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Global ocean indicators: Marking pathways at the science-policy nexus

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ABSTRACT

Ocean knowledge is crucial for shaping policies that enable sustainable development, adaptation, and well-being at all levels, as everyone—either directly or indirectly—depends on the ocean, which today faces escalating threats from climate change, pollution, and biodiversity loss, pushing us beyond critical planetary boundaries. Ocean indicators are crucial for translating ocean science and data into practical metrics, guidance, and tools informing on the state and health of the ocean that can be directly applied by policymakers, practitioners, and the public. Despite their critical importance, ocean indicators trail behind those for continental areas, limiting effective monitoring and policy integration. Developing reliable, comparable, and regularly updated ocean indicators, backed by a unified international framework, is essential for delivering coherent, actionable insights that can guide global goals and protect the ocean's future. This paper establishes a scientific foundation for ocean indicators through international and multidisciplinary collaboration, presenting defined criteria and a set of pilot indicators for the ocean's physical, biogeochemical, biodiversity, and ecosystem aspects. The proposed framework offers a solid foundation for generating indicators that not only track the ocean state but also provide outputs for application in informing policy and decision-making.

1. Introduction

Ocean science, supported by ocean data disseminated through national and international ocean -, weather-, and climate services, provides critical input to operational forecasts and a foundation for evidence-based decision-making [56]. To maximize the impact of ocean science, raw data has to be uniformized and quality controlled, but also translated into metrics, practical guidance and tools that can be directly applied by policymakers, practitioners, and the public [7]. One such tool is ocean indicators translating complex data and science on the status and health of the ocean into simpler meaningful and useful metrics. When effectively designed and applied, they can prove very effective to support informed decision-making [231], such as for marine spatial planning, governance and management ensuring the protection, sustainability, and resilience of the ocean [245].

Ocean knowledge is essential to inform policies for sustainable development, adaptation, safety, wellbeing and prosperity at all scales. All people on Earth rely on the ocean, either directly or indirectly. Nearly 28 % of the global population lives in close proximity to the coasts and maintains a deep connection with the ocean [98]. The ocean sustains life, regulates the Earth's climate, and provides services and resources for society, such as food, sustainable societal resilience, well-being, cultural identity, and economic growth [4]. The ocean offers opportunities for climate-resilient and adaptation solutions urgently needed as Earth faces increasing pressure from the interconnected crises of human-driven global warming, pollution, and biodiversity loss [96,98]. These crises have already pushed us beyond six of the nine planetary boundaries [173].

The ocean provides essential services for developing effective solutions for climate action under the Paris Agreement, while also contributing to the achievement of Sustainable Development Goals (SDGs) [92]. The ocean absorbs about 90 % of the heat trapped by human-induced greenhouse gas emissions, and 25–30 % of anthropogenic CO2 emissions that would otherwise further increase global warming [68,232,64]. Many nature-based solutions in the ocean that aim to mitigate climate change and pollution can also maintain or improve marine and coastal ecosystems' health and services, thereby also addressing challenges associated with biodiversity loss. These include design of climate-smart networks of marine protected areas [23,191,9], provision of clean energy and resources for human health [138], and increased global food security [188]. A protected, sustainable and resilient ocean is essential for the planet's health and the well-being of all people today and in the future [185,210].

Addressing these issues requires some metrics that can help us track the state and changes to the environment and biodiversity over time and space. To this aim, a suite of environmental indicators have been developed over the last decades and are now incorporated into international climate change and biodiversity assessment frameworks [97,98,99]. These indicators, alongside societal and economic indicators, are used regularly in international agreements to help focus the efforts of nations in tracking and achieving commonly set targets such as those associated with the [209] Sustainable Development Goals [214], the 1.5°C target established under the Paris Agreement [213] and those set through the Convention on Biological Diversity [19]. The United Nations Environment Programme (UNEP) also uses indicators in support of regional conventions and global environment situation monitoring [217]. Under the United Nations Framework Convention for Climate Change (UNFCCC), countries are mandated through Nationally Determined Contributions (NDCs), to determine their own indicators for reporting in their Biennial Transparency Reports (BTRs). However, the development of environmental indicators for the ocean remains significantly behind that for continental areas.

Since the 27th UNFCCC Conference of the Parties, ocean action is to be included in national climate goals [223]. The UNFCCC Global Stocktake [222], designed to assess global progress under the Paris Agreement [215], is also facing growing calls to explicitly include the ocean in its evaluation. There is therefore a clear opportunity to facilitate the development of national indicators that can be aggregated to create global indicators, and to better integrate the ocean into the international policy dialogue. International policy frameworks are increasingly recognizing the importance of monitoring the ocean's environmental and marine life status to support the management of ocean use by national governments, First Nations, and the private sector, such as raised in the Convention on Biological Diversity's Kunming-Montreal Global Biodiversity Framework [216]. Additionally, this is also stated in the agreement under the newly ratified United Nations Convention on the Law of the Sea on the Conservation and Sustainable use of Marine Miological Diversity of Areas Beyond National Jurisdiction (BBNJ agreement, [209]), in the frameworks for biodiversity protection and invasive species detection under the International Maritime Organization [40], and in the Global Goal on Adaptation within the Paris Agreement [221].

Existing environmental indicators used in these initiatives vary in terms of the data and information required, the disciplines and methods necessary to generate them, and the level of rigor involved in the process. To be effective, environmental indicators must be based on reliable and comparable methodologies, be updated frequently, and be spatially and publicly available [107,231,147]. Insufficient dialogue at the science-policy interface can hinder the transfer of indicator-based knowledge that are critical to reliably monitor global goals, such as the 1.5°C target, and which are today challenged for example by differences in methodologies and baselines used [103,16]. Science-driven international initiatives are addressing these challenges through indicator-specific community efforts. These quantify environmental, biology, and biodiversity change, facilitate in-depth assessments of uncertainties, observing system status, limitations, and science priorities, and drive innovations in monitoring and analysis techniques. Examples include the indicators of global climate change [64], the global carbon budget [67], the global sea level budget [238], the Earth heat inventory [232], and indicators on ocean acidification [47], and ocean deoxygenation [183]. International assessment reports such as those produced by the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science Policy Platform for Biodiversity and Ecosystem Services (IPBES) have now included definitions of indicators in their glossaries [97,100]. Indicator-based frameworks such as Biodiversity Indicators Partnership (BIP), and the Global Climate Observing System (GCOS) also provide scientifically sound definitions and criteria for scalable indicators [19,71].

In 2019, the decadal OceanObs'19 Conference brought together 2400 scientists from 60 nations to collectively produce Community White Papers outlining the state of the ocean observing system and priorities for the next decade [198]. The final Conference Statement highlighted the need for ocean indicators based on globally coordinated frameworks for ocean observations: *'Indicators based on ocean observations help nations meet national goals and targets of the United Nations 2030 Agenda on Sustainable Development, the Paris Climate Agreement, the Sendai Framework for Disaster Risk Reduction, the Convention on Biological Diversity, and the Small Island Developing States Accelerated Modalities of Action Pathway. Ocean observations are fundamental to increase the scientific and information content of indicators, contribute to the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) and are coordinated by Global Ocean Observing System (GOOS) and Group on Earth Observations (GEO).'* [155]. Despite this consensus, there is still no internationally agreed-upon comprehensive set of ocean indicators to characterize ocean physical, biogeochemical, biological and ecosystem variables. Likewise, a unified framework with standardized methodologies for evaluating their status is lacking, although it would align individual efforts and establish the shared understanding and baselines required for transparent, coherent and effective ocean monitoring. Reconciling the inconsistencies in methodologies, data sources, and baselines used to generate ocean indicators is essential to prevent the dissemination of fragmented or contradictory ocean information. Adopting an international, multidisciplinary approach will strengthen the coherence of ocean knowledge, providing more reliable insights for policy and decision-making.

To this aim, the Global Ocean Observing System (GOOS), whose main sponsor is the Intergovernmental Oceanographic Commission (IOC) of UNESCO, established a task team on ocean indicators, bringing together experts from various fields to propose a core set of indicators. Through international and multidisciplinary collaboration, the team seeks to establish a scientifically agreed-upon foundation for ocean indicators. Building on the Framework for Ocean Observing [131], this effort intends to improve the accuracy, consistency, and utility of ocean data for global monitoring and decision-making. Standardization is critical for aligning international initiatives, tracking progress under global environmental agreements, and providing actionable insights for adaptation, sustainable development, and ocean resilience.

