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Bridging the *in situ* data gap: a satellite- and model-based framework for operational monitoring of marine harmful algal blooms and temperature-related threats in emerging economies

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Emerging and developing economies often face constrained financial, technical, and institutional capacities to establish and maintain the ocean-based *in situ* observational networks that underpin marine decision support applications. This limitation heightens their exposure and sensitivity to the cumulative impacts of marine environmental hazards, including harmful algal blooms and marine heatwaves. In this perspective, we present an example of an operational, co-developed ocean monitoring framework that is explicitly structured around user requirements, local scientific expertise, established software engineering practices, and openly available satellite and numerical model data and algorithms. The framework is instantiated through the South African National Oceans and Coastal Information Management System (OCIMS) Fisheries and Aquaculture Decision Support Tool, which is employed as a representative implementation case study and potential reference architecture for application in other regional contexts. We demonstrate that satellite-derived and model-based products can markedly accelerate the establishment of operational marine environmental monitoring capabilities in settings where dense, long-term *in situ* observing systems are absent or sparse, thereby enhancing societal preparedness and adaptive capacity in relation to intensifying, climate-driven marine risks. Furthermore, we discuss how such frameworks can underpin resilient, equitable, and evidence-based blue economy development in the Global South.

KEYWORDS

blue economy, co-development, harmful algal blooms, hydrodynamic ocean models, marine heat waves, operational monitoring, satellite remote sensing

1 Introduction

1.1 Marine environmental threats in emerging economies

Ocean observations are crucial for sustainably managing ocean resources and ecosystem services (Rayner et al., 2019). Within the blue economy, fisheries and aquaculture depend on suitable temperature ranges and good water quality, making them vulnerable to harmful algal blooms (HABs) and thermal stress events such as Marine Heat Waves (MHWs) and Marine Cold Spells (MCS), which can impair growth, increase physiological stress, and cause economic losses. MHWs can directly cause loss of marine species and habitats (e.g. Oliver et al., 2017; Yañez-Arenas et al., 2025) and are frequently associated with HAB events (Cavole et al., 2016; Trainer et al., 2020). In South Africa, HABs - mostly extreme dinoflagellate blooms have negatively affected commercial fisheries (e.g. Ndhlovu et al., 2017; Van der Lingen et al., 2016) and aquaculture operations (Pitcher and Calder, 2000; Pitcher et al., 2019).

MHWs are occurring more often and lasting longer regionally (Mawren et al., 2022) and globally (Oliver et al., 2018), with disproportionate impacts on vulnerable populations, such as low- and middle-income countries (IPCC, 2022; Gray et al., 2025). Although HAB frequency and impacts are widely thought to have risen in recent decades (Townhill et al., 2018), analyses of global *in situ* datasets suggest this trend largely reflects intensified monitoring and enhanced recognition of impacts (e.g. on aquaculture) (Hallegraeff et al., 2021). These datasets remain spatially and temporally sparse in coastal waters of Africa and Southeast Asia (GlobalHAB, 2021; Hallegraeff et al., 2021). In contrast, satellite studies indicate that blooms (not specifically HABs) have expanded and intensified globally, with particularly strong increases in bloom frequency in the Global South (Dai et al., 2023).

The occurrence, toxicity, and risks of HABs are projected to increase with ongoing climate change, driven especially by ocean warming and rising atmospheric and seawater CO₂ (Bindoff et al., 2019; Brandenburg et al., 2019), with the greatest vulnerabilities expected in poorly monitored regions (Bindoff et al., 2019). Economic and societal constraints limit environmental hazard monitoring, and many developing nations lack the financial, technical, and institutional capacity for sustained long-term observations. In Sub-Saharan Africa, marine HABs have been recorded in the Gulf of Guinea (Davies et al., 2019; Séverine et al., 2025), the southern Benguela ecosystem (Pitcher and Louw, 2021), and Kenyan coastal waters (Oduor et al., 2023), but most work has used *ad hoc*, short-term sampling. Despite repeated calls for expanded and systematic HAB monitoring, routine long-term *in situ* HAB observation programmes are largely absent in the region.

1.2 Why a satellite- and model-based framework is needed

Conventional HAB detection relies on *in situ* sampling and laboratory analyses that require specialised expertise and are often costly, labour intensive, and limited in spatial and temporal

coverage. Few countries have the technological capacity and infrastructure for sustained *in situ* monitoring of the physical marine environment (e.g. moored buoys, autonomous gliders, research vessels), which could also enable direct MHW detection.

Satellite remote sensing has been used for decades to identify marine phytoplankton blooms (Blondeau-Patissier et al., 2014), HABs (IOCCG, 2021), and MHWs (Mumby et al., 2004; Pearce and Feng, 2013), providing a robust, operational, and cost-effective complement to other monitoring programmes. In regions with sparse *in situ* observations, remote sensing can guide targeted field sampling and validation, optimising limited observational resources. However, satellite observations have inherent limitations. Optical and thermal sensors sample mainly the surface layer, offering no direct information on subsurface conditions, and most constellations provide only a single daily overpass per location. In many regions - especially equatorial and monsoon-influenced areas (Modi et al., 2022) - persistent or seasonal cloud cover and other atmospheric effects often obscure the ocean surface, causing missing observations and temporal gaps. Interpolation schemes are used to fill these gaps but introduce errors in areas with complex temperature structures, particularly coastal upwelling systems (Carr et al., 2021; Meneghesso et al., 2020).

Sparse surface measurements can be complemented by operational ocean models, which provide spatially and temporally cohesive ocean state forecasts throughout the water column. These models simulate physical and biogeochemical bloom drivers and temperature extremes indicative of MHWs. While they describe the environmental conditions preceding a bloom, HAB evolution is often tracked operationally by coupling forecasts with a Lagrangian particle tracker to predict bloom trajectories (Bedington et al., 2022). Models describe ocean state changes across different scales, from past to near- and long-term future, and thus support MHW tracking. They are used operationally by institutions such as NOAA (<https://psl.noaa.gov/marine-heatwaves/>), New Zealand's Moana project (<https://www.moanaproject.org/marine-heatwave-forecast>), and the Balearic Islands Coastal Observing System (SOCIB: <https://www.socib.es/en/what-we-do/ocean-forecasting>).

In this perspective we delineate the fundamental components of a satellite- and model-based operational framework designed to support the blue economy, using the South African National Oceans and Coastal Information Management System (OCIMS) (Krug et al., 2024) Fisheries and Aquaculture Decision Support Tool (DeST) as a representative implementation case study.

2 Building blocks

2.1 A collaborative, co-developed framework

In 2015 the OCIMS project, grounded in value of information reasoning, fundamentally changed the approach to regional marine and maritime service development. Earlier South African marine information systems mainly delivered scientific information to regulatory agencies and researchers (Fawcett et al., 2006;

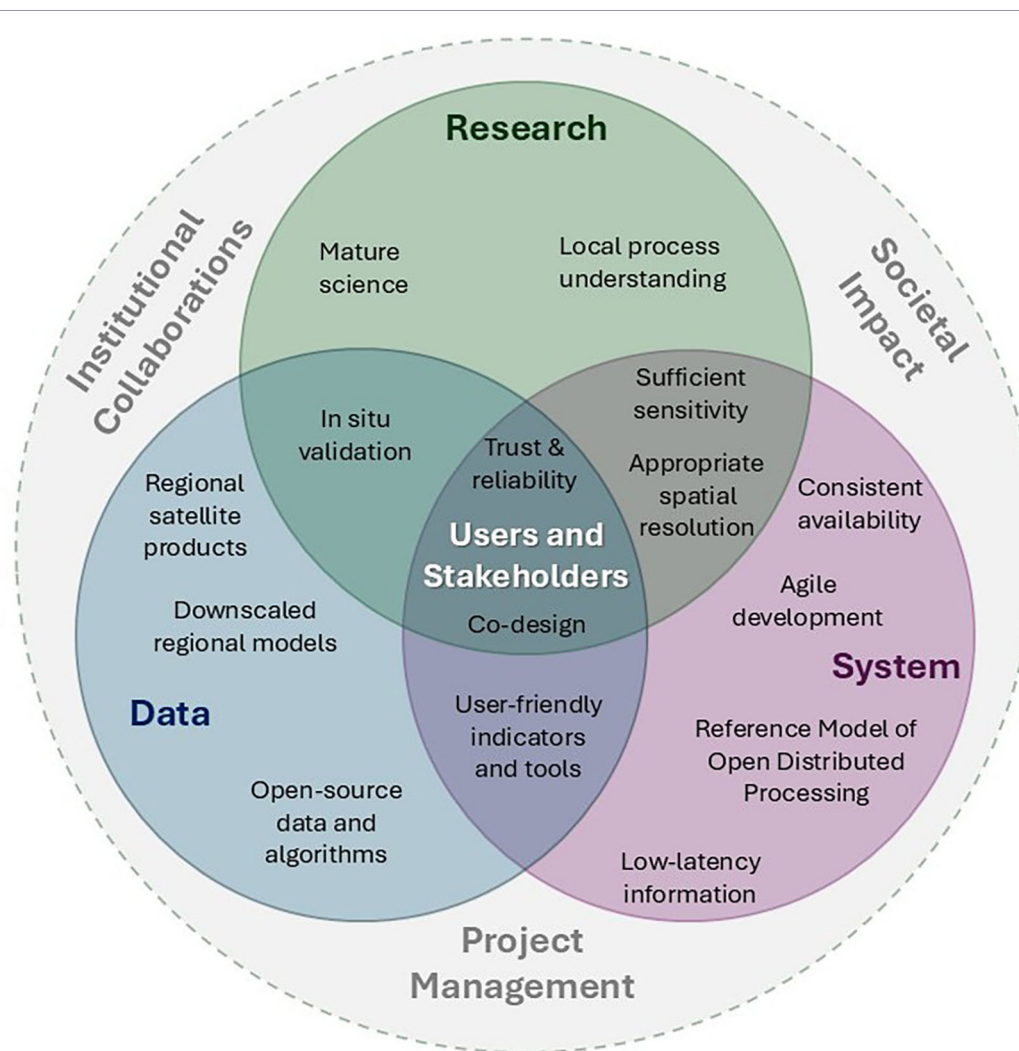


FIGURE 1

Conceptual framework illustrating the integration of the fundamental components of an impactful operational environmental monitoring system, as exemplified by the OCIMS Fisheries and Aquaculture Decision support tool.

Hutchings et al., 2009), or data and products to the broader African scientific community (Byfield et al., 2012). In contrast, OCIMS adopted a user-centric design grounded in clearly articulated stakeholder needs and intended user impacts, implemented through structured service co-design frameworks (Krug et al., 2024). Capabilities were refined through iterative, practice-based learning, enabling aquaculture farms to develop daily HAB risk assessment plans tailored to their operational requirements (Mtetandaba, 2021). Technical advisory groups — including scientists, industry stakeholders, government officials, and municipal representatives — systematically defined user requirements and characterised the operational decision-making processes the system had to support.

This collaborative framework of OCIMS includes formal partnerships among key national marine and atmospheric research institutions: the Department of Forestry, Fisheries and the Environment (DFFE), the South African Weather Service (SAWS), the South African Environmental Observation Network (SAEON), and the Council for Scientific and Industrial Research (CSIR). Collaboration between SAWS and SAEON has produced improved, locally optimised regional ocean models, while SAEON

and CSIR are developing HAB trajectory prediction capabilities. The OCIMS community of practice has enabled a coordinated response to national imperatives and better use of expertise and resources across institutions.

Regional co-development initiatives, such as the Climate and Ocean Support Program in the Pacific (COSPPac), have achieved similar success. Through COSPPac, National Meteorological and Hydrological Services from 15 Pacific Island countries have been capacitated to design, implement, and maintain tools and systems for operational climate and ocean services. The Pacific Ocean Portal (<https://oceanportal.spc.int/explorer>), supported by the Governments of Australia and New Zealand, demonstrates the effectiveness and impact of these efforts.

2.2 Mature science base and local process understanding

OCIMS implementation drew on a mature science base to deliver ecosystem-relevant earth observation products at appropriate geophysical and spatio-temporal scales. Decades of regional

HAB research enabled: 1) validated, HAB- and region-specific algorithms and products using diverse ocean colour and infrared sensors (Weeks et al., 2006; Smith et al., 2018; Smith and Bernard, 2020), and 2) demonstrated use of these products to analyse regional bloom dynamics, ecology, and impacts (Pitcher et al., 2008, 2014, 2019). Within OCIMS, this process understanding is converted into region-specific indicators, such as HAB proxy indices tuned to upwelling and estuarine systems.

Ocean models complement sparse *in situ* observations, facilitate controlled numerical experimentation, and enable projections of future ocean states. Although freely available, state-of-the-art global circulation models provide robust representations of large-scale processes, they lack the resolution and process fidelity required to accurately resolve nearshore and bay-scale dynamics (Cuervo-Londoño et al., 2026; Russo et al., 2022). In contrast, dynamically downscaled regional models can reliably capture higher-frequency and smaller-scale processes, including coastal upwelling (Fearon et al., 2023; Troupin et al., 2012), submesoscale filaments and frontal structures (Hauschildt et al., 2021), as well as eddy activity in marginal seas (Zhan et al., 2014). In the South African context, regional modelling studies have substantially advanced understanding of the dominant physical processes governing oceanic and coastal dynamics and associated ecosystem productivity (Veitch and Penven, 2017; Malan et al., 2018; Ragoasha et al., 2022; Fearon et al., 2023; Rogerson et al., 2025; Tedesco et al., 2019). Under the OCIMS framework, users are provided with locally optimised and rigorously validated regional forecast models which, when combined with in-depth process understanding, deliver impactful information.

2.3 Operational design and reliability of the service

Historically, service development was led mainly by scientists, often without rigorous user requirements, using *ad hoc*, weakly formalised development cycles, suboptimal architectures, and limited technical expertise and resources. Under OCIMS, new collaborations were formed among marine and data scientists, geospatial service engineers, and experienced project managers. Partnerships with geospatial engineers were especially important, adding advanced skills in systems engineering and architecture, spatial database and infrastructure design, spatial analytics, and user experience and front-end development.

Previously, design was driven by available technology and operated outside formal policy and governance, resulting in siloed, non-interoperable systems. Introducing governance and legislative prescripts provided clear guidelines on standards for long-term sustainability, centred on openness, which shaped the systems and architectures for OCIMS and Marine and Coastal Operations in Southern Africa and the Indian Ocean (Sibolla et al., 2023). These principles extend beyond service and component design to data management across the full service life cycle. Adopting formal development frameworks such as the Reference Model of Open Distributed Processing (RM-ODP) (McFerren et al., 2018) enabled systematic elicitation and characterisation of user

needs and archetypes, from both functional and semantic perspectives. The RMODP computational, engineering, and technology viewpoints were then used to design the service system architecture and its components. Open-source components used in the OCIMS Fisheries and Aquaculture DeST include: PostGIS (PostGIS Development Group, 2026) for storing and processing vector data, Geoserver (GeoServer Project, 2026) to provision web feature services, ESA Sentinel Application Platform (SNAP) (European Space Agency, 2026) for pre-processing satellite data, and Python programming language for automating backend processes and Application Programming Interfaces.

Involving experienced project managers introduced formal workflows and outcomes-based management, implemented within agile software development frameworks. To realise and sustain these designs, software engineering principles had to be followed, not only to deliver an operational system but to continuously release highly scalable, reliable IT products. Services also had to offer high availability (up to 99.5% uptime), security, and trustworthiness for critical, high-risk government operations. OCIMS provides operational services delivering low-latency HAB and temperature indicators on a daily or multi-daily basis for aquaculture farm management, fisheries advisories, and coastal monitoring. Service availability and consistent data delivery are supported by automated pipelines, cloud infrastructure, and dedicated monitoring, which together build user trust.

2.4 Open satellite and model data

Global ocean colour products may not always provide accurate retrievals, particularly under bloom conditions or in optically complex coastal waters (Sathyendranath, 2000; IOCCG, 2021), and often necessitate regional validation, calibration, or innovative techniques to improve performance. For instance, the HAB Forecasting Branch within NOAA's National Centers for Coastal Ocean Science routinely produces a suite of advanced satellite-derived products (Wynne et al., 2026) that include quantitative estimates of phytoplankton biomass as well as a range of optical indicators and proxies designed to differentiate bloom types and to identify HAB events within optically complex coastal and inland aquatic systems across the United States. Under the OCIMS Fisheries and Aquaculture DeST several regionally optimised, open-source ocean colour algorithms have been developed to support HAB detection and improve retrievals under high biomass blooms conditions (Smith et al., 2018; Smith and Bernard, 2020). Using free satellite data and open-access algorithms in this way enhances the transparency, reproducibility, and scalability of the framework for both researchers and practitioners.

Early HAB remote-sensing work in South Africa relied on the Medium Resolution Imaging Spectrometer (MERIS) (Bernard et al., 2005; Matthews et al., 2012) because of its suitable spectral configuration and relatively high spatial resolution. This provided a smooth transition to the EU's Sentinel-3 mission, which was designed with strong MERIS heritage, allowing MERIS-optimised algorithms and processing chains to be directly adapted for the Ocean and Land Colour Imager on Sentinel-3. We advocate

systematic development of operational earth observation capabilities that use multi-satellite constellations to improve temporal sampling, and long-term, internationally funded flagship missions such as those under the Copernicus Programme. This approach is vital for securing sustained, high-quality observational time series into the future and ensuring long-term continuity, robustness, and sustainability of HAB and MHW monitoring and related environmental services. Likewise, active and systematic engagement with space agencies and other data providers through demonstrable, high-impact use of their products can be mutually beneficial, as it helps build evidence-based support for sustained funding of the underlying data provision infrastructures.

Lastly, the benefits of validated and regionally downscaled models have been described in section 2.2. SAEON supports OCIMS with freely available <1 km, regionally tailored operational forecast models forced by winds from a ~4 km atmospheric model run by SAWS (<https://catalog.somisana.ac.za/catalog/>). These provide best-estimate forecasts of temperature-related threats and nearshore circulation relevant to HAB transport. Surface temperature projections generated by these models are now integrated into the OCIMS Fisheries and Aquaculture Decision Support Tool (DeST) for selected coastal sites, thereby providing forecasts of a core physical indicator of water quality.

3 Conclusion: transferability and outlook

3.1 Open, transferable framework for emerging economies

Research agendas and technologies for HABs have historically been concentrated in high-GDP countries of the Global North, targeting species with the greatest regional economic impacts. Consequently, social and ecological impacts not directly tied to these economic concerns have often been marginalised. Applying Design Justice principles through the participatory co-creation of new environmental monitoring systems is crucial for addressing these inequities by more fairly aligning with the needs, priorities, and rights of local stakeholders (Record et al., 2025).

Environmental data and information services must match users' socioeconomic and technological realities. For instance, an advanced browser-based interface is inappropriate where most users lack personal computers, as it disadvantages lower-income groups. The Global Findex Database 2025 (Klapper et al., 2025) reports that only about 45% or fewer adults in Sub-Saharan Africa and South Asia use the internet, typically via smartphones; although about 74% of Sub-Saharan Africans own mobile phones, only 32% are smartphones. Decision-support tools must therefore account for these constraints to stay accessible, inclusive, and widely used. WhatsApp, for example, is widely used for group communication in low bandwidth, remote areas because it requires little data (Ro, 2023; Shahreza and Basit, 2025). Within OCIMS, WhatsApp groups have helped familiarise stakeholders with earth observation data by sharing and explaining satellite images (e.g. chlorophyll-*a* maps)

during bloom conditions and later enabled rapid dissemination of critical information for real-time decisions.

Transferability of HAB and MHW detection can be supported through open-source code repositories and cloud-based infrastructures, which lower the barrier for emerging economies to adopt or adapt monitoring tools without investment in local servers, proprietary software, or high-cost licensing. AlgaeMap (Lobo et al., 2021), a Google Earth Engine (GEE) interface developed in Brazil and extended regionally, exemplifies this model by providing algal bloom indicators on an entirely satellite-derived, cloud-based tool. The MHW definition of Hobday et al. (2016) has been implemented as openly available code, in Python (Oliver, 2016) and R (Schlegel and Smit, 2018), directly applicable to *in-situ*, model-derived, or satellite-derived datasets. Open data infrastructures such as Digital Earth Africa - built on the Open Data Cube (Killough, 2018) - further support transferability by offering analysis-ready data, cloud computing infrastructure, and example code to build from rather than requiring national agencies to develop detection pipelines from first principles (Mubea et al., 2020, 2022).

3.2 Challenges, limitations and future directions

Persistent challenges remain in emerging economies such as Africa and the global south, including limited *in situ* information for validation, lack of real-time *in situ* observations (e.g. dissolved oxygen, phytoplankton imagers), as well as limited institutional capacity and long-term funded programmes to sustain technical teams. While this perspective highlights the potential of satellite- and model-derived information within integrated observing systems, it is essential to recognise their inherent uncertainties (see sections 2.2 and 2.4); consequently, systematic efforts should be made to rigorously evaluate and validate the performance of these products and models (Bailey and Werdell, 2006; Seegers et al., 2018; Sotillo et al., 2024) in regional contexts.

In regions where *in situ* sensor networks are absent or sparsely distributed, or in remote areas that lack established regulatory monitoring frameworks (FAO et al., 2023), members of the public can be systematically engaged to collect environmental observational data through approaches commonly referred to as citizen science or crowdsourcing. Such approaches have demonstrated utility for the early detection and warning of HABs (Manik et al., 2023). For temperature monitoring, Smartfin devices—data-logging fins designed for surfboards and stand-up paddleboards—have been deployed for satellite data validation purposes (Brewin et al., 2021). Similarly, the BlueDOT initiative, led by MARUM – Center for Marine Environmental Sciences, aggregates temperature profiles obtained from personal scuba diving computers within the upper 40 m of the water column to monitor temperature variability and MHWs, as well as validate physical model performance, in the Mediterranean Sea. OCIMS has implemented several mechanisms to enhance the acquisition, storage, and visualisation of marine observational datasets. Leveraging from ESRI's ArcGIS Online platform and software suite, crowdsourcing initiatives using Geo Apps - applications designed to capture, store and analyse spatial data - are increasingly being used to allow citizens to report in-field

observations (Krug et al., 2024) and offer the benefit of being available via internet browser or deployed as an application on any Windows, Android or IOS device. In particular, OCIMS hosts a dedicated Geo App for the recording of phytoplankton counts at aquaculture facilities and *ad hoc* sampling. Data standards are implemented on the user end, making submitted data immediately available for analysis and visualisation. Although this service is based on proprietary software, open-source platforms such as Open Data Kit (<https://getodk.org/>) provide cost-effective alternatives that could be deployed in emerging economies.

Operational prediction and forecasting of marine HABs based on satellite observations remain relatively uncommon and are predominantly concentrated in the Northern Hemisphere (Caballero et al., 2025). Data-driven approaches, including machine- and deep-learning models, recently gained prominence in the HAB forecasting research domain (Caballero et al., 2025); however, these methods may exhibit systematic biases and structural imbalances, encompassing social, economic, and environmental biases embedded in existing data repositories (Record et al., 2025). The adoption of algorithmic accountability frameworks may help to mitigate the introduction and amplification of such biases and to promote fairness in artificial intelligence and machine learning models deployed within decision-support and decision-making systems (Grasso et al., 2020).

Physical models are increasingly being integrated into operational forecasting systems. Numerous international HAB forecasting frameworks employ hydrodynamic circulation models coupled with Lagrangian particle-tracking schemes to simulate bloom trajectories and cellular advection (e.g. Wynne et al., 2013; Davidson et al., 2021; Bedington et al., 2022). In parallel, machine learning and deep learning approaches are yielding encouraging skill for MHW prediction (e.g. Welandawe et al., 2025 and references therein), although their deployment in near-real-time operational settings remains limited. Enhanced monitoring and predictions of MHWs has been shown to help blue economy and management sectors build resilience and response strategies (Hartog et al., 2023). Future enhancements of OCIMS may include tighter coupling with regional physical ocean models, investigating the use of artificial intelligence approaches for improving HAB forecasting, integration of low cost sensors or citizen science data, and embedding HAB and MHW risk indicators into national blue economy planning frameworks.

The recently initiated Ocean Prediction Enhancement in Regions of Africa (OPERA) project, funded by the European Commission and implemented by Mercator Ocean International, aims to enhance ocean prediction capabilities across the African continent and to facilitate evidence-based decision-making. The project is aligned with the priorities articulated in the Ocean Decade Africa Roadmap and Africa's Blue Economy strategy, and seeks to achieve its objectives through the development of high-resolution, high-quality ocean forecasting models for the marine domains of sub-Saharan Africa, the co-design of downstream applications in partnership with end users, and the strengthening of human and institutional capacity required to maintain, operate, and further advance these forecasting systems and their associated services.

3.3 Concluding perspectives

While the coverage imbalances seen in global *in situ* databases could be used to motivate more research and monitoring in areas with limited surveillance (Record et al., 2025), a further anticipated impact of the present system is to enhance awareness among users and policy makers of the existing gaps across both *in situ* and modelling infrastructures. Such awareness may, in turn, provide an evidence-based rationale for future investments in observational capacity, research, and technological development.

A review of regional HAB observing systems in the USA, the EU and Asia found that while there was no single approach applicable for all environments, the most successful programmes included a combination of strong stakeholder coordination (i.e. clear need and buy-in from end-users), institutional support (i.e. ownership and maintenance of operational systems), and integration into national programmes (i.e. policy and funding support) to facilitate long-term stability and continuity (Anderson et al., 2019). In regions with limited funding, the nationally coordinated, collaborative approach is particularly critical to achieve rapid, high-impact outcomes and to maximise the utility of scarce financial and human resources.

A collaborative, co-developed framework (illustrated in Figure 1) — grounded in a mature scientific knowledge base, leveraging open-access satellite and model data, and emphasising stakeholder coproduction of tools and services — is already operational in South Africa, with demonstrable impact through the mitigation of stock losses in both the fisheries and aquaculture sectors (Krug et al., 2024). The more than decade-long success of OCIMS provides a clear demonstration of how satellite and modelling products can substantially accelerate the development of operational marine monitoring capabilities in the absence of dense, long-term *in situ* observing networks. Operational systems such as OCIMS can serve as reference architectures whose system design, data-processing workflows, and indicator derivation logic can be systematically adapted to other coastal regions with similar HAB-forming species and exposure to MHWs. Wider adoption and adaptation of such frameworks have the potential to support the development of resilient, equitable, and data-informed blue economies in the Global South, thereby strengthening societal preparedness and adaptive capacity in the face of intensifying climate-related marine environmental risks.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

MS: Writing – original draft, Conceptualization. SB: Writing – review & editing. GF: Writing – review & editing. MK: Writing –

review & editing, Conceptualization, Funding acquisition. RM: Writing – review & editing. JV: Writing – review & editing. LV: Writing – review & editing. LW: Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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