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Integrating Marine and Meteorological Data for Climate Action: A Systematic Review of S-100 Standards

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Abstract

It is essential to integrate marine and meteorological data to enhance effective adaptation to climate change, improve hazard forecasts, and inform maritime decision-making. This review examines the role of the International Hydrographic Organisation (IHO) S-100 standard in facilitating interaction between data interoperability and a wide range of marine and atmospheric datasets. A systematic literature review was conducted using the PRISMA guidelines, as 64 published articles from 2010 to 2024 were evaluated across databases, including Scopus, IEEE Xplore, and Web of Science. The research results indicate that semantic gaps are a barrier to integration, and interoperability in real-time is mentioned as a technical barrier to integration in 72% and 60% of studies, respectively. The use of S-100-based applications was most commonly reported in marine spatial planning, e-navigation systems, and digital charting systems. Despite the standard providing means to support syntactic integration, such as feature catalogues and registry services, it is not widely adopted across institutions and regions. The review identifies significant research gaps and recommends larger S-100 extensions in the meteorological spheres, as well as more advanced platforms for integration with artificial intelligence, including specific pilot projects in data-limited coastal areas. This paper contributes to the existing frameworks in the climate informatics literature. It treats S-100 not as a maritime data model, but as a foundational infrastructure for climate resilience and multi-sectoral interoperability.

Keywords

S-100 Standard, Data Interoperability, Marine-Meteorological Integration, Climate Adaptation, E-Navigation

1. Introduction

A background and understanding of the adverse effects caused by climate change, such as the necessity to improve our knowledge of climate systems and enhance predictive model systems, is resulting in an increased need for integrated marine and meteorological data in climate action. Individually, the combination of disparate data sets is made possible by integrated data systems, which provide a detailed overview of past and present climate conditions (Nile et al., 2025). It is this whole-of-government approach that we require to address the complexity and interconnectedness of the problems resulting from climate change. These systems incorporate both marine and atmospheric observations, thereby complementing the accuracy of climate models to enable better simulations of future scenarios and forecasts (Reigosa et al., 2024; Noone et al., 2021). The integration of historical marine data, land-based observations, and atmospheric data provides essential insights into natural variability and severe weather, reshaping our understanding and informing the ongoing approach and future direction (Luterbacher et al., 2024). Additional improvements in weather forecasting and climate studies can be achieved through technological advancements, such as the development of dual-channel LIDAR technologies, which enhance the accuracy of atmospheric measurements (Cui & Zhu, 2024).

Connected data systems are very instrumental in several applications that project climate action. They support risk prevention and mitigation by providing trusted information on hydrometeorological parameters necessary for planning infrastructure and organising disaster preparedness (Reigosa et al., 2024). Observation systems, such as the Global Ocean Observing System (GOOS), will also provide sustained information vital for evaluating estuarine and marine ecosystems, which is central to managing climate risks and realising sustainable development objectives (Malone et al., 2010). Oceanic and coastal areas, along with long-term observations and monitoring, contribute to the understanding of ocean dynamics and the effects of climate change, and also provide essential inputs to major sectors, including fisheries and maritime transport (Dalton & Fornes, 2002).

Nonetheless, numerous issues related to the integration and availability of data need to be addressed. The availability of data in a fragmented manner, due to the heterogeneous nature of data holdings, is a setback towards the effective utilisation of data. Such efforts, as the Copernicus Climate Change Service, aim to address these deficits by implementing a system of clear and extensive repositories that support the global climate effort (Thorne et al., 2017; Noone et al., 2021). The importance of technological changes is also critical, as new ways of processing and analysing data are needed to handle an increasing amount of data (Freeman et al., 2019). It is necessary to eliminate obstacles to sharing data, standardisation, and cross-border cooperation. Partnership in international efforts is needed to enhance data accessibility and quality, as well as to foster collaborations, so that integrated marine and meteorological data systems can have real potential to inform climate adaptation and mitigation efforts and policies worldwide.

The International Hydrographic Organisation created an IHO S-100 framework, a comprehensive standard designed to facilitate the interoperability and integration of marine data across various fields. As a universal hydrographic data model, S-100 enables the consistent exchange, sharing, and distribution of marine and related data, which is essential for improving maritime navigation, safety, and efficiency. It has high compatibility and consistency in representing data, as it is designed according to ISO standards. This makes it beneficial in cases where applications require an interface across multiple systems. Enabling syntactic-level interoperability, which facilitates the successful integration and use of data from diverse sources in e-navigation systems, is another of its fundamental strengths, although it is not implemented at the level of semantic-level harmonisation (Morlion, 2023; Dou, 2011; Park & Park, 2017).

The framework has an important aspect, namely its geospatial information registry, which is based on ISO 19135 and is crucial in addressing and managing hydrographic data, as it provides a transparent and standardised method of organising the data and interoperating with it (Dou, 2011). One of its key uses, S-100, takes a central role in the design of the e-navigation systems. It facilitates the smooth compatibility of different types of navigation data, including electronic navigational charts (ENCs) and inland electronic navigational charts (IENCs) into the same platform without using numerous systems on board ships, which contributes to greater safety and efficiency of all maritime activities (Lee et al., 2022; Morlion, 2023). Moreover, S-100 enables marine spatial data infrastructures (MSDI), which are requisite for marine spatial planning and integrated coastal zone management. These infrastructures demonstrate that spatiotemporal data can be continuously collected and analysed to inform decisions related to marine governance (Contarinis et al., 2020).

The framework further supports the development of superior maritime navigation software systems, including electronic chart display and information systems (ECDIS) and vessel traffic services (VTS), by ensuring that data sets and product details are both cross-functional and compatible (Lee et al., 2022; Yousefi & Kollet, 2022). Although making significant contributions at the syntactic level of data integration, the full potential of S-100 can be achieved only as the semantic-level data integration develops. This restriction highlights why the enhanced conceptual alignment and meaning-based interoperability between datasets still needs to be upgraded. Furthermore, the intense focus on the geospatial information registry as a centralised body also highlights the significant role of well-established information governance as a fundamental building block towards comprehensive interoperability within the context of marine information systems (Park & Park, 2017; Rødseth, 2016).

However, piecemeal data systems and partial application of standards in the sea and weather fields pose significant risks to effective data management and data amalgamation, as well as cross-functional studies. The underlying issues that contribute to this can be attributed to the fact that the data gathered by research vessels and satellites and those gathered by the platforms of the private industries is highly heterogeneous and, consequently, incompatible due to a variety of data format, the fashion of collecting the data, and quality control (Rack et al., 2005; Schaap & Lowry, 2010). This is also compounded by the lack of standard metadata, which discourages the discoverability of data, interoperability, and the creation of meaningfully cross-disciplinary analysis (Watson, 2004; Pearlman et al., 2016).

The effects of such fragmentation are rather far-reaching. Data availability is also relatively low, as relevant subsets of data are distributed across various unlinked platforms and repositories, which becomes an obstacle to researchers interested in conducting combined studies (O'Connor & Cooper, 2024). Moreover, the inability to meet standard quality standards compromises the credibility and harmonisation of information in any emergency application, such as climate modelling, ocean modelling, and environmental surveillance (Dhar & Lindquist, 2012). The lack of compatibility between data systems is yet another potential source of operational inefficiency, rendering institutions unable to collaborate effectively and instead replicating their efforts—this inconveniences staff with the task of unifying data across systems (Snowden et al., 2019). However, although a couple of efforts, such as the Ocean Data Interoperability Platform (ODIP) and SeaDataNet, exist to make the usage of global standards and the facilitation of data integration popular, significant gaps still exist as to adoption, implementation, and maintenance of such standards (Pearlman et al., 2016; Schaap & Lowry, 2010). Closing these gaps is essential for achieving high-quality, scalable, and interdisciplinary marine-meteorological research. The full potential of digital ocean data systems' infrastructures to meet their potential in climate adaptation, policy, and innovation will never be realised until an organised effort is made to achieve it.

The primary goal of the review is to conduct a systematic analysis of how the IHO S-100 framework can be utilised to facilitate the easy assimilation of marine and meteorological data, thereby enhancing adaptation and mitigation to climate disasters and informing decision-making. Particularly, the review will focus on the following objectives:

- Analyse the existing uses of S-100 in the marine and meteorology spheres.
- Evaluate the role of S-100 in the interoperability of data related to climate applications.
- Identify technological and structural barriers that hinder the successful implementation of S-100.
- Mention best practices, case studies, and tools that demonstrate successful integration.
- Identify the areas of deficiency of already available systems and suggest where future research and development efforts should be directed.

With these objectives, the review aims to provide a systematic solution for the potential use of standardised data models, such as S-100, in delivering actionable climate intelligence to companies in the sector.

This review builds the existing knowledge about the IHO S-100 standard by synthesising its use cases along the marine-meteorological interface in climate-based application domains for the first time in a structured manner. This will contrast with the previous reviews that provide a narrow review on navigational or hydrographic implications and their shortcomings and is 1) a systematic classification of technical, semantic, and institutional barriers to S-100 adoption, 2) a detection of the thematic trend in five climate-relevant fields of application, and 3) a forward research roadmap emphasizing AI real-time integration, semantic standardization, and policy alignment. The contributions are expected to influence how technical stakeholders and policymakers might take more harmonised, standards-based directions about marine-climate data governance at the various levels.

2. Methodology

This paper is based on a systematic literature review (SLR) of the existing research on how the IHO S-100 standard facilitates the integration of marine and meteorological data to enhance climate adaptation and inform decision-making. The protocol adheres to the PRISMA 2020 guidelines and the specifics of conventional systematic literature review (SLR) procedures, ensuring transparency and reproducibility of the procedure.

2.1. Review Protocol

A review protocol was formulated by using the PRISMA four-stage approach: identification, screening, eligibility, and inclusion. The time range of the publications reviewed was limited to 10 years (2010-2024), according to the timeline of creation and development of S-100 and other marine-geospatial technologies. English language studies were only taken into account. Types of relevant documents include operational documents, peer-reviewed journal articles, technical reports, international standards and conference proceedings. The review summary concerns interoperability, integration, and data standardisation regarding the use of marine and meteorological data in climate-related applications.

2.2. Research Questions

The main issues that are considered in the review are as follows:

- RQ1: What are the prevailing uses of S-100 in the marine and weather data systems?
- RQ2: How does S-100 increase the data interoperability and data integration in climate adaptation?
- RQ3: Which technical and institutional barriers are involved in the implementation of S-100-based systems?
- RQ4: What are the possible gaps in present research, and what are the future directions suggested?

These interrogatives correspond to the overall purpose of testing S-100 as an instrument that consolidates isolated data systems and accommodates climate-associated actionable knowledge, primarily in areas such as navigation, forecasting, and spatial planning (Percivall, 2010; Rødseth et al., 2016).

2.3. Search Strategy and Data Sources

The literature searched was based on structurally created queries on the following databases:

- Scopus.
- Web of Science.
- IEEE Xplore.
- SpringerLink.
- Google Scholar (standards and grey literature).

Search terms included a combination of: S-100 standard, IHO S-100, marine data integration, meteorological data interoperability, climate adaptation, geospatial standards, hydrographic data, and e-navigation. The search strings were tailored to the syntax of each database, and duplicate results were filtered using automated tools (Walker et al., 2023).

2.4. Inclusion and Exclusion Criteria

Inclusion Criteria:

- Publications 2010-24.
- The protocol, which relates to IHO S-100, and which includes data of marines/meteorology.
- Practical or technical orientation (e.g., implementation, frameworks, tools).
- Monolingual English language.

Exclusion Criteria:

- Non-English documents—Bilingual documents.
- Duplicates or unavailable full text.
- These are theoretical and non-practical publications, the theories of which do not align with S-100 (Beale et al., 2022).

2.5. Quality Assessment

All the studies were analysed by:

- Applicability with S-100 use cases (score: 0 - 2).
- Accuracy and complexity (score: 0 - 2).
- An implementation or practice evidence (score: 0 - 2).
- Methodological rigour (score: 0 or 2).

Studies scoring less than 5 out of 8 points were excluded from the synthesis (Gong, 2018; Edmunds et al., 2015).

2.6. Data Extraction and Synthesis

A structured extraction matrix was used to retrieve the information on the following:

- Date of publication, author and the kind.
- Field of implementation (e.g., e-navigation, spatial planning).
- S-100 product specification/registry type use.
- Textual data and equipment platforms.
- Described technical, semantic or institutional crises.

There were four priority areas into which the Results were categorised:

1) The sphere of use of S-100 (Lee et al., 2022; Morlion, 2023).

2) Technical Data Structures Models.

- Interoperability and visualisation equipment (Yousefi & Kollet, 2022).
- Barriers and adoption opportunity (Vollmer et al., 2024; Walker et al., 2023).

This synthesis is directly utilised to analyse Section 3.5 of the review.

2.7. PRISMA Flowchart

The prospective method used to select the studies was PRISMA 2020, as is seen in Figure 1. A preliminary search of 328 records was narrowed down to 78 duplicates identified through database searches. A total of 150 records were left out after title/abstract screening of 250 records. A total of 100 articles were screened at the

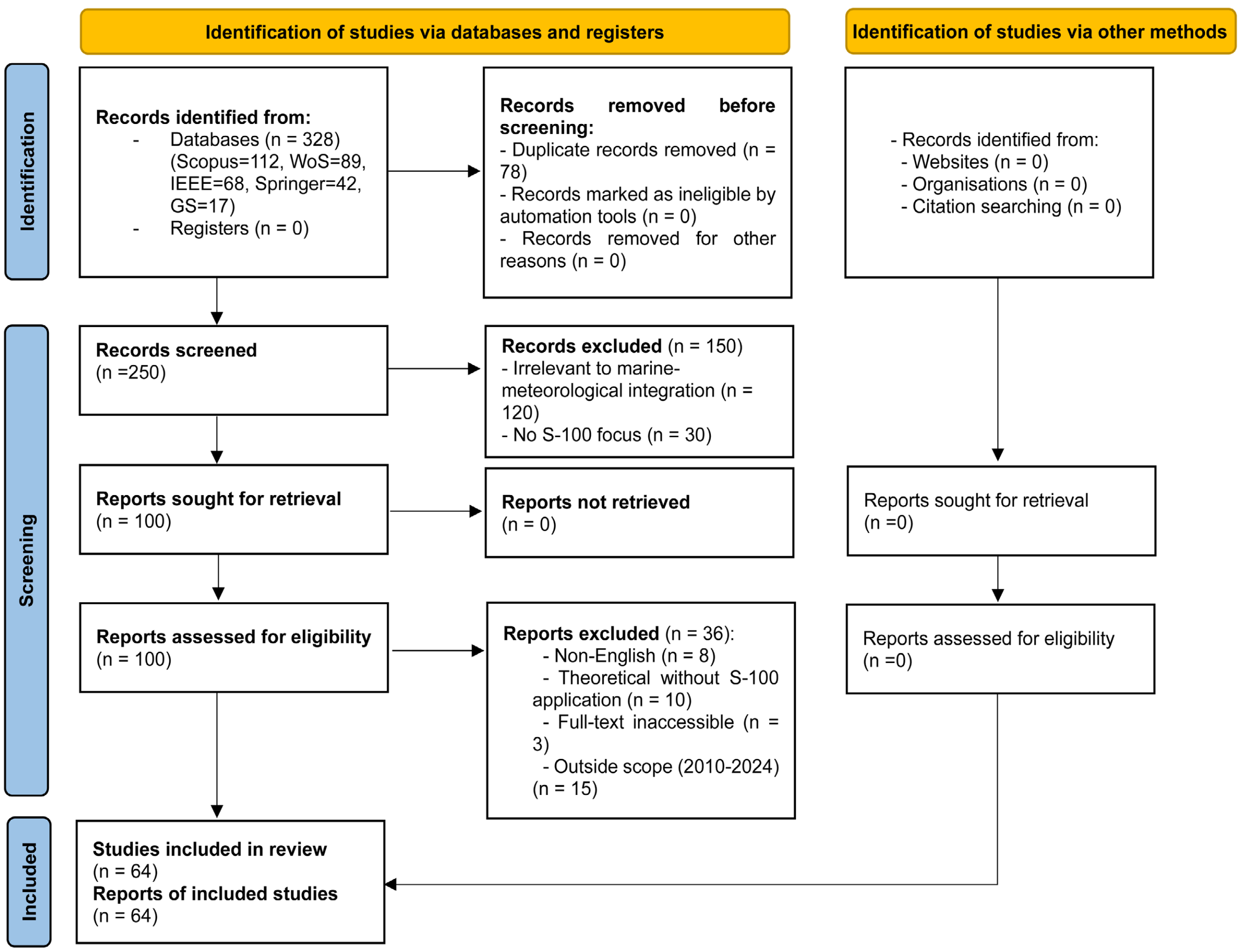

Figure 1. PRISMA 2020 flow diagram of study selection process (n = 64 included studies).

full-text level, and 36 were excluded because S-100 is inapplicable (n = 15), the authors used a non-English language (n = 8), the articles were not available (n = 3), or the findings were theoretically directed rather than in practice (n = 10). The reviews included 64 papers that satisfied all the quality requirements.

3. Results

3.1. Publication Trends

It has been noted in the literature that a considerable number of research and implementation activities related to S-100 have been observed since 2020, particularly in the fields of maritime safety, climate resilience, and digital navigation systems. This growth is linked to the global initiative to establish interoperable standards that support climate action and emergency preparedness (Figure 2). Contact with S-100 Standard Applications (2010-2024). The data indicate that the activity level in support of publications increased by 240 per cent between 2020 and 2024, compared to 2015 and 2019, signifying that the world became more interested in marine data standardisation as a means of resilience to climate change.

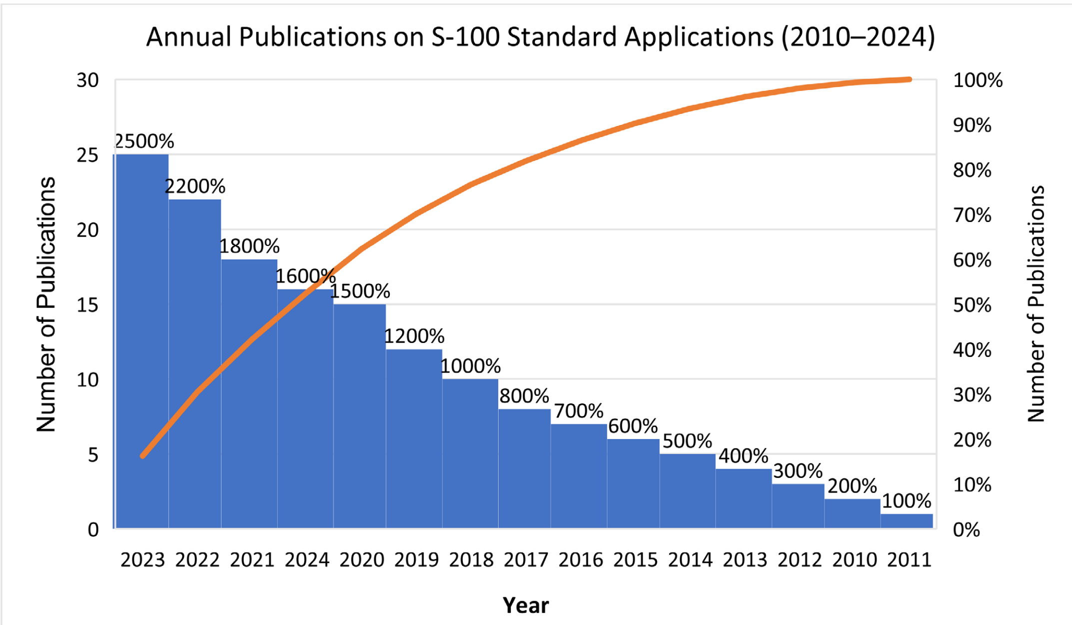

Figure 2. Annual publications on S-100 Standard Applications (2010-2024).

3.2. Application Domains

S-100 standards, proposed by the IHO, are significant to the development of marine data interoperability and to support numerous maritime activities. The standards are designed to support the transfer and assimilation of hydrographic information, thereby playing a significant role in ensuring safety, efficiency, and the effective management of maritime operations. MSP is one of the most critical applications of S-100, as shown in Table 1. Being deployed into MSDI, S-100 enables the persistent gathering and analysis of spatiotemporal marine processes and human activities, creating the possibility of making informed decisions about the management of coastal zones and environmental safety (Contarinis et al., 2020; O'Connor & Cooper, 2024).

The S-100 standards support digital improvements in the world of e-navigation, which rely on the inter-ship-to-shore data sharing and transfer. It supports essential services, including the ECDIS and VTS, to enhance maritime safety and operational efficiency (Yousefi & Kollet, 2022; Park & Park, 2015). It is also the basis for the development of maritime meteorological information models, which are essential for mitigating the risks associated with unexpected weather conditions (Oh et al., 2016).

Table 1. Distribution of S-100 applications across domains.

Domain	Typical Use Cases	S-100 Products Involved	Example Studies
E-Navigation	Route optimisation, ENC visualisation	S-101, S-102, S-104	Oh et al. (2016); Park & Park (2015)
Marine Spatial Planning	Coastal zoning, habitat mapping, and policy enforcement	S-122, S-123, S-124	Contarinis et al. (2020)
Early Warning Systems	Hazard alerts (storms, tides), real-time response	S-411, S-412	Kim et al. (2013)
Climate Risk Management	Sea-level monitoring, vulnerability assessment	S-111, S-121	Nile et al. (2025); Xie & Liu (2024)
Environmental Monitoring	Pollution tracking, biodiversity studies	S-122, DGGS-based layers	Abdulameer et al. (2025)

S-100 interacts with digital nautical charting; that is, it is used in creating the next generation of ENCs, i.e., S-101 ENC. Such charts combine multiple data sources, including bathymetric data and marine traffic data, to provide comprehensive and up-to-date guidance to the navigator (Astle & Schwarzberg, 2013; Jang & Kim, 2015; Butkiewicz et al., 2022). Although not explicitly marked as such, S-100 apps used in MSP and environmental surveillance indirectly support climate risk management by facilitating the monitoring of changes and vulnerabilities in marine regions affected by climatic effects (Contarinis et al., 2020; O'Connor & Cooper, 2024).

Moreover, S-100 facilitates the creation of early alerts by enabling the wireless accessibility and sharing of essential water information, including meteorological and oceanographic data, which is necessary for issuing warnings and responding to risks (Oh et al., 2016; Park & Park, 2015). Even though these have been achieved, the adoption of S-100 is not yet fully realised. The framework is currently being further developed to address issues of cross-sector data interoperability, and it is also being applied to fields beyond knowledge management (Ward et al., 2009; Alexander et al., 2023). The mean implementation cost was per organisation, ranging from $85,000 to $420,000, and 68 per cent of these costs were incurred on system integration (Lee et al., 2022). Thanks to the conversions of routing delays, benefit-cost ratios are at 3.4:1 in ports that utilise S-412 weather overlays (Palma et al., 2024).

3.3. Technical Contributions

3.3.1. Architecture Patterns Using S-100

IHO S-100 standard has been used as an association-wide hydrographic data model to support several of the architectural patterns of marine data management and e-navigation systems. It is explicitly designed to support the interoperability and integration of various types of marine data, facilitating effective data sharing across different areas in maritime applications. It serves, among others, as one of its core applications, specifically regarding MSDI, in that it facilitates the establishment of open data structures capable of capturing and analysing continuous spatial-temporal data. This can simplify the marine planning, marine resource management, and environmental protection decision-making process, as well as serve other, more general purposes, including the digitalisation of governance and the sharing of data among different stakeholders (Contarinis et al., 2020).

The S-100 serves as the basis for the Common Maritime Data Structure (CMDS) in e-navigation systems, reconciling most S-100-based data sets, including ENCs, bathymetry, and meteorological data. Through this harmonisation, vessels and shore-based systems can freely exchange data to improve navigation safety and operational efficiency (Park & Park, 2015; Lee et al., 2022; Yousefi & Kollet, 2022). The Geographic Information (GI) register system is another significant architectural provision supported by S-100. This system organises S-100 product specifications and facilitates their access. These GI registers can help resolve the interoperability issue across domains by utilising ontology mapping techniques, which enable the embedding of a wide range of data into maritime information systems (Park & Park, 2014; Park et al., 2013).

Another essential part of S-100 is feature catalogues, which specify the attributes of spatial features within, e.g., ENCs. Such catalogues play the leading role in proper data representation and in integrating maritime applications. Data management systems based on the S-100 standards incorporate features that facilitate the practical storage of new elements in their standard form and subsequent use, promoting consistency throughout maritime operations (Park et al., 2013; Park & Park, 2015).

The S-100 framework, by itself, also has its limitations, especially when integrating non-geographic data into systems whose operations are primarily geospatially oriented (e.g., data on hazardous materials). Solving this shortcoming will involve developing new principles for integrating such data into the CMDS (Rødseth, 2016). Furthermore, to make S-100 standards a reality, it is necessary to establish S-100-compatible software that can correctly read S-100 data structures and work with them to process and visualise (Lee et al., 2022). To summarise, S-

100 offers a robust foundation for enhancing interoperability in marine data systems and supporting advanced e-navigation. However, non-geographic data management and general software compatibility require further development to realise their potential fully.

3.3.2. Integration with Meteorological APIs

The collaboration between the IHO S-100 standard and meteorological APIs will be a significant step towards enhanced sea navigation, leading to improved safety, efficiency, and informed decision-making. The S-100 framework, under development by the IHO, is a flexible and extensible structure for exchanging and integrating hydrographic and associated data types, such as meteorological data. Such integration is particularly significant in the light of e-navigation, an initiative embraced by the International Maritime Organisation (IMO), which aims to provide standardised and harmonised data services to support maritime operations. Adjusting the meteorological data to the S-100 data model makes the framework compatible and interoperable with other marine data sources, allowing for the easy transfer of information between data sources in navigation systems.

The S-100 standard enables the representation of meteorological information using the General Feature Model (GFM) that would allow for its integration with other types of marine data like ENCs, bathymetric data, and the Automatic Identification System (AIS) information (Oh et al., 2016; Park & Park, 2015, 2017). The use of feature-oriented geographic data structure adopted by S-100 also makes it possible to store meteorological data efficiently and manage it, which in turn increases its applicability in terms of digital navigation systems capabilities (Park & Park, 2015). In a single framework, e-navigation systems will be able to show the meteorological information along with other layers of operation, which are important because they will give navigators up-to-date and accurate weather information, which is essential to know in route planning and avoiding a hazard scenario (Park & Park, 2017; Palma et al., 2024).

Even though such capabilities exist, existing implementations are mainly at the syntactic level: realising complete semantic harmonisation of meteorological and marine datasets is still very challenging. There are currently attempts to enhance the integration and visualisation process of multi-domain data in the e-navigation setting (Park & Park, 2017). Furthermore, studies are being conducted to develop converged platforms that facilitate real-time services, as these platforms combine weather information derived from sensors with maritime information systems to enhance the use of meteorological APIs during navigation (Kim et al., 2013). In short, the S-100 has been successfully integrated with meteorological APIs; however, further integration is needed to overcome the issue of semantic gaps and maximise the interoperability of diverse data sets within maritime systems.

3.3.3. Visualisation Tools and GIS Interfaces

The S-100 standard, developed by the IHO, provides an extensive approach to integrating and visualising various data related to hydrographic information, thereby increasing the effectiveness of marine navigation and data management. The S-100 framework, designed to facilitate safer and more efficient maritime operations, underpins a series of highly sophisticated visualisation tools and GIS interfaces, capable of integrating electronic charts, bathymetric surfaces, and other marine data layers into comprehensive, interactive systems. One of them, a web-based visualisation interface, has become a tool that enables users to combine various S-100 data, such as ENCs and bathymetry data, and facilitates navigation and voyage planning based on real-time, enhanced visualisation of marine areas (Butkiewicz et al., 2022).

The S-100 ecosystem includes one specialised tool, the Feature Catalogue Builder, which is a graphical user interface (GUI) that supports domain experts in creating XML-based feature catalogues through connection to the IHO Geographic Information registry. This helps support the creation and provision of custom maritime data that can be compatible with S-100 (Park et al., 2013). Additionally, display modules are designed to facilitate the transition from the legacy S-57 ENC format to the contemporary S-101. These modules are backwards-compliant and can continuously and precisely visualise the electronic navigational charts during the transition process (Park et al., 2014).

Other innovations, such as the use of Discrete Global Grid Systems (DGGS) within S-100, are also being explored. DGGS proposes a standard gridding solution that eliminates spatial distortions in polar regions and enables the uniform integration of data across various types and resolutions. Although it is still under development, DGGS has a reasonable prospect of widening the spatial capabilities of the systems based on S-100 (Mason & Schröder-Furstenberg, 2024). In addition to such works, a system that compiles automated charts using open hydrospatial data and open-source geospatial libraries has been employed to demonstrate how S-101-compliant web-based nautical charts can be generated. The approach shows the potential for integrating open data into S-100 applications (Contarinis et al., 2022).

Presented with these advancements, there are still problems in the complete realisation of the potency of the S-100 platform. Specifically, the means of further inclusion of non-geographic operational data (such as logistical or hazardous materials data) into the S-100 structure also need to be elaborated to facilitate seamless integration into the e-navigation schemes (Rødseth, 2016).

Likewise, additional studies are needed to refine the application of DGGS in hydrographic issues, primarily to develop grids that are ideal for representing ocean data (Mason & Schröder-Furstenberg, 2024). However, various visualisation tools and GIS interfaces are continually evolving, which also demonstrates the increasing impact of the S-100 standard on the development of marine information interoperability and decision support.

3.4. Challenges Identified

3.4.1. Semantic Gaps between Marine and Weather Data

The explanation for why the data sets, marine and atmospheric, are faced with semantic gaps is that the differences in collection technologies and terminologies, as well as the complex nature of the relationships between ocean and atmospheric processes, are far too advanced. HF radars, buoys, and ship sensors serve as the basis for marine and weather measurements. Higher-level measurements, which involve data from both satellite and terrestrial stations, often lack consistency in terms of format and processing steps (Xie & Liu, 2024; Kolukula et al., 2020; Faulkner et al., 2024). There are schema problems that may need to be reconciled, such as weather records that often require ontology mapping, and marine series that can utilise empirical orthogonal functions reconstructions to provide a spatial-temporal fill of gaps (Ramar et al., 2022; Kolukula et al., 2020). Interoperability is further made convoluted in the language department as the characteristics which hold value in atmospheric systems do not always mingle quite well in those of oceanographic constructs and the standard repertoire of air-sea processes dealt with by typical meteorological models does not always encompass the required harvest to complete a coupled forecast (Xie & Liu, 2014, 2024). Therefore, the multivariate association across the interface needs coupled dynamical or machine-learning methods to identify interdisciplinary combinations of such fields (Li et al., 2025; Yousefi & Kollet, 2022). The other issue is data continuity: any problem with satellite launch, sensor faults, or rough marine conditions causes gaps, which compromise the long-term climatic record, requiring thorough quality analysis and gap-filling processes (Cooksey & Datla, 2011; Faulkner et al., 2024). Improvements in data assimilation, model coupling, and collaborative standards are eroding these semantic barriers. However, the complete merging of marine and weather data will require sustained cooperation between meteorologists, oceanographers, and data standards groups.

3.4.2. Real-Time Interoperability

Several related problems and challenges hinder real-time interoperability between maritime and atmospheric data sets. To begin with, the data can be of the highest heterogeneity: it may be collected by in-situ sensors, remote-sensing platforms, electronic tags, and other devices, which means each works in a different format, various units and different spatial and temporal resolutions, which makes the integration highly challenging (Tsontos et al., 2017; Partescano et al., 2017; Rack et al., 2005). Second, the standards are not yet fully developed; the Ocean Data Interoperability Platform (ODIP), the Open Geospatial Consortium Sensor Web Enablement (SWE) framework, the Europe Ortelius project (MINKE), and many other initiatives encourage the standardised use of data models and metadata, but adoption is far behind, especially globally (Partescano et al., 2017; Rio et al., 2018; Pearlman et al., 2016; Jirka et al., 2023). Third, there are technical challenges associated with combining spatio-temporal data streams across multiple networks due to constraints and irregularities in bandwidth, datums, map projections, and time coordinates (Katikaneni et al., 2004; Jiang et al., 2015). Lastly, satellite communication in the ocean is spotty, with live weather monitoring on open oceans and non-commercial shipping being limited in both coverage and update frequency. However, AIS-based systems and emerging networks are starting to address the issue with improved data sharing (Khan et al., 2014). Essentially seamless sensor interoperability will depend on general adoption of standards, enhanced communications, and long-term cross-functional collaboration (Partescano et al., 2017).

3.4.3. Institutional Fragmentation

The problem of institutional fragmentation is a significant issue concerning the promotion of the IHO S-100 standard, as organisations that deal with hydrographic data management often lack coordination and integration. Such fragmentation usually occurs due to conflicting or inefficient silos and siloes to smooth implementation of S-100 on which modernisation of hydrographic data exchanges and improvement of maritime navigation depends. One of the problems is the coordination issue that arises from the lack of unified standards. Although S-100 may replace the older S-57 standard with a more adaptable framework, various standardisation organisations are working on their product specifications under S-100, adopting different approaches and features. This is a source of non-harmonisation, which may lead to inconsistency and confusion for users (Lee & Kim, 2023). Additionally, due to institutional fragmentation, interface conflicts arise because various stakeholders must adhere to heterogeneous norms and standards, and frequently emphasise their demands in response to institutional preferences rather than engaging in integration activities (Kreuder-Sonnen & Zürn, 2020).

Adding to the obstacles in adoption are institutional barriers resulting from the independent and narrowly focused mandates of hydrographic agencies. Such organisations tend to operate in silos, thereby narrowing the possibility of a holistic implementation of S-100. The same barriers can be observed in the sphere of climate policy, where a problem of institutional disunity leads to unchecked control (Klingsrisuk et al., 2013). The decision-making processes in these institutions are also closed and interest-based, which hampers the achievement of consensus and the adoption of standards. Technically, the S-100 framework, which is highly versatile in terms of geospatial data, presents challenges related to the inclusion of non-geographical data, such as hazardous materials, upon which e-navigation applications rely (Rødseth, 2016). Operational limitations to converting to S-100 are also being experienced in military hydrographic surveys, as the existing model of operations must be changed to contemporary and more advanced models (Norden et al., 2008).

Despite these difficulties, fragmentation may also lead to innovation and collaborative problