A framework for enabling data sharing and accessibility in a transdisciplinary federated marine spatial infrastructure

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Abstract

The Sustainable Development Goals and the United Nations Ocean Decade require preservation of the oceans and the efficient management of marine resources, contributing to sustainable use of oceans resources and the blue economy. Oceans span a wide area with exclusive economic zones of different countries adjacent to each other. This therefore necessitates the collaborative management of these resources across several countries in a region. Data is essential for providing trusted information, which in turn drives knowledge generation from science to policy implementation, towards informed decision making regarding the ocean resources. Harmonising data into decision support tools becomes a challenge due to two main reasons. Firstly, this is due to the transdisciplinary nature of the ocean, where data is governed by a variety of standards. Secondly, regional collaboration requires the data and knowledge to be shared in a federated environment in order to preserve data ownership by the custodians, while also cognisant of the network challenges in developing countries. This paper presents a standards compliant framework for enabling data sharing and access in these environments based on lessons learnt in the Marine and Coastal Operations for Southern Africa and Western Indian Ocean region, a project supported by the African Union Commission’s GMES and Africa program.

1. Introduction

The Sustainable Development Goals (SDGs) (Carlsen and Bruggemann 2022) have elevated the importance of the marine and coastal environments, towards preservation of the environment whilst extracting economic benefits and supporting livelihoods. The terms blue economy and oceans economy have become synonymous with “socially equitable, environmentally sustainable and economically viable ocean industries” (Cisneros-Montemayor et al. 2021) culminating with the United Nations declaring the oceans decade from 2021 to 2030 (Guan et al. 2023; Intergovernmental Oceanographic Commission 2022). Fisheries, safety at sea, marine spatial planning and pollution are some of the critical issues that headline the ocean decade (Santos 2023).

It is also widely understood that efficient usage of ocean resources and effective management of the marine environment need to be supported by well-established policies and governance frameworks (Vadrot et al. 2022). Due to the nature of the oceanic environments, such policies and governance frameworks need to be in place across adjacent regions as the ocean waters know no boundaries. The GMES and Africa Marine and Coastal Operations for Southern Africa and Indian Ocean (MarCOSIO) was undertaken in the Southern Africa and the Western Indian Ocean regions. These two regions fall under South African Development Community (SADC) and the Small Islands Development States (SIDS) respectively. The African Union leads the development of continental strategies such as the Africa integrated maritime strategy and the Africa blue economy strategy (Guerreiro 2022). Several regional policies conventions and agreements are observed, concerning maritime safety and security, marine spatial planning and intergovernmental governance of the marine environment. These include the Nairobi Convention (Kern 2016) and Benguela Current Convention (Hamukuaya 2020; O’Toole 2009). In addition, these individual countries have their own governance structures for managing the oceans and marine environments. Guerreiro (2022) presents a comprehensive review of the government structures, policies, institutional and legal frameworks that manage national ocean strategies, blue economy and maritime spatial planning in the SADC and SIDS that form the Southern African and Western Indian Ocean region described in this paper.

Similarly, the oceans encompass several scientific themes, ranging from the physical to the biological and geological aspects. Thus, a multidisciplinary research approach is essential for understanding the complex nature of the ocean. Each of these scientific disciplines produce their own data that represents an aspect of the ocean in a relevant manner. The data and products are then governed by different scientific communities, including the International Hydrographic Organization (IHO), World Meteorological Organisation (WMO) with UNESCO’s Intergovernmental Ocean Commission (IOC) playing a coordination role (Ryabinin et al. 2019). Understanding of the ocean, its processes and activities is thus a transdisciplinary exercise as it requires data that is created across multiple disciplines and areas of specialisation with different formats and characteristics.

Given the drive towards democratisation of data to facilitate decision making, data governance has become quite a mature concept with several scientific communities formulating their domain specific standards (Lefebvre et al. 2021). Whilst democratisation of data is not synonymous to open data and open knowledge, open data is seen as one of the mechanisms of facilitating data democratisation (Awasthi and George 2020). Due to the multidisciplinary nature of the oceans and the marine environments, and the inherent relationship with the geospatial and earth observation domain, several standards are utilised. The most notable are the International Organisation of Standards (ISO) particularly the ISO/TC 211 – ISO 19100 group of standards that focus on geographic information and Geomatics, the Open Geospatial Consortium (OGC) (Leibovici et al. 2023; Rüh and Bill 2012) and Climate and Forecasting (CF) standards (Sorg and Kunkel 2015).

Whilst there are high levels of policy regulation and data governance, the implementation of a federated Marine Spatial Data Infrastructure that transcends exclusive economic zones, territories and demarcations as well as transdisciplinary applications in support of decision making in the region, remains a challenge.

This paper explores the linkages between policy and science considerations that drive the implementation of a transdisciplinary, federated Marine Spatial Data Infrastructure towards the realisation of SDG 14, Life Below Water and the success of the blue economy, with lessons learnt from the MarCOSIO project.

The paper is organised as follows; Section 1 characterised the transdisciplinary nature of oceans and marine environments and their governance. Section 2 discusses the various ocean types and related data sources. Section 3 presents and discusses work related to the implementation of Marine Spatial Data Infrastructures and highlights the gaps related to the suitability of this use case. Section 4 presents the transdisciplinary federated Marine SDI considerations and the implementation done by the authors. The paper concludes in Sections 5 and 6 by presenting challenges experienced during the implementation stage and recommendations for future work, respectively.

2. The state of ocean data

Further to the policies and data governance that influence the oceans and marine environment as described in the previous section, data about the ocean and the marine environment has been discussed in previous studies, focusing on the observation types and phenomena under observation (Amani et al. 2022; Bonnet-Lebrun et al. 2023; Bridges and Howell 2025; Haupt et al. 2025).

The main sources of marine and ocean data that are used in the Southern Africa and Western Indian Ocean region within the MarCOSIO project are summarised in Figure 1. Several countries in the region make use of geoportals such as Geonode and CKAN to catalog and make their data holdings discoverable. Application Programming Interfaces (APIs) are then used by third parties to gain access to the datasets. Regional projects such as Digital Earth Africa (DEA) (Gimode et al. 2025; Mubea et al. 2022) and the South African National Oceans and Coasts Information Management Systems (OCIMS) (Krug et al. 2024) make use of data cubes to store analysis ready satellite data and derived products. These data cubes are derivatives of the open data cube initiative described by Killough (2018). The Joint Research Centre of the European Commission eStations are generally used in the region to receive relevant European Space Agency related satellite data products that are necessary to fulfil joint research initiatives. Amongst others, the virtual eStation 3.0 (Software Based) provides access to ocean products derived from the Copernicus satellite program without the need to maintain complex hardware. Supplementary to the eStation, data is also received via the EUMETCast service using National Research Networks infrastructure (NRENs).

For the purpose of developing a Marine Spatial Data Infrastructure described in this publication, ocean data is also classified based on the characterisation of the state of data; stationary data (data at rest), data in use (active data) and data on the move (data in transit). Data at rest refers to data that is stored in various formats, such as databases in a resting phase, data in use is data processed in memory and data in transit is data that is in active movement between locations on a computing infrastructure (Nandakumar et al. 2021; Swanzy et al. 2024). This characterisation is important because it describes how the data will be sourced, stored and transformed, in preparation for analysis. In this context, marine data in transit includes real time observations of in-situ data, vessel Automatic Identification System (AIS) and other forms of ship transponder data that are often received continuously, in real time (Sibolla et al. 2018). Besides the fact that this data describes the movement of vessels, it is used in transit form before it is eventually stored or discarded. Similarly, data at rest includes large satellite imagery and ocean variable models that are received and produced periodically and stored on the computing infrastructure for use on request (Sibolla et al. 2018).

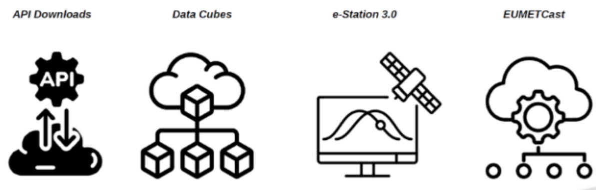

Figure 1. An illustration of the diverse ocean data sources used in the GMES and Africa Marine and Coastal Operations for Southern Africa and Indian Ocean (MarCOSIO) project

3. Existing SDI frameworks

The concept of Spatial Data Infrastructures (SDI) has been in existence for close to three decades, initially focusing on the description of data and making it suitable for transfer, to facilitate accessibility (Aalders and Moellering 2001). The most widely accepted description of SDI is that by Rajabifard et al. (2006), which describes the role of SDIs as facilitating and coordinating sharing of spatial data between stakeholders and the spatial data community with governments playing a central role. Various improvements have been introduced over time coinciding with advances in technology. Advances in computing and cloud infrastructure have enabled enhancements relevant to this study to go beyond the need for just interoperability and the ability to harvest data to the implementation of federated systems and SDI.(Hendriks et al. 2012; Nugroho and Supangkat 2021).

Marine Spatial Data Infrastructures have been discussed in several contexts throughout literature. The applications range from local implementations that focus on localised needs, to global scale implementation guidelines and frameworks (Contarinis and Kastrisios 2022; McFerren et al. 2018; Racetin et al. 2022; Tavra et al. 2017). Contarinis and Kastrisios (2022) describe the Marine SDI as an extension of the terrestrial SDI, based on cyberinfrastructure that facilitates the accessing, sharing, managing and dissemination of hydrospatial data. They describe the main pillars of this framework as data, standards, systems and stakeholders, whilst recognising the marine SDI contributions by the OGC. The incorporation of FAIR principles in future Marine SDI implementations is also discussed by Contarinis and Kastrisios (2022) and further demonstrated by Foglini and Grande (2023).

This paper contributes to existing literature by presenting a Marine SDI (MSDI) that is cognisant of the transdisciplinary nature of ocean data, whilst considering the distributed nature of cyberinfrastructure, with a focus on open system development, whilst also preserving regional policy and governance mandates. This marine SDI is in alignment with the four pillars presented by Contarinis and Kastrisios (2022) the policy and governance mandates represent the requirements of the users and stakeholders. We extend the characterisation and representation of the ocean data within the SDI, and its suitability for representation within a geospatial information environment.

4. Transdisciplinary federated SDI

This transdisciplinary federated marine SDI is based on the four pillars described by Contarinis and Kastrisios (2022) depicted in Figure 2. The four pillars are described as follows. The two main components of the SDI are the data and services, underpinned by the standards that facilitate the FAIR principles, whilst also providing information that is relevant and suitable to the needs of the stakeholders.

The data used in this implementation include information about the state of the ocean (sea surface temperature, ocean currents etc.), along with objects found in the ocean (shipping vessels), elements of marine pollution (floating debris and oil spills) and marine regions boundaries (EEZ and coastal boundaries). Other important data that can be included are seabed habitats, species distribution, human activities (mariculture, research and industrial infrastructures, energy installations). Capturing and checking completeness of the metadata forms a critical part of the data component.

The system pillar describes the components of the cyberinfrastructure which forms the technology deployment of the SDI. This includes the client software, middleware, storage infrastructure and the connecting networks. These are underpinned by the standards that ensure interoperability amongst the components of the system and the data nodes. Data preprocessing mechanisms for data harmonisation are also incorporated into the systems pillar.

The stakeholder layer is the driver of the SDI as it is imperative that the needs of the stakeholders are met. In this case, the stakeholders include the member states of the Southern African region and Western Indian Ocean regions, including, marine scientist, policy makers, citizens of the coastal regions, representatives of various sectors such as fisheries, aquaculture, national coasts guards, and the tourism sector amongst others. The countries in the region are independent, states which have their own governance structures and policies. It is therefore important that the policy and governance structures are represented from regional to local perspective throughout this SDI implementation to enhance intergovernmental collaboration.

The transdisciplinary nature of the data sources requires adherence to standards across different disciplines. This means that the data may not always be readily ingested into traditional geospatial SDI architectures, which necessitates a full understanding of the source data standards. This understanding guides the development of data adaptors and bridges that need to be implemented to enable seamless interoperability and ingestion into the geospatial environment. For instance, a service may be required to utilise sea surface temperature, chlorophyll concentration and ocean currents to determine potential fishing zones for the nearest vessels using AIS data. To ensure effective functioning of such services, all these datasets that are described in different standards, formats, spatial references and units of measure need to be harmonised to ensure that they can be used together.

The first step of the methodology is thus reviewing and formulating an understanding of the standards, formats and technical characteristics of the data. This is described in the following section.

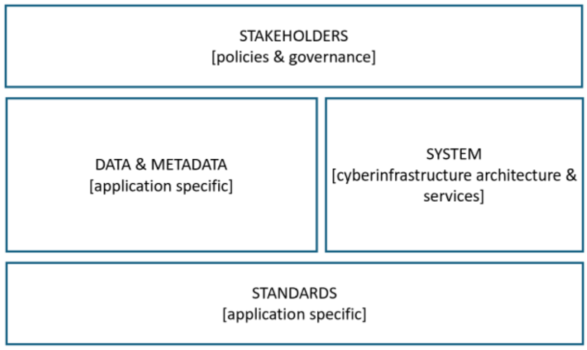

Figure 2. the four pillars of the transdisciplinary federated marine SDI, adapted from (Contarinis and Kastrisios 2022)

4.1 Review and selection of transdisciplinary standards

The standards and regulatory bodies that influence the ocean environment were reviewed and aligned with the standards utilised by the geospatial community. This step was carried out because the visualisation and user interaction components of the system, which form the decision support tools, are built on geospatial technology, hence it is important to ensure that all data can be used in this environment. The significant standards and regulations are described below.

The geospatial information community is well regulated with two organisations largely responsible for the geospatial standards. The ISO 19100 series of standards, that are developed under the ISO/TC 211 group describe geographic information and geomatics standards (Ostensen and Smits 2002). The Open Geospatial Consortium implements a series of closely aligned standards for working with geospatial data on the web (Reed 2011).

The United Nations’ International Maritime Organisation (IMO) has the mandate of ensuring safety and security in shipping, as well as monitoring ocean pollution that results from marine traffic. The IMO implements a common data model that is used to facilitate the sharing of all information regarding navigation (Cauwer et al. 2021; Contarinis and Kastrisios 2022).

The International Hydrographic Organisation (IHO) plays a coordinator role towards ensuring the accurate and seamless mapping and charting of the oceans. The IHO has developed s-100 standard for hydrographic mapping, these standards support representation of gridded data, three-dimensional data, time varying data and also to support marine GIS data. This standard is aligned to the ISO/TC 211 developed ISO 19100 group of geospatial standards, using the s-100 standard, datasets such as bathymetry that can be ingested into GIS systems (Kastrisios et al. 2022; Ward et al. 2008).

The World Meteorological Organisation (WMO) is responsible for the regulation of standard global weather forecasting procedures (Citaristi 2022). Forecasts of ocean meteorological data such as wind speed, wind direction and ocean currents are described according to the specification of the WMO.

An understanding of these standards and specifications enabled the development of bespoke rules that prepared the data to formats that could be ingested into native geospatial components within the implementation architecture described below.

4.2 Architectural design of the federated Marine SDI system

The architecture of this marine SDI is modular, based on several fit for purpose components, as described below. The general overview of the architecture is depicted in Figure 3. The system adopted a simple 3-tier architectural design where the presentation layer incorporates the human machine interface through dashboards, notebooks and other forms of geovisualisation. All the processing, intelligent logic and backend interfacing are performed within the business logic layer. The data layer consists of a data warehouse with data marts that house data for specific business functions. Each of the layers is abstracted from the other and may only interface when required.

4.2.1 Data acquisition layer

Large geospatial data are acquired from different sources through scheduled processing chains in the business logic. Data acquisition sources discussed in Section 2, are each handled by a specific chain custom to the type of data and amount of preprocessing required. Data are then transformed, described and stored in specialised warehouses. The backend was designed to handle multidisciplinary data by providing various methods to store data. Simple and flexible B-SON data are stored in a MongoDB database while structure and relational data are stored on PostGIS databases. The business logic works in conjunction with the data layer to ensure there is incremental data backup.

4.2.2 Data presentation layer

The presentation layer leads with a load balancer (NGINX) that optimises resource usage and reduces latency by increasing throughput. Human machine interface may be performed in various ways, which include, online notebooks such as Google Colab, MapStore2 dashboards and Cesium 4D visualisation tools. All of the highlighted components perform specialised functions from multiple disciplines to ensure full operationalisation of the marine SDI.

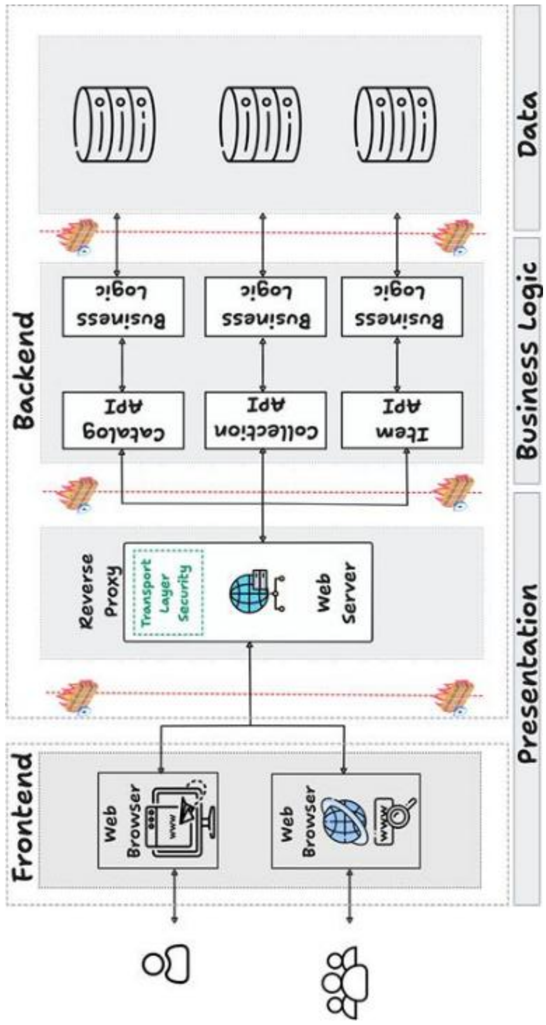

Figure 3. The logical overview of the marine SDI, showing the human computer interfaces on the front end, and the back-end logic.

4.2.3 Data accessibility and description

Proper data sourcing and acquisition forms the cornerstone of all effective data pipelines. Depending on the use and long-term preservation of the data, it is essential to adopt modular and sustainable data sourcing mechanisms. The Spatio Temporal Asset Catalog (STAC) is used as the main mechanism of ingesting and indexing data to make it discoverable. This enables geospatial data curators to share and expose the description of their datasets in a standard format. The Spatio Temporal Asset Catalog (STAC) component is based on the STAC specification which aims to provide a common model for describing geospatial temporal data. Spatiotemporal data is periodically ingested from known data providers and processed through our pipeline using proprietary algorithms and saved securely. To create a single data item, dynamic metadata extraction is triggered on file reception and combines dynamic fields with static fields to populate a standard compliant metadata template. The template is converted to a JSON object and inserted into a NoSQL database. All items created are linked to a unique collection. Catalogs and collections are generated from a template with dynamic fields to update and link to collections and items, respectively. They are also inserted into the NoSQL database and prepared for user requests. All user calls retrieve information through the API that reads from an efficient document database.

The marine STAC automated metadata publishing works as follows. Firstly, it provides a web-based API that comprehensively describes spatiotemporal datasets as individual items, a collection of items and a catalog that describes all the collections. Secondly, it references replicated databases for redundancy and improved accessibility but has a single source of truth. Furthermore, multiple API microservices work in a synchronised manner to retrieve data from the catalog store. Finally, internal processing chains execute, at a scheduled time, to acquire data from different sources and ingest them into a data bucket or lake.

The process flow is described in Figure 4.

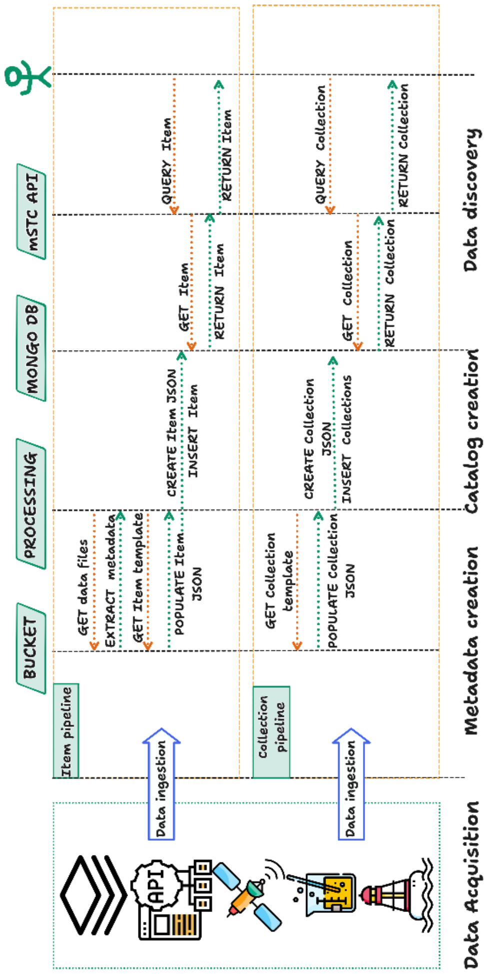

Figure 4. The process flow of the marine STAC component that implements the STAC specification

4.2.4 Data preservation

The ingestion is followed by the data storage component which implements the Open Data Cube (ODC), an open earth observation architecture that was developed by leading space agencies with the aim of increasing the value of earth observation data (Killough 2018). The ODC is extensible, modular and customisable, thus making it suitable for storing data at rest in the transdisciplinary marine SDI. Based on this architecture, it is possible to store data in data marts (subsets of a data warehouse which focuses on a specific function).

The Marine Open Data Cube (MODC) is a data management platform that focuses on the access, discovery, and processing of long-term time series of earth observation data specific to maritime, marine and coastal environments. The data is then indexed into the data cube through customised product metadata files and dataset descriptions. The descriptions of the data include the bands that are available, the area covered by the dataset, as well as the descriptions of the satellite products (sensor instrumentation that captured the data). The data in the cube is stored as at least a 4-dimensional (spatiotemporal + thematic dimension), multidimensional file, of which a subset can be “sliced” at any given time to return only data that is suitable for the users' needs.

The service also provides Jupyter notebooks and a Google Colab data analysis environment for performing analysis on the data as per the users’ requirements, hence enabling the user to only download and access the subset of data that they are interested in. The database that forms part of the MODC is used to store references to the data as well as session specific information pertaining to usage details. This information then forms part of the data provenance and is stored with the metadata.

The service also links to the regional oceans information systems OCIMS and Marine and Coastal Operations for Southern Africa and the Indian Ocean (MarCOSIO) to accesses the data products that are generated by these two systems (Krug et al. 2024; Smith and Mbugua 2022).

The systems currently create short term datasets that are visualised through the decision support tools, and the Cloud Optimised GeoTiffs (COGs) are stored in the data server. Through the data cube the datasets are then described through the STAC as spatiotemporal assets and indexed into the data cube. The descriptions are based on the GeoJSON objects and are collectively stored as “collections” in yaml format.

The communication between the data cube and the STAC is through the API. In the data cube these COGs are stored as multidimensional datasets which hold a longer term timeseries than what is available in the OCIMS and MarCOSIO tools.

The MODC is then made available to the users using the Python notebooks and external to the host institution through the Google Colab platform. In Google Colab one can log into the data cube, explore available data sets and run custom applications.

Figure 5 shows an illustration of the architecture of the marine MODC, illustrating the connection to the marine STAC and other related data ingestion and publishing systems.

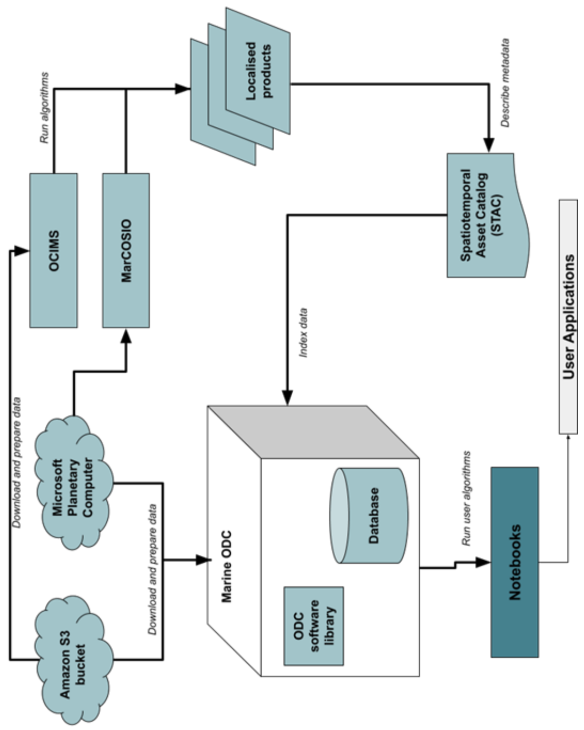

Figure 5. An illustration of the conceptual design of the Marine Open Data Cube based on the open data cube technology.

5. Discussion and challenges

Our finding is that the Southern African and Western Indian Ocean region is rich in policy and governance structures. The African Union Commission provides overarching guidance on continental policies regarding the blue economy and the integrated maritime strategy. Based on these, regional policies and governance structures are formulated and implemented in the regional communities. Understanding the policy landscape is key to understanding the needs of the stakeholders and thus formulating and implementing a framework that is suitable to these requirements. Technical implementation of the marine SDI system was successfully completed. Large marine datasets require high bandwidth, which is a challenge in the region. The key to a successful implementation of this framework was in the ability to use software components that allow granular access to data along with efficient data access provided through eStations. The availability of the regional Research Networks (NRENs) presents an opportunity to gain access to faster internet connection that is required for data transfer.

6. Conclusion and future work

This paper presents a framework for component-based implementation of the transdisciplinary federated Marine Spatial Data Infrastructure. The main considerations of this framework are, firstly, to preserve the control of data by the custodians in the region, allowing them to share their data according to their national data policies. Secondly, the framework allows ocean related data that is generated across various disciplines, use diverse standards and regulations, to be harmonised and made compatible to geospatial systems. This is achieved using custom code adaptors and standards compliant specifications such as the SpatioTemporal Asset Catalog . Thirdly, the framework allows the remote slicing and dicing of large amounts of stored ocean data through the marine Open Data Cube, an implementation of the Open Data Cube initiative. These technologies assist countries with bandwidth challenges to use the system and only access the amount of data they needed within reasonable bandwidth usage.

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