Here we present the first outputs of this initiative, in the form of criteria and definition for viable ocean indicators, together with a set of pilot examples for their development. Building on ongoing international efforts such as in IPCC, and IPBES, and the GCOS indicator framework, we outline the methodological approach for producing standardized ocean indicators, discuss criteria for indicator development, and demonstrate their application. We define what a science-based ocean indicator is and identify the criteria that an indicator should meet as applied across the three disciplinary domains covered by the GOOS expert panels: ocean physics, ocean biogeochemistry and ocean biology and ecosystems. We examine the application of these criteria to nine pilot indicators identified by GOOS expert panels and explore opportunities for leveraging ocean indicators to inform decision-making, shape policy processes and guide scientific advances.

Table 1
Examples of definitions for climate and ocean indicators from various sources.

Indicator definitions	*Reference*
The Global Climate Indicators are a set of parameters that describe the changing climate without reducing climate change to only temperature. They comprise key information for the most relevant domains of climate change: temperature and energy, atmospheric composition, ocean and water as well as the cryosphere.	WMO [247]
A quantitative or qualitative factor or variable that provides a simple, measurable and quantifiable characteristic or attribute responding in a known and communicable way to a changing environmental condition, to a changing ecological process or function, or to a changing element of biodiversity.	IPBES [97]
Climate indicator - measures of the climate system, including large-scale variables and climate proxies.	*IPCC* [100]
A proxy climate indicator is a record that is interpreted, using physical and biophysical principles, to represent some combination of climate-related variations back in time.	IPCC [98]
A simple easy to understand tool to describe, measure and monitor a complex ocean phenomenon. The ocean indicator may change globally to locally, at different time scales, and can be utilized for ocean literacy, and to build a sustainable ocean observing system for holistic scientific assessment and stewardship.	Von Schuckmann et al. [231]
Marine ecosystem indicators are quantitative measurements that represent key attributes of interest.	Heim et al. [90]
An indicator can be defined as a 'measure based on verifiable data that conveys information about more than just itself'. This means that indicators are purpose dependent - the interpretation or meaning given to the data depends on the purpose or issue of concern.	BIP [18]

2. Ocean indicators: Definition and criteria

A science-based ocean indicator requires a robust, standardized methodology for its production and a sound narrative that balances the need for rigor with simplicity of application. This presents an inherent challenge in design but facilitates practical application. In general, a science-based indicator should aim to provide broad, easily understandable insights to a process or complex system and how this change in space (e.g. pattern, phenomena between locations and regions) and/or time (e.g. variations or trends). Building on the main definitions for indicators provided to date (Table 1), experts from ocean physical, biogeochemical, and biology and ecosystems disciplines, along with specialists in sustainability and international environmental diplomacy, have agreed on the following definition for science-based ocean indicators:

Ocean indicators refer to measures based on scientifically verified approaches and data that allow for the identification of the state in ocean phenomena across a range of temporal and spatial scales that are accessible to inform decision makers and beyond.

The definition emphasizes the need for verified scientific approaches grounded in peer-reviewed evidence, collected through standardized ocean observing procedures based on both in situ and remote sensing data, such as those adopted by the GOOS panels, and completed by standardized modeling efforts. '*Ocean phenomena*' encompass a variety of environmental characteristics (e.g., species distribution, salinity, temperature, sea level), processes (e.g., surface ocean heat flux, net primary productivity), or events (e.g., algal blooms, heat waves, transient ocean currents) that have distinct spatial and temporal scales but are equally informative about the state of the ocean and its biodiversity [74,75]. This definition requires that indicators be tailored to be informative for and accessible to decision makers and the wider public. This includes governmental (e.g., policy), organizational (e.g., executives), community-based (e.g., local leaders), Indigenous and Traditional (e.g., Elders & cultural leaders) decision makers, experts (e.g., scientists and advisors) and collaborative (e.g., multi-stakeholder groups and coalitions) bodies.

A foundation for the development of science-based ocean indicators is provided by existing international monitoring frameworks such as the Essential Ocean Variables (EOVs) and the Essential Climate Variables (ECVs) developed by the GOOS and GCOS international programmes. GOOS EOVs are defined as the minimum set of ocean variables that are needed to assess ocean state and variability for important global ocean phenomena, and to provide essential data for applications that support societal benefit. They are derived from sustained individual measurements, or combinations of measurements, that can be undertaken at global scale and in a cost-effective manner (Martin Miguez et al., submitted). GOOS define the EOVs and the panels of experts curate them and develop observational requirements for three main applications: climate, operational oceanography and ocean health. The ECVs cover atmospheric, oceanic, and terrestrial domains [20]. The oceanic ECVs include several of the GOOS physics, biogeochemistry, and biology and ecosystem EOVs. The Essential Biodiversity Variables (EBVs) are established by the Group on Earth Observations Biodiversity Observation Network (GEO BON), and use a time series of observations or modeled results to advance the use of biodiversity information at multiple levels of biology and ecosystems organization [151,161]. Essential Variable frameworks can serve as fundamental building blocks for creating indicators, as they represent the essential measurement foundation from which indicators are derived. Often, a single indicator may be developed from multiple EOV datasets, involving the setting of thresholds and combining with other data.

Applying clear scientific quality criteria to the endorsement and development of ocean indicators will facilitate consistency of content, identification of the data streams and methodologies needed, and ensure that they are scientifically robust and relevant. For indicators, variations exist in data availability, uncertainty characterization, regional specificity, in ocean practices (methodologies, protocols and standards), applications, and user priorities. Limited long-term observations, or delays in the availability of observational data, hinder the calculation of ocean indicators and uncertainty estimates. Uncertainty estimates help to detect real change with confidence (*e.g.,* real change rather than observational error). Many existing ocean measurements that seek to track change can benefit from more robust uncertainty estimates, including clear documentation of accuracy and precision, better metadata documentation (e.g., sensor stability, platform, or standards), and guidance on errors that may be due to the observing procedures. The building of some indicators also involves complex and varied methodologies which, if not adequately described, may affect transparency and implementation in operational services, assessments, or reporting mechanisms.

Clear quality criteria for ocean indicators production will also make them more understandable, usable, and accessible to decision makers, stakeholders, rights holders, and the public. These criteria should be based on methodologies that adhere to Findable, Accessible, Interoperable, and Reusable (FAIR) and Collective Benefit, Authority to

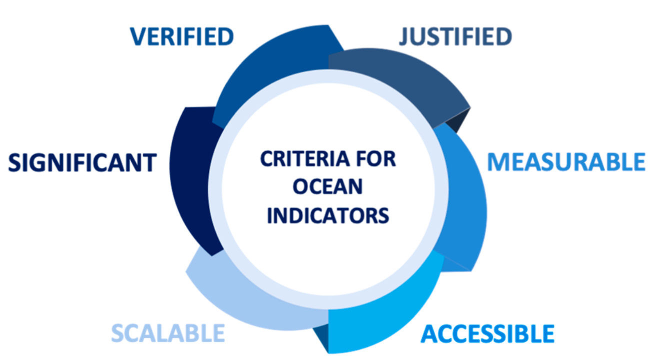

Fig. 1. Overview of the six science-based quality criteria identified by the GOOS cross-panel task team on ocean indicators, using the climate and biodiversity indicator criteria [19,246] as a starting point. Each of the six criteria must be met for the establishment of an ocean indicator.

Control, Responsibility, Ethics (CARE) principles for data and knowledge gathering [205,26], to boost credibility and reliability of ocean observing networks, including the delivery of information. By promoting transparency in EOVs or ECVs selection for indicator production, and in their implementation processes, the provision of clear criteria fosters accountability, ensuring reporting of change. Ultimately, science-based indicators that adhere to clear and commonly accepted criteria will provide a solid foundation for evidence-based decision-making, and enhance the effectiveness of indicators. Building on the successful implementation of the WMO and BIP criteria, GOOS has developed a comprehensive set of six specific quality criteria for ocean indicators (Fig. 1):

(1) **Verified.** The indicator must represent a state of an ocean phenomenon that relies on a peer-reviewed scientific rationale of the fully traceable indicator approach.

(2) **Significant.** The indicator must provide robust information on the state of an ocean phenomenon within a scientific framework.

(3) **Scalable:** An ocean indicator should be scalable spatially and temporally, and where possible interoperable.

(4) **Justified:** The indicator should be relevant to inform and support decision-making, and be understandable to a broad audience.

(5) **Measurable:** The indicator should be determined where relevant via one or more Essential Variable framework, such as EOVs, ECVs, or EBVs.

(6) **Accessible:** The ocean indicator should be provided whenever possible on a regular basis guided by CARE and FAIR principles, and enables past and near-term information, forecasts, and projections.

Ocean indicators should only be endorsed as **verified,** if they are generated using a method or an approach based on a solid theoretical background, evaluated through rigorous scientific analysis, and confirmed to be accurate and reliable, validated through peer review to ensure consistency and credibility. To be listed as **significant**, they will require to be grounded in a robust and rigorous scientific framework, considering uncertainties that may influence their interpretation, reliability, and the perceived accuracy of the data used in their calculation. To be **scalable**, ocean indicators should be applicable across different spatial scales (e.g., local, regional, or global levels) and temporal scales (e.g., extremes, short-term, seasonal, or long-term trends). Additionally, they should be based on interoperable information, meaning it should rely on consistent approaches, and can integrate with other datasets, systems, or models to enable seamless comparison, sharing, and analysis, enhancing its utility across various contexts and disciplines. The ability to downscale the indicator from a global to a regional/local level will help explain how various regions exhibit unique environmental patterns and understand the factors driving these differences. To be **justified,** ocean indicators will need to be clearly relevant for informing and supporting decision-making processes, addressing specific environmental, social, or policy needs. They will also need to be presented in a way that is accessible and understandable to a broad audience, including stakeholders, knowledge holders, decision makers, and the public, ensuring their practical value and usability. To qualify as **measurable**, indicators should be quantifiable and, where applicable, derived using established essential variable frameworks, which rely on an internationally coordinated governance for the global ocean and climate observing systems. Finally, to be **accessible,** ocean indicators should be made available regularly, ensuring consistent updates for users, which underlines the critical role of regular services for sustained data and indicator dissemination. They should follow CARE principles to respect data sovereignty and ethical considerations, including those of interest to Indigenous and Local Communities, and adhere to FAIR principles to maximize scalability over time and space and scientific utility. Additionally, they should include historical data, current information, and near-term forecasts or projections to support informed decision-making and planning.

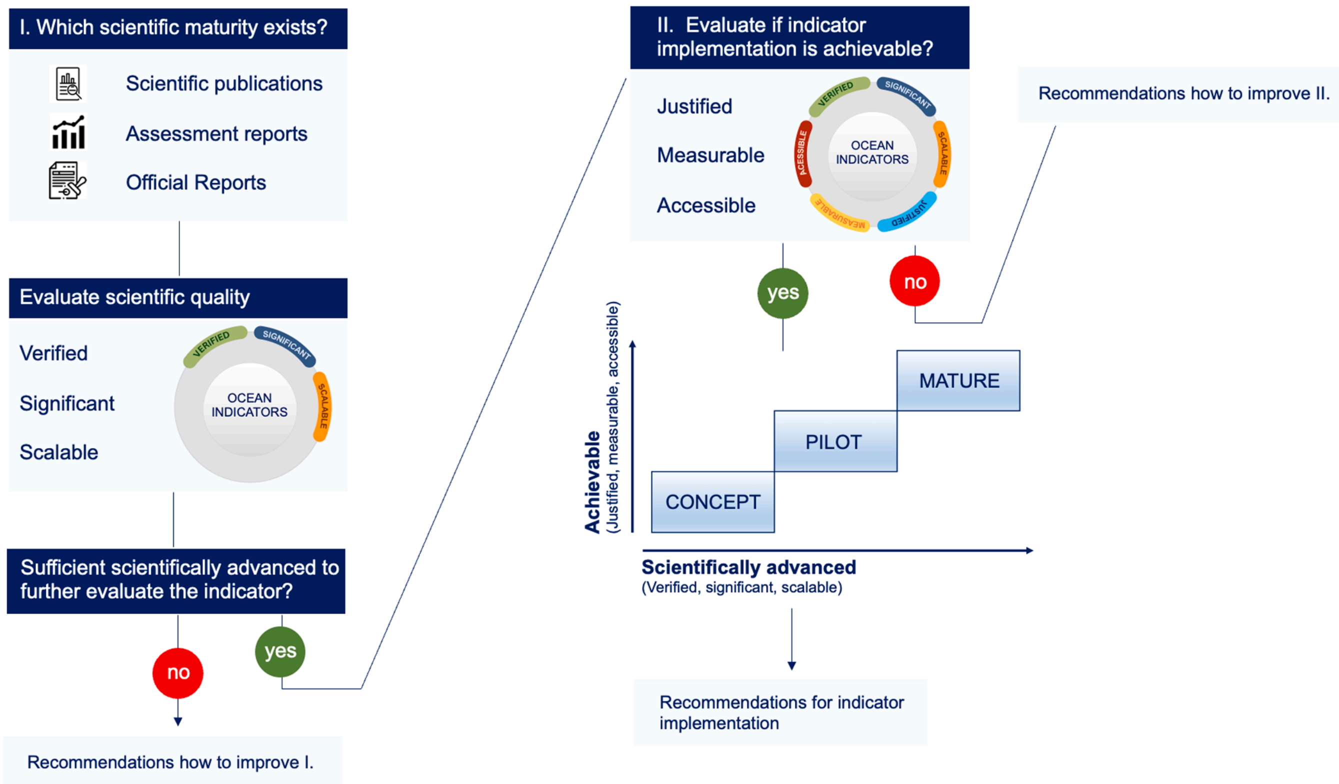

Fig. 2. A guide for applying expert judgment in the evaluation of a proposed ocean indicator. This illustration depicts the process that assessment experts should apply in evaluating and communicating the readiness level of a proposed indicator. It relies on assessing the scientific maturity and quality of the proposed indicator (criteria 1–3), and if its implementation is achievable (criteria 4–6), allowing to judge if the proposed indicator can be classified as at the "concept", "pilot" or "mature" stage. This approach is derived from the methods of Ara Begum et al. [13] and Mantovani et al. [135].

3. Evaluating ocean indicators

The above definition and quality criteria for ocean indicators are intended to enable their effective implementation. Following the methods of Ara Begum et al., [13] and Mantovani et al., [135], we propose a stepwise pathway for systematically assessing a candidate ocean indicator (Fig. 2). This framework allows for the development of expert-based recommendations for expanding the scientific capacity needed for effectively contributing to the indicator in question. In addition, this guided expert judgment enables informed recommendations on the observing systems needed to contribute data for estimating a specific ocean indicator. Finally, the framework supports decision-making and appeals to a broad audience.

The first proposed step in assessing whether a proposed metric is a viable ocean indicator is to assess how scientifically mature it is, based on criteria 1–3, i.e. on whether it is Verified, Significant, and Scalable. The scientific maturity of the indicator should also be evaluated based on peer-reviewed publications, i.e. on scientific literature and national and international assessment reports (Fig. 2). If the proposed indicator does not meet the criteria, a set of expert recommendations should be provided to enhance the scientific quality of the methodology, strengthen the rationale, and refine the uncertainty framework for its production, or to improve its scalability in space and time.

If the proposed indicator is scientifically mature, the expert assessment may proceed to assessment step II (Fig. 2). This assesses the maturity and readiness for routine implementation, for example in an environmental department, a policy framework, or an operational center. This step II focuses on three criteria (4–6): the availability of reliable data (measurability), the ability to update the indicator regularly (accessibility), and the relevance of the indicator for policy and beyond (justified).

If the expert assessment passes these initial two steps, results can be expressed as part of an assessment matrix (Fig. 2 lower right). This helps determine if the proposed indicator is concept, pilot or mature [219]. Outputs from the two steps include a set of expert recommendations needed to improve the scientific quality and/or to improve the implementation of limited and emerging ocean indicators. By adhering to these three structured steps, the proposed framework ensures that endorsed ocean indicators are scientifically robust and comparable across regions.

4. Application of Framework: Examples of Ocean Indicators

To illustrate the utility of the proposed framework, nine pilot ocean indicators were considered (Fig. 3). All align with the criteria outlined above, and integrated data from EOVs and ECVs to address various aspects of ocean health and climate variability. These indicators were selected by the GOOS expert panels to showcase the ocean indicator framework's ability to integrate diverse data sources, ensure standardization, and maintain scientific consistency. Suggestions for use of indicators that track these EOVs have already been made by the international community for global assessments, such as those conducted by the IPCC and IPBES. By adhering to a standardized baseline and by including estimates of uncertainty, these indicators offer consistent metrics that facilitate cross-comparison and trend analysis for multiple applications including in national, regional and global assessments of ocean variability and state, linking to temporal and spatial changes in stressors. These examples highlight how the proposed framework can be applied across multiple disciplines, ensuring scientific rigor and relevance to broader policy applications. While this paper presents nine pilot indicators as examples, other potential ocean indicators considering for example ocean circulation aspects, trophic ocean states or species abundance and habitat may be considered in the future.

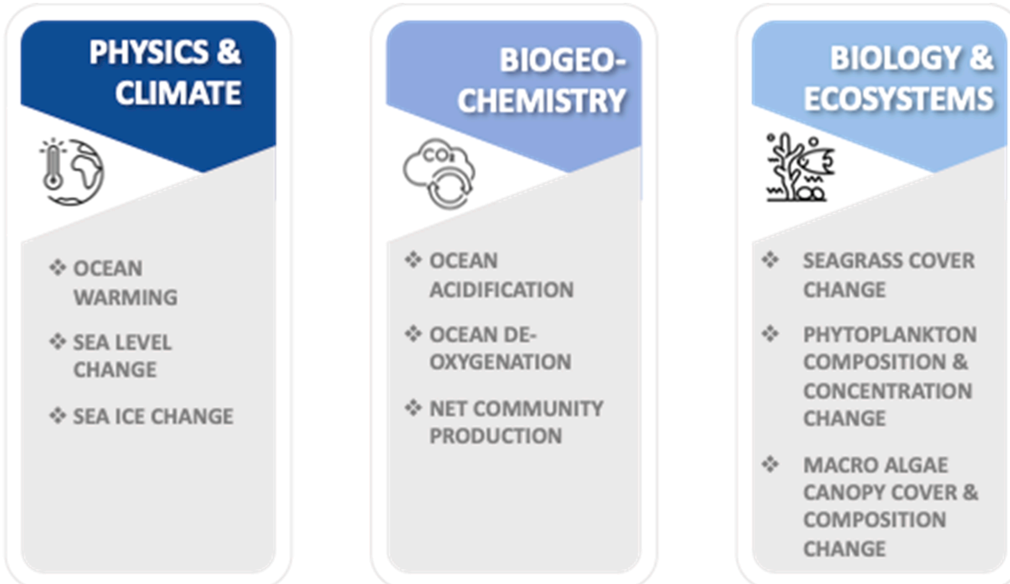

Fig. 3. The nine pilot indicators proposed by GOOS for three general disciplines: physics & climate, biogeochemistry, and biology and ecosystems.

1. Ocean Warming

Criteria for indicator scientific maturity

Verified: Integration of ocean temperature over depth provides a measure of heat stored in the ocean, and its rate of change offers insights on ocean warming [130,2], and on the Earth energy imbalance [232].

Significant: This indicator relies on a peer-reviewed scientific rationale, grounded in a robust and rigorous scientific framework, including a robust uncertainty characterization (e.g., [32,130,230]). The indicator is used in IPCC assessments [100].

Scalable: The indicator is scalable in space and time, with observing system limitations in continental shelves, coastal zones, and polar areas where there are not enough observations to characterize variations and trends at a local level (e.g., [233]). Before the Argo float era in the 2000's, sub surface observations were more limited and with higher uncertainties (e.g., [32]).

Criteria for indicator implementation status

Justified: This indicator is highly relevant for climate change monitoring and it manifests the role of the ocean as a sentinel for planetary warming. Changes over time of ocean heat storage provide insight into how fast surplus energy is accumulating in the Earth climate system due to human activities; about 90 % of this global signal is accumulating in the ocean [232,64]. This indicator also reveals that Earth system heating has been accelerating over the past century [145,201,33]. Ocean warming has implications for the ocean's biogeochemical processes and biodiversity variations and state [32,96,98].

Measurable: Ocean warming is measurable with well established methods outlined in the Essential Ocean Variable and Essential Climate Variables for surface and subsurface ocean temperature. The indicator combines in situ and full-depth estimates from in situ and remote sensing observations [32,86,137]. These allow for routine, repeated and frequent global views of the sea surface [146] and interior ocean temperatures. A limitation is that current autonomous technologies provide routine observations over large regions only to 2000 m depth [176], while the average depth of the ocean is about 4000 m and maximum depths exceed 10,000 m.

Accessible: The indicator is accessible from national (e.g., IAP,[1] NOAA[2]) and multi-national and international services (e.g., Copernicus, WMO). The fundamental observations largely follow FAIR principles. At projected time scales, the indicator is accessible via international assessment efforts (e.g.,[99,232,64]). For operational use, this indicator goes back in time to at least 1970, with some in situ observations available from the late 1800's but increasingly limited before that. Earlier historical observations are obtained by proxy from the composition of minerals in the sediment or structures of biological organisms (fossils). The indicator is best implemented based on an international intercomparison approach (e.g., ensemble mean of different products) to monitor continuous data quality with associated uncertainties.

Recommendations and research needs for maturing the indicator

This indicator is mature. To fully mature this indicator, continuing and expanding measurements of subsurface ocean temperature is highly recommended (Argo programme, and other), with particular socio-economic importance to improving observing infrastructure in high latitudes, confluence zones, the deep ocean and shelf and coastal areas [232,32]. Finally, more research and development is needed for ocean warming scalability to improve regional assessments and forecasts.

2. Sea Level Change

Scientific maturity

Verified: the Sea Level Change indicator delivers an integrated view on the melting of land ice, changes in groundwater drainage, and steric volume changes (changes in volume of a water mass due to variations in its temperature) [99,30].

Significant: This indicator relies on a peer-reviewed scientific rationale, grounded in a robust and rigorous scientific framework, including a robust uncertainty framework [157], and is integrated into IPCC assessments [98].

Scalable: This indicator is scalable in space and time, with data limitations before the year 1993 due to observing system limitations (e.g., Cazenave and Moreira, 2022).

Indicator implementation

Justified: Sea level change is highly relevant for climate change monitoring. Sea level rise increases the risk of coastal floods and consequent loss and damage [98]. Sea level rise has increased

[1] http://www.ocean.iap.ac.cn/pages/dataService/dataService.html

[2] https://www.ncei.noaa.gov/access/global-ocean-heat-content/

community and infrastructure vulnerability and food security risk, particularly in low-lying areas and island states [98]. Episodes of decreased sea level in an area also indicate marked changes in ocean circulation, including upwelling, nearby ocean currents, or wind effects [157].

Measurable: The indicator is measurable as it relies on the Essential Ocean Variable sea surface height. Depending on the measurement technique used, information on two forms of sea level change can be obtained. Relative sea level as obtained from tide gauges is referred to the height of the sea surface relative to the sea floor, and thus to land, at a given location (e.g., [235]). Sea level from satellites (from 1993 onwards) is linked to what is known as absolute sea level, which is the height of the sea surface at a given location relative to the reference ellipsoid (e.g., [1]). Locally, time series of several decades are available from tide gauge instruments. When combined at a regional scale, these measurements allow for understanding on the causes of sea level change.

Accessible: The indicator is accessible at national (e.g., NASA,[3] CNES[4]) and multi-national and international service level (e.g., Copernicus, WMO, PSMSL) for past information following FAIR principles. At projected time scales, the indicator is accessible via international assessment efforts (e.g., IPCC, 2021).

Recommendations and research needs for maturing

This indicator is mature. To further mature this indicator, it is essential to sustain the satellite platforms and *in situ* tide gauge and other monitoring, that allow research and development activities, and that are needed for characterizing uncertainties and biases at national and regional scales. Data rescue efforts of historical manual tide recordings are also important to help complete the historical record.

3. Sea Ice Change

Scientific maturity

Verified: This indicator provides an integrated view of sea ice state and changes in terms of mass, dynamics, area cover, and for characteristics that are important for atmosphere-ocean interactions, such as heat and carbon fluxes (e.g., [51]).

Significant: This indicator relies on a peer-reviewed scientific rationale, grounded in a robust and rigorous scientific framework, including a robust uncertainty framework (e.g., [125]), and is integrated into IPCC assessments (IPCC, 2021).

Scalable: This indicator is specific to the cryosphere, where it has been scalable in space and time from the 1970 s onwards (e.g., [190]). This indicator is integrated into IPCC assessments (IPCC, 2021).

Indicator implementation

Justified: Sea ice is an active system that controls the exchange of heat, water and carbon with the ocean, and is hence a fundamental actor in physical, biological and biogeochemical processes in the cryosphere (IPCC, 2019). Besides its role in affecting ocean circulation and processes (e.g., through water mass modification), sea ice plays a prominent role through the ice-ocean-albedo feedback, which is a central process amplifying high latitude warming [104,105,111,174,76]. Sea ice harbors various biogeochemical tracers and species at the base of the food chain, which play a central role in the biological carbon pump and support key higher trophic species [121].

Measurable: The indicator is measurable as it relies on the Essential Climate Variable [Sea Ice] which includes seven ECVs sea ice quantities: concentration, thickness, motion, age, surface temperature, albedo, and snow depth [125]. Metrics of sea ice require different observation techniques with each at a different maturity level. Sea ice concentration is at the most mature stage and can be obtained at (mostly) daily resolution from remote sensing techniques since late 1978 (e.g. [143, 126]). Long-term satellite-derived records are also available for sea ice motion (e.g. [123,208]), surface temperature (e.g. [115,152,36]), albedo (e.g. [175]) and snow depth (e.g. [194,253,184]), but at a lower stages of maturity, while sea ice thickness (e.g. [63,189] and age (e.g. [144,208]) are less mature and only available at lower temporal (thickness) and spatial (age) coverage.

Accessible: The indicator is accessible at national (e.g., Canadian Ice Service (CIS),[5] NOAA National Snow and Ice Data Center (NSIDC),[6] US national ice service (NIC)[7]; Finnish Meteorological Institute[8]; Danish Meteorological Institute,[9] Arctic and Antarctic Research Institute (AARI[10]) and multi-national and international service level (e.g., Copernicus Climate Change Service,[11] Copernicus Marine Service,[12] Centre for Environmental Data Analysis (CEDA) archive[13]; EUMETSAT The Ocean and Sea Ice Satellite Application Facility (OSI SAF)[14]) for past information following FAIR principles. At projected time scales, the indicator is accessible via international assessment efforts (e.g., IPCC, 2021) and has been in the focus of international model intercomparison projects such as the Sea-Ice Model Intercomparison Project (SIMIP) and the Climate Model Intercomparison Project (CMIP) (e.g. [177,196, 113]).

Recommendations and research needs for maturing:

This indicator is mature. Recommendations for this indicator include continued research and development efforts to improve the maturity of all sea ice ECVs [125], particularly thickness and snow depth, the regionalization of the indicator with focus on the Southern Ocean, and continued efforts to collect, quality-control, and make non-satellite observations of the sea ice environment available.

4. Ocean Acidification:

Scientific maturity

Verified: As the ocean takes up human-induced carbon dioxide from the atmosphere, ocean acidity increases [106]. The chemical expression is a decrease in pH and a decrease in the saturation state of carbonate ions (e.g. seawater aragonite, Ω_{ar}) [133]. These chemical changes are referred to as ocean acidification (e.g., [158,17]).

Significant: This indicator relies on a peer-reviewed scientific rationale, grounded in a robust and rigorous scientific framework, including a robust uncertainty framework [133,17,84], is integrated into IPCC assessments [98], and is essential to UN Sustainable Development Goal Target 14.3.

Scalable: The indicator is scalable in space and time, with limitations before the late 1980s due to measurement constraints (e.g., [72, 133]).

Indicator implementation

Justified: Carbonate ions and other biogeochemical compounds and specific elements change their state based on pH. These changes are critical for marine organisms, like corals, shellfish, and some plankton. Many of these build shells and skeletons using calcium carbonate. As a result, ocean acidification can impact marine life at the level of an individual organism by affecting its physiology or behavioral patterns [48, 61,169,38], and by altering population dynamics or altering community

[3] https://sealevel.nasa.gov/

[4] https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html

[5] https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/about-ice-service.html

[6] https://nsidc.org/home

[7] https://usicecenter.gov/

[8] https://en.ilmatieteenlaitos.fi/ice-conditions

[9] https://ocean.dmi.dk/arctic/icecover.uk.php

[10] https://www.aari.ru/en

[11] https://climate.copernicus.eu/

[12] https://marine.copernicus.eu/

[13] https://archive.ceda.ac.uk/

[14] https://osisaf-hl.met.no/

structure [48,87,88,241]. Measurements of any two of these parameters allow calculation of the remaining components of the inorganic carbon system, for example.

Measurable: The indicator is measurable as it relies on the EOV "Inorganic Carbon", which includes sub-variables for dissolved inorganic carbon (DIC), total alkalinity (TA), partial pressure or fugacity of CO_2, and pH. Any two of these parameters can be used to calculate the remainder of the inorganic carbon system, including Ω_{ar}. Prior to the 1980s, the availability of measurements for some key parameters of ocean acidification is limited and uncertain, but has since then gradually improved, following the refinement of spectrophotometric pH measurement methods, the establishment of standard protocols, access to reference materials [45,46], and international coordination efforts through GO-SHIP, GOA-ON, GLODAP and others (e.g., [206]). Most recently, the advent of the biogeochemical Argo network has strongly increased potential measurement availability [35], supported by advancement in statistical methods (e.g., [72,83,133]), although there are still unresolved issues around the consistency of ocean pH measurements for the global observing system (e.g. [122]).

Accessible: The indicator is accessible at multi-national and international service level (e.g., Copernicus, WMO, GOA-ON, IOC-UNESCO, EuroStat) for past information following FAIR principles. At projected time scales, the indicator is accessible via international assessment efforts (e.g., IPCC, 2021).

Recommendations and research needs for maturing:

This indicator is mature. Recommendations for this indicator include continued sensor development, including development of sensors for measuring DIC and TA, improved accuracy of existing sensors measuring pH and CO_2, further development of sensors that are calibrated in situ, and the development of lower-costs sensors that can be deployed at scale [95]. Improved access to certified reference materials is also critical for ensuring the global observing community can continue to validate the quality of ocean acidification measurements [95].

5. Ocean Deoxygenation

Scientific maturity

Verified: Oceanic measurements of dissolved oxygen have a long history, and oxygen (O_2) is the third-most often measured water quantity after temperature and salinity [70]. Sub-surface oxygen concentrations in the ocean everywhere reflect a balance between supply through circulation and ventilation and consumption by respiratory processes by marine organisms, the absolute amount of oxygen in a given location is therefore very sensitive to changes in either process [70]. Oceanic oxygen has been therefore proposed as a bellwether indicator of climate change [82]. It has decreased over the last few decades due to ocean warming and increased loads of nutrients and organic wastes particularly in coastal waters, this process being called deoxygenation ([21]a, b).

Significant: This indicator relies on a peer-reviewed scientific rationale, grounded in a robust and rigorous scientific framework, including a robust uncertainty framework (e.g., [202,203,44]; R. E. [112,193,21,119]), and is integrated in the IPCC assessment [98,99] and European Marine Board agenda [80].

Scalable: The ocean deoxygenation indicator can be provided at regional and global scales, thanks to the existing data sets (e.g., [80]). It can be evaluated since the 60's, however expanded observation is immediately required for more accurate documentation and prediction of ocean oxygen changes, and for improved understanding of its causes and consequences.

Indicator implementation

Justified: The implementation of a full-fledged observatory of oxygen in the ocean is critical to measure and understand the large (mostly) decreasing trends in the concentrations of dissolved oxygen in the ocean over these past decades. These deoxygenation trends have important implications for our understanding of anthropogenic climate change. Deoxygenation disrupts marine ecosystems, affects fish stocks and aquaculture and leads to loss of habitat and biodiversity. Deoxygenation can accelerate global warming via enhanced marine production of greenhouse gases under low oxygen conditions.

Measurable: This indicator is measurable as it relies on the Essential Ocean Variable Oxygen with sub-variable dissolved oxygen [11] with a high maturity level in observation techniques (https://www.ioccp.org/index.php/oxygen). The Winkler [244] titration method performed on seawater samples is still the reference method for measuring oxygen in the ocean. Modern variants of this method still underpin best practices in oceanographic oxygen measurements today [120]. In the 70 s, the inclusion of Clark oxygen electrodes [34] in a standard Conductivity-Temperature-Depth device allowed continuous measurements of oxygen in the water column to be made. Later in the 2000s, low-power sensing optical sensors, called optodes, with good long-term accuracy and precision, have permitted oxygen to be measured at increased spatial and temporal ranges when implemented on lagrangian autonomous platforms such as Argo floats or gliders (e.g. [79]). The data quality that can be obtained from optodes relies on their calibration method.

Accessible: The indicator is accessible at national (e.g., WOD) and multi-national and international service level (e.g., EMODnet, Copernicus, GLODAP) for past information following FAIR principles. At projected time scales, the indicator is accessible via international assessment efforts (e.g., IPCC, 2021).

Recommendations and research needs for maturing:

This indicator is at the pilot stage. Recommendations for this indicator include continued efforts to collect, quality-control, and make *in situ* observations of dissolved oxygen available, sustaining Eulerian and Lagrangian observing systems acquiring oxygen data to maintain long-term monitoring, and particular research and development activities for advancing our knowledge on ocean oxygen dynamics, including deoxygenation, meaning for instance better understanding historical, current and future ocean deoxygenation rates, or better understanding how deoxygenation will impact marine life and ecosystems, from populations to ecosystems [119].

6. Net Community Production (NCP)

Scientific maturity

Verified: Net Community Production (NCP) is an indicator that represents the metabolic state of the system and allows the evaluation of the capacity of an ecosystem to produce or consume dissolved oxygen and CO_2. It is fundamental in efforts to evaluate possible sources and sinks of CO_2 (i.e., acting as a CO_2 source from the ocean to the atmosphere, or a sink where atmospheric CO_2 may be absorbed and removed from contact with the atmosphere) (e.g. [207]). This indicator provides an estimate of the amount of organic carbon that can be exported to depth [148,53].

Significant: The Net Community Production (NCP) is the amount of photosynthetically produced organic carbon available to heterotrophs (e.g., bacteria, zooplankton, fish). It is the difference between the Gross Primary Production (GPP) and respiration by autotrophs and heterotrophs (i.e., community respiration, CR) [53]. NPP (Net Primary Production) is the net biomass production by autotrophs after autotrophic respiration, and represents the rate at which food and energy are generated for food webs to function [127,187,31]. The NCP indicator relies on a peer-reviewed scientific rationale, grounded in a robust and rigorous scientific framework, including a robust uncertainty framework (e.g. [24,27,101,108,242,49].

Scalable: NCP methods rely on budget calculations to partition observed tracer variations into physical or biological processes occurring over timescales greater than a few hours or a day [101]. Presently, multiyear in situ and remote sensing NCP time series are feasible at near-weekly resolution from several in situ methods and from remote sensing observations. In situ NCP series use consecutive or simultaneous ship or Argo float deployments at local scales. Results, however, are sensitive to the choice of tracer used in the budget calculations and uncertainties in the budget parameterizations employed across different NCP approaches. The indicator is scalable in space and time, with the above limitations [101].

Indicator Implementation

Justified: Monitoring the estimates of NCP is instrumental to understanding the future ocean functioning regarding delivery of regulating ecosystem services (e.g. carbon sequestration) [237]. NCP determines if an ocean region is net autotrophic (net production, indicated by NCP >0) or net heterotrophic (net consumption and NCP <0). GPP measures community-wide photosynthesis, representing the total production of organic carbon (if reported as gross carbon production -GCP-) or O2 (if reported as gross oxygen production -GOP-) by autotrophs (e.g., phytoplankton, cyanobacteria) and represents the photosynthetic energy available to the entire food web [101].

Measurable: This indicator can be estimated based on measurements of Essential Ocean Variables such as Oxygen, Particulate Organic Carbon (sub-variable of Particulate Matter EOV), Nitrate (sub-variable of Nutrients EOV), and Ocean Colour combined with estimates or measurements of total alkalinity (TA) and dissolved inorganic carbon (DIC), both sub-variables of the Inorganic Carbon EOV. Well matured observation techniques exist for all of these measurements, including in situ and remote sensing techniques [14,117,165,171,186,149]. These tracers are selected because their concentrations in the sunlit ocean are impacted by primary production (photosynthesis and respiration). Other sources and sinks, such as exchange across the air–sea interface, transport and/or sinking and grazing, also impact the concentrations of these tracers. A variety of approaches has been used to estimate the NCP indicator, with early methods using natural seawater samples incubated in light and dark bottles and measuring the evolution of O2 or with 18O-labelled water (GOP; e.g. [60]) to trace temporal changes in O2 production under realistic incubation conditions. Sampling via instrumented moorings similarly enabled high resolution time series of NCP estimates at fixed stations [239,57]. Yet, all these approaches required tradeoffs between temporal, horizontal, and vertical measurement resolution. There were also attempts to derive NCP estimates from satellite data together with measurements of changes in O2 (e.g. [207]). Furthermore, the advent of autonomous platforms such as Argo floats and gliders made this indicator scalable in space and time [101,160,25,37,93]. Large uncertainties in alterations to NPP in response to climate change exist [204] as well as for the total open ocean respiration [43]. Remote sensing estimates have led to better understanding of the distribution of NCP, and helped understand the link between surface NPP and biodiversity and abundance of organisms in the ocean [148,168].

Accessible: The indicator is accessible at basin scale (e.g., Table A1 in [101]), globally from multiple remote sensing products and services [117,14,186] and at international service level (e.g. BGC-Argo float data GDAC, NASA Ocean Color, Oregon State University Ocean Productivity, NOAA CoastWatch) following FAIR principles.

Recommendations and research needs for maturing of the indicator:

This indicator is at the pilot stage, and as such requires dedicated efforts leading to its maturity across the required scales. Recommendations for this indicator include continued research and development efforts to improve the maturity of all EOVs involved in its determination, including development of sensors for measuring TA and DIC, improved accuracy of existing sensors measuring O_2, pH and nitrate, improving the combination of remote sensing and in situ observations, and quality controlling these measurements [95]. To facilitate global-scale determinations of the carbon export potential, the development of lower-costs sensors to be deployed at scale [95], and improved algorithms for satellite remote sensing, including evaluation of changes in productivity, are also critical.

7. Seagrass Cover Change.

Scientific maturity

Verified: Changes in seagrass cover have a significant impact on ocean services [225]. Seagrasses have a global distribution (except in Antarctica). They grow mostly in soft sediments, bioengineer their local environment and are sensitive to various stressors [153,225]. Because seagrass meadows represent a foundational habitat for many species, Seagrass Cover Change is an important indicator of marine biodiversity status and changes.

Significant: Seagrass beds are important for fisheries and biodiversity, carbon sequestration, and storage as well as stabilizing coastlines [50,65,154,153,224,226,227]. The seagrass cover change indicator relies on a peer-reviewed scientific rationale, grounded in a robust and rigorous scientific framework [141,178,225,250]. It is integrated into World Ocean Assessments [249,248], IPBES [97] and is important to the UN Sustainable Development Goal Target 14, especially 14.1 (reduce marine pollution) and 14.2 (protect and restore ecosystems).

Scalable: The Seagrass Cover Change indicator can be provided at local to regional to global scales. At present, while some local areal extent estimates have high confidence [167], regional to global estimates have low confidence because mapping efforts are patchy and have high uncertainty [141]. Further, there is a minimum of FAIR seagrass data [141]. Substantial efforts are being made to address this to enable this indicator to be scalable in space and time with higher confidence.

Indicator implementation

Justified: Extent of natural ecosystems is one of the headline indicators for Goal A of the Kunming-Montreal Global Biodiversity Framework. Seagrass areal extent directly contributes to this headline indicator. Change in seagrass cover, species composition and the distribution is relevant to coastal system functioning, natural forms of coastal protection and carbon storage and sequestration potential (blue carbon). Changes in seagrass cover will affect the quality and extent of essential habitat and nursery areas for many associated species [128,195,225,226,89]. Seagrass is affecting water quality positively, but is also sensitive to degradation in water quality. Although seagrasses comprise in the order of 0.2 % of the world ocean, they are estimated to contribute > 10 % of all carbon buried annually in the sea [65]. Vigorous photosynthesis by seagrasses can also reduce the acidity of surrounding water by removing dissolved carbon dioxide.

Measurable: Seagrass cover change is derived from the EOV Seagrass Cover and Composition. This EOV consists of three sub-variables; Seagrass percent cover, species composisiton and areal extent. Seagrass percent cover and species composition is typically measured in the field. Most commonly it is measured with quadrats (<1 m^2) and visually estimated directly in the field or through images. Seagrass areal extent is most typically evaluated using different remote sensing methods. This can include observations from surface vessels or from underwater surveys. Some approaches use visible images, including photography and video from autonomous airborne platforms (drones) and observations collected with cameras attached to animals that repeatedly swim across a region (e.g., [69]). Substantial progress has been made in mapping seagrasses over larger regions using high spatial resolution satellite images [132,181,234,229].

Accessible: Substantial seagrass presence records are available in the Ocean Biodiversity Information System (OBIS) as polygon and individual geographic data points, and in EMODnet as geospatial data (geotiffs/shapefiles) the latter for the European Seas. Increasingly these records have other information such as cover (density of seagrasses), productivity, and other metrics. At present, databases for regional and global seagrass cover are based on incomplete observations that have high uncertainty [141]. The World Conservation and Monitoring Centre's (UNEP-WCMC) seeks to aggregate observations into a "Global Distribution of Seagrasses" database [218], in parallel with OBIS that is focusing on seagrass EOV data.

Recommendations and research needs for maturing of the indicator:

This indicator is at the pilot stage. There is substantial work needed to achieve single as well as repeated, routine seagrass percent cover, species composition and areal extent surveys that follow FAIR principles to make data accessible. Additional work is needed for the seagrass observing community to converge on interoperable protocols and on Standard Operating Procedures (SOPs). The community needs to work toward accomplishing this and report a minimum of the EOV observations with metadata.

8. Phytoplankton Concentration and Composition Change.

Scientific maturity

Verified: Phytoplankton is a key indicator of ecosystem health and plays a vital role in essential ecosystem services such as food provision and biogeochemical cycling. As such, changes in the overall composition of phytoplankton is increasingly recognized as important to understand the overall health and structure of aquatic food webs. Phytoplankton concentrations are also used as indicator of local water quality, including eutrophication or the presence of harmful algae blooms. Also, phytoplankton monitoring provides information about the general status and trends of marine ecosystem health, about greenhouse gas exchange across the ocean surface, and as tracers of ocean circulation, among many applications (see series of reports produced by the International Ocean Colour Coordinating Group ([94]; see also [166,139]).

Significant: A comprehensive review of the value of phytoplankton is provided by Estes et al. [54] and Grigoratou et al. [81]. Phytoplankton represent food at the base of most marine food webs. They also play a key role in the uptake and generation of gases such as oxygen, carbon dioxide, nitrogen oxides, and other gases, and in the cycling of elements in the water column. The phytoplankton are responsible for about half of the world's annual primary productivity [54]. They reproduce and disperse rapidly, largely carried by ocean currents, although many have the ability to swim or control buoyancy and therefore move vertically in the water column [136,142]. The biodiversity of phytoplankton, specifically their functional traits, can define how food webs may be characterized in any one region at any time. Phytoplankton are also relevant when considering the drivers of ecosystem structure. For example, top-down ecosystem control occurs when predation and consumption of phytoplankton dominates, and effects of availability of phytoplankton cascade down the food chain. Instead, bottom-up control occurs when phytoplankton production and abundance are controlled by resources (such as nutrient limitation controls), and this, again, has impacts on the food web. The short-term, seasonal to interannual variations in phytoplankton concentration at any one location has significant implications for food web integrity and health (e.g., [66,164]). While most phytoplankton may be considered important to food webs in this context, some phytoplankton can be harmful, and toxic blooms can lead to mass mortality of fish and other organisms, hypoxic conditions, and can affect human health and the economy of areas affected.

Scalable: Measures of the concentration or abundance of phytoplankton are among the most common observations in marine ecosystem research and in operational monitoring. These measurements are often also done in an interoperable way, as concentration of particular phytoplankton pigments such as chlorophyll-a, or for composition as cell counts. These are scalable. A limitation is that in situ data are reported in different formats and through different platforms, many of which are not interconnected, and therefore scaling to regional or global assessments is not straightforward. Ocean color satellites have provided coverage of global surface ocean phytoplankton concentration as chlorophyll-a concentration estimates since 1976, and near continuous observations since 1997. Measurements of the composition of the phytoplankton have not been as common or accessible and may be collected and counted via several different methods, which has made it more difficult to aggregate to regional or global assessments. However, this is possible and can be translated into FAIR data as demonstrated in the initiative to standardize and document historical compositional data across Australia [41].

Indicator implementation

Justified: Changes in phytoplankton are considered among the most sensitive ecosystem responses to both anthropogenic pressure [12] and global environmental/climate change [243]. In addition, perturbations in biogeochemical cycles can also result in harmful algal blooms (HABs) and alter the overall health of marine habitats and are in many ways, the foundation for the 'blue economy' [22]. Under the Global Ecosystem Typology phytoplankton are identified as a functional group of Epipelagic Ocean Waters in support of the monitoring system for the Kumming-Montreal Global Biodiversity Framework. The plankton manifesto [212], a collaborative resource involving 30 international experts, advocates for 'plankton based solutions' to address 'The Triple Planetary Crisis' using emerging and existing technologies.

Measurable: Phytoplankton concentration and composition can be derived using measurements listed under the Phytoplankton Biomass and Diversity EOV and products considered under the Ocean Colour EOVs. The phytoplankton biomass and diversity metrics also form part of the plankton ECV. Phytoplankton composition observations are often localised and collected with nets or bottles. At larger regional and global scales, phytoplankton concentration is routinely and repeatedly evaluated by various in situ methods (autonomous buoys, gliders), ship observations, and by satellite remote sensing (Phytoplankton Biomass and Diversity EOV, Ocean Colour EOV). Cyanobacteria, while technically encompassing several taxonomic orders of bacteria, are often included in phytoplankton surveys for phytoplankton biomass (as a stock) and productivity (the rate of change of biomass per unit time and unit area or unit volume). Ocean Best Practices standardized methods for quantifying microscopic and molecular counts of phytoplankton have been developed and adopted [110]. The International Ocean - Colour Coordinating Group (IOGCC) also has a collection of Ocean Best Practice documents on protocols, including those for Harmful Algal Blooms.

Accessible: The regional and global phytoplankton concentration indicator is accessible from multiple national agencies (e.g., NASA Ocean Color website, NOAA CoastWatch, Copernicus Marine Services, and numerous regional data services provided by local groups). The satellite observations follow FAIR principles. Limited regional and global assessments of biomass variability and trends were conducted by the International Group for Marine Ecological Time Series (IGMETS; [124]). Global databases of ocean color EOV sub variables, including phytoplankton concentration, composition, and bio-optical parameters are available from the NASA SeaBASS database,[15] OBIS,[16] and Valente el al. [228].

Recommendations and research needs for maturing of the indicator:

This indicator is mature. The underlying EOV for this indicator can continue to develop by concentrating on methods of standardising collection for compositional samples and encouraging the use of accepted taxonomy references such as WoRMS[17]). Measurements should also embrace new technologies to enhance information collections. For example, improvements in flow imaging microscopy, in equipment such as FlowCam, and the associated AI image recognition software, for example Ecotaxa,[18] will make processing samples for composition much more efficient and accessible to those without the necessary taxonomic skills. Advances in eDNA and molecular techniques could also make sampling more accessible. However, automated methods and molecular tools still require a continued investment in taxonomy, particularly in the development of robust libraries and databases required to support the automated analysis of samples. To facilitate this, maintaining and supporting trained taxonomists remains essential. For concentration measurements the availability of hyperspectral ocean color satellite sensors, such as the PACE Ocean Color Instrument (PACE OCI), provide an opportunity to conduct advanced research into detection of

[15] https://seabass.gsfc.nasa.gov/
[16] https://obis.org/
[17] https://www.marinespecies.org/index.php
[18] https://ecotaxa.obs-vlfr.fr/

phytoplankton functional groups discriminated by their relative concentration of different pigments.

9. Macroalgae Canopy Cover and Composition Change.

Scientific maturity

Verified: Macroalgal forests and intertidal canopies are iconic on rocky subtidal and intertidal reefs around the world. These diverse ecosystems provide roughly 10 times the net primary production of coastal phytoplankton [163]. Their high biomass and complex structure enable many other functions and services including– provision of nursery areas [102,162], human food resources, protection from coastal erosion, and contribute substantial biomass towards blue carbon [62]. Experimental studies validate their sensitivity to warming, nutrient shifts, and invasive species [197,39]. However, a lack of standardisation for global metrics such as cover and composition, for example % canopy loss and species turnover rates along with variation in existing methods such as transect and drone surveys can vary regionally, hindering global comparisons.

Significant: Macroalgae are critical for SDG 14 (Life Below Water) and the Kunming-Montreal Global Biodiversity Framework (Target 2: ecosystem restoration) and serve as early warning indicators for ecological tipping points for coastal eutrophication (Teicherberg et al., 2010), overfishing [200], and warming (Suskeiwicz et al., 2024). For example, kelp declines in Tasmania due to marine heatwaves [156] and climate driven range expansions of urchins (Ling 2008). Further, due to their role as primary producers, we are beginning to see a limited integration of macroalgae into national biodiversity assessments (e.g., for blue carbon as in [140]).

Scalable: Spatial scalability is possible with satellite-derived canopy metrics (Bell et al., 2021) and drones to enable broad-scale canopy mapping (see [85] for an example in Norway or [29] for California) or other novel technological solutions [28]. However, there are limitations to these methods. Turbid coastal waters can limit optical remote sensing. Remote sensing and sidescan sonar methods do not capture understory species diversity. Records are also limited in temporal extent by when technology was first employed. Temporal scalability, however, exists from long-term human observed datasets in regions like California [118], Australia's Great Southern Reef [251], the UK (Hawkins et al., 2022), and more. Many national governments and private companies conducting ecological impact assessments have long-term macroalgal records spanning decades. However, not all records ate discoverable and accessible.

Is the indicator implementation achievable?

Justified: Macroalgal forests provide a sensitive and well understood indicator of changing coastal marine environments [39]. They are also models for understanding more complex interactions influencing marine communities [55]. Under the Global Ecosystem Typology, kelp forests are identified as a functional group in support of the monitoring system for the Kunming-Montreal Global Biodiversity Framework. Macroalgal forests are directly tied to blue carbon strategies (kelp contributes ~3 % of global ocean carbon export; [116]), and the loss of macroalgae correlates with fisheries collapse (e.g., abalone in California sensu [182]) providing clear links to policy, management and economies.

Measurable: Change in macroalgal cover and composition is derived from the macroalgae cover and composition EOV. The macroalgae cover and composition EOV forms part of the Marine Habitats ECV under GEO BON's Essential Biodiversity Variables (EBVs). Global interoperability is a challenge (e.g., Europe uses % cover; Australia uses biomass density, *Macrocystis* forests are often assessed with stipe counts) and taxonomic reporting resolution varies (e.g., species- or genus-level vs. functional group). Further, how to compare intertidal and subtidal shifts is currently understudied.

Accessible: This indicator is accessible at the OBIS (Ocean Biodiversity Information System), GBIF (Global Biodiversity Information Facility), and regional portals (e.g., EMODnet). Many long-term monitoring sets are not public or even digitized, as they may come from government or industrial monitoring programs. Indigenous/traditional knowledge (e.g., Māori kelp harvest records as in [240]) are rarely digitized or CARE-compliant (https://www.gida-global.org/care) despite containing some of the oldest knowledge. While some academic data sets are not digitized, the growth of data sharing and large-scale databases (e.g., OBIS, the Environmental Data Initiative, etc.) have begun to remedy this situation.

Recommendations and research needs for maturing of the indicator:

This indicator is at the pilot stage. In terms of standardisation, it is recommended that unified metrics such as canopy area, loss %, and functional group shifts are developed by partnerships with GEO BON and/or GOOS to align with the Global Ecosystem Typology for kelp forests [114]. It is recommended for the macroalgal monitoring community to develop and adopt community standards for data recording. Further, it is recommended that technology such as satellite data, eDNA metabarcoding (including the development of global barcoding libraries such as [252]), along with low cost sensors (e.g., underwater photogrammetry rigs) be standardized along with standard operating procedures prioritizing ease-of-use, especially for data poor regions (such as Africa and Southeast Asia). Priority actions include: 1) adoption of standardised metrics and data schemas in temperate regions with existing data (e.g., NE Pacific and Australia/New Zealand); 2) expand training for monitoring and data creation/deposition in data poor regions; 3) expand monitoring to polar regions potentially using eDNA and ROVs. 4) Integrate Indigenous knowledge and improve CARE compliance, such as working with communities of the circumpolar Arctic [170,236,5], New Zealand [42,150], many small island states and territories [77,211], and of other locations [129].

5. Conclusion

The present efforts to foster an international dialogue and develop a robust and comprehensive framework for ocean indicators lay the groundwork for advancing the effective application of ocean indicators, as outlined in this article. Through a multidisciplinary approach, this initiative has provided a clear definition and co-developed criteria for ocean indicators. This study presents a structured framework designed to standardize and enhance the development of scientific ocean indicators that can improve current ocean monitoring systems. By integrating scientifically validated methods, harmonized data sources, and clear uncertainty quantification, the proposed framework offers a solid foundation for generating indicators that not only track the ocean state, but also provide outputs for application in informing policy and decision-making.

The launch of the first set of pilot indicators (Section 4) marks a significant milestone. The ambition behind introducing a set of pilot ocean indicators supported by GOOS is to generate momentum within the international community by demonstrating the tangible value of robust ocean indicators. These pilot indicators will act as a foundation for future steps, such as developing comprehensive transdisciplinary ocean narratives by showcasing how shifts in the ocean state directly impact economic growth, livelihoods, and societal well-being (Fig. 4). For example, this framework opens avenues for reflecting understanding built on multiple knowledge systems including those held by Indigenous Peoples and shared across local communities [220]. Climate change impacts on Indigenous Peoples and local communities are ongoing, tangible, widespread, and affect multiple elements of their social-ecological systems [172,192]. The integration of local and indigenous knowledge with science is a promising tool to increase the climate change resilience of communities during crises such as from natural hazards [52,8,91].

Indicators presented here should not be viewed as independent. A co-design process focused on addressing the causes and consequences of a particular application or ocean problem may require consideration of

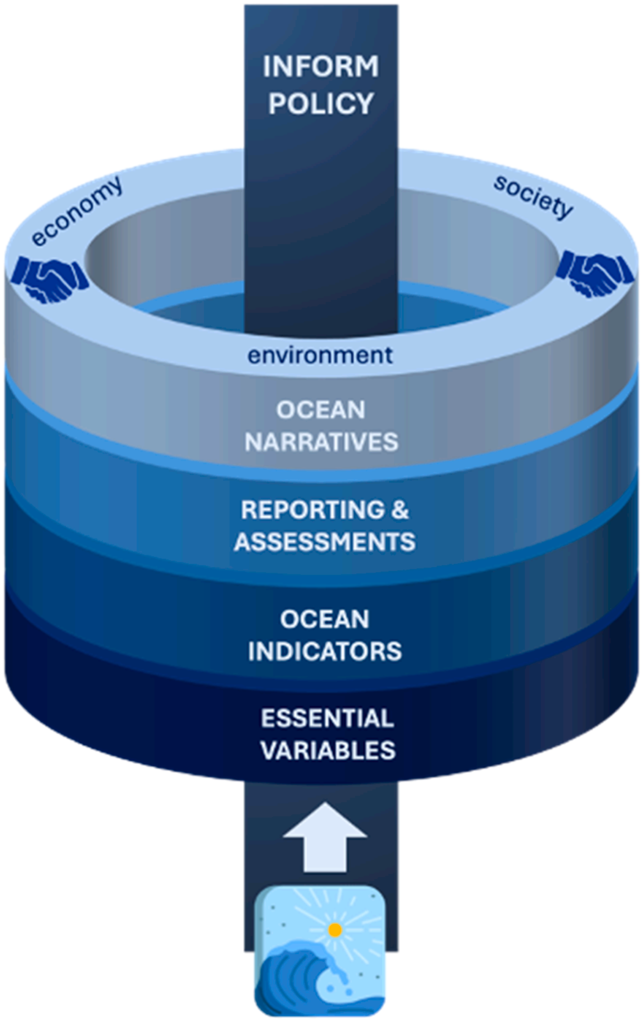

Fig. 4. The multi-layered chain to streamline evidence-based and tailored ocean knowledge transfer from science to policy.

sets of indicators. These should be evaluated together to understand change and the driver(s) of change, to help model and forecast impacts and evaluate possible scenarios relevant to weigh policy options. Often, just monitoring one indicator may be helpful to detect change in a particular environmental state. But ancillary and complementary indicator monitoring is useful to manage impacts and possible consequences of change in a particular ocean process, resource, or area. For example, in order to understand and model changes in ocean acidification indicators, the physical and biological drivers of those changes must also be measured and understood (for example, [59,58,73,10]).

Coastal communities would benefit from information and resources to support active adaptation to local impacts [159]. The proposed GOOS pilot indicators are relevant for adaptation planning and can strengthen associated decision-making capacity for local communities such as for sea level (e.g., [134]), sea ice (e.g., [15]); ocean warming (e.g., [3]); ocean acidification [6,78] or ocean deoxygenation [109]. For this purpose, the scalability of ocean indicators to regional and local scale is essential to provide relevant area- and context-specific information.

The next phase of this initiative is to expand the pilot indicators into a robust, globally recognized framework for ocean indicators. This will require coordinated efforts to further validate and refine each indicator's methodology and applicability, ensuring they meet the needs of diverse stakeholders from policy makers to local communities. A key step is adopting global standards and best practices for consistent data collection and reporting. The development of indicators extends the functionality of Essential Variables so that they can be incorporated into a broader set of assessments undertaken at varying scales and therefore deliver some clear guidance to the in terms of national monitoring and reporting. Building on the Essential Variable frameworks, this initiative complements existing climate (GCOS) and biodiversity (BIP) indicators, addressing a critical gap in the international discussion on the ocean's role in the broader environmental context. Strengthening collaboration among academia and international organizations will then be essential to broaden the use of these indicators and incorporate them into global frameworks and services.

Ongoing engagement with stakeholders will help to iteratively refine the indicators, aligning them with emerging science and societal needs, and ensuring they effectively capture the complex, evolving dynamics of ocean health and sustainability. Also, these indicators are pivotal in advancing our understanding of how the ocean's health interacts with Planetary Boundaries [173,179,180,199]. By systematically tracking ocean change, they will help us assess where we stand concerning critical thresholds—such as ocean acidification, biogeochemical cycles, and climate regulation—that define the safe operating space for humanity. Aquatic deoxygenation has been proposed as an additional planetary boundary process that is critical to the integrity of Earth's ecological and social systems, and that both regulates and responds to ongoing changes in other planetary boundary processes [183]. Refinement of the ocean acidification boundary has also been proposed by extending it into the ocean's interior so that it also represents the functioning and habitability of the planet more generally (Findlay et al., 2025, in review). This knowledge will not only inform us on how close we are to crossing these boundaries but will also provide actionable insights to prevent or mitigate the risks of transgressing them, supporting global efforts to maintain a resilient Earth system.

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Data availability

No data was used for the research described in the article.

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