty quantification to identify potential marine climate change and related impacts; (ii) identifying adaptation options and solutions addressing regional and local scale user needs and (iii) developing end user products and delivering services. This procedure has been adopted by some EU member states in establishing national marine climate service (e.g. Denmark and Germany).

Such a pan-European service fits nicely into national, ROOS and EuroGOOS strategies on providing marine climate information service. As focal points of the national ocean, climate and/or weather services, ROOS members have extensive experience in working with citizens, stakeholders and decision-makers at national, regional and municipality levels. They have successfully collaborated on developing operational oceanographic service in the last two decades, mainly based on a volunteer basis. Marine climate service has evolved as a service area by ROOS members and some of them have developed high-resolution downscaling ocean-ice-wave-biogeochemical projections for national 'Green Transition' and adaptation activities. ROOS members have a strong wish to form a critical mass on developing marine climate service capacity to fill the current gaps and integrate our existing best practices.

Currently, marine service for the future climate is urgently needed at the member state level, something that is not available from the existing pan-European Copernicus service. Considering ROOS members have already initiated marine climate adaptation service at the national level, while still lacking critical mass to address major challenges in the area, it is timely to establish a public, sustainable marine climate service to address marine adaptation options and pathways for national and sectoral users. At the same time, European capacity on marine climate service will be built up by integrating and further developing existing member states best practices.

Seamless, co-design and integration are keywords: seamless is the service concept while 'co-design with users' and 'integration of best practices' are methodologies for the implementation. Here a 'seamless' service has several meanings: in time, it means a service ranging from forecasts in days to projections in decades; in spatial, it means a service in all EU regional seas and resolving from open sea to coastal-estuary continuum with high-resolution local information; in parameter spectra, it means a service addressing meteo-ocean-wave-ice-biogeochemical-biological variables and human activities, i.e. the entire earth system; in sector, it means a service addressing major ocean climate adaptation and mitigation pathways for low-carbon and climate resilient future, e.g. blue carbon in coastal waters, green shipping, offshore renewable energy, aquaculture and fishery and coastal adaptation.

The methodology to develop the proposed service is illustrated in Figure 1, including five major modules: gap-filling and data integration, user engagement and service co-design, product and service development, information service platform, service delivery and user evaluation.

Gap-filling and data integration: the purpose of this module is to establish a seamless database including high-resolution ocean-ice-wave-BGC-biological projections, which is a basis for building up the marine climate service. High-resolution modelling capacity developed in operational applications for the open sea-coastal-estuary area can be used for producing marine climate projections (She and Murawski *et al.*, 2018). Data integration aims to quantify uncertainties in hindcast models and projection products by inter-comparing model products and observations and between multiple models.

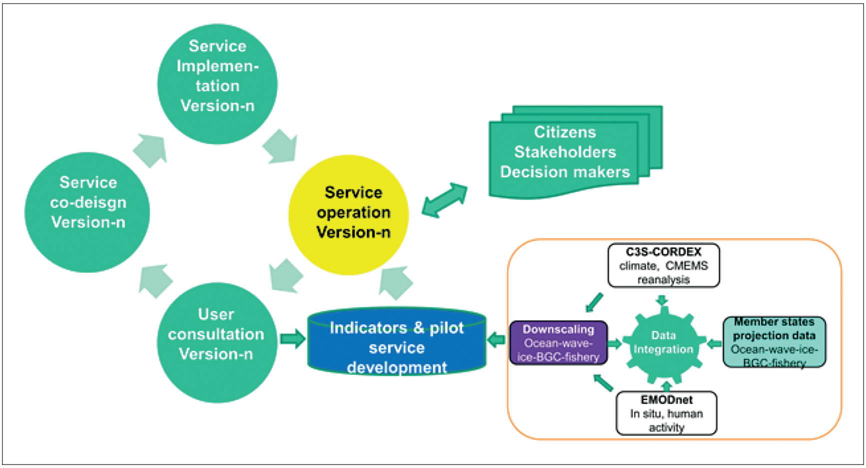

Fig. 1. Pert Chart of workflow for building up seamless marine climate change service. The service design – evolution – implementation – operation – user evaluation is a repeated cycle which is presented as 'version-n'.

User engagement, service co-design and delivery: including users in the service evolution cycles will ensure our service products fit for the purposes of citizens, stakeholders and decision-makers. Most of the ROOS members are national marine climate service thus already have extensive knowledge on national and sectoral user needs.

Product and service development: this part will focus on developing i) a pan-European Sea Marine Climate Atlas Service (EMCAS) in which trend, current status and future projections of marine climate indicators and marine health indicators will be generated, ii) model ensemble (MME) service for which technologies have already been in place and best practices available in some of the regions, and iii) pilot services where technologies are yet to be developed or available but yet to be applied which address major marine climate change adaptation pathways. EMCAS should include basic statistics of major EOVs, extremes with return periods, ocean health and ocean climate indicators in past and future climate in European seas. Integration among ROOSs and between ROOSs and external climate research communities are essential for developing EMCAS and MME.

Information service platform: ROOS members have already developed some marine climate information service platforms (Table II). These platforms may be integrated and further developed into a distributed information service system.

Main scientific and technological challenges for implementing the above solutions include, but not limited to, effective methods to quantify and reduce uncertainties of climate models and projection products; efficient climate modelling such as high performance computing, high resolution earth system models resolving effectively open sea-coastal sea-estuary waters, especially their ecological dimension and methods to quantify compound extremes with different return periods in the future climate considering both non-stationarity and multi-variate, spatiotemporal covariates.

Table II. Some of the existing web-services related to marine climate adaptation currently maintained by ROOS members.

SERVICE & PROVIDER	WEBSITE
Aqua-farm siting tool	https://au-bios-model.shinyapps.io/MYTIGATE/
Ecological Assessment and Maritime Spatial Planning Tool	https://azti.shinyapps.io/VAPEM-tool/
Wave Energy Converters Ecological Risk Assessment Tool	https://azti.shinyapps.io/wec-era/
BOOS multi-model ensemble forecast service	http://www.boos.org/multi-model-ensemble-of-forecast-products/
Leisure boat service SINDBAD	https://www.sindbad-liguria.it/Mapviewer2/#/portale
Beach erosion climate service	https://ideib.caib.es/impactes_costa_canvi_climatic/
Klimaatlas coastal flooding service	https://www.dmi.dk/klima-atlas/data-i-klimaatlas/?L=&paramtype=sea&maptype=kyst
Beach and coastal operational service	http://playas.ieo.es/

3. Coordination and Organization

The development of integrated marine climate services cannot successfully be accomplished without a strong and efficient coordination and organization. It is essential that marine climate change service development in the EuroGOOS and ROOS community should be designed and implemented in a coordinated way, including the sharing of technology as well as the expertise and best practices. It is recommended that working groups should be established to facilitate such an effort, as shown in Figure 2. The four working groups are coordinated by EuroGOOS-ROOSs. WG1 works on user engagement, user needs identification, service co-design and user evaluation. WG2 is responsible for filling gaps in the marine climate projections, developing EMCAS and MME products. WG3 coordinates information system development and WG4 develops pilot marine climate service for the marine pathways of climate change adaptation, e.g., blue carbon, green shipping, clean ocean energy, sustainable aquaculture and fisheries and resilient coasts and infrastructures. A successful implementation of EuroGOOS marine climate service will need external funding to support the coordination and joint research and development. Coordination and synergies with CMEMS, C3S, ESA Digital Earth, regional conventions and regional climate and earth system research community are essential when developing EuroGOOS marine climate service.

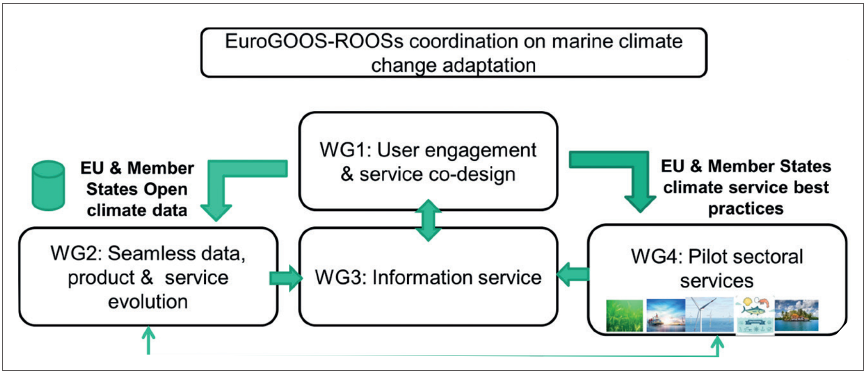

Fig. 2. Proposed organization structure for implementing EuroGOOS marine climate service, consists of 4 Working Groups (WGs).

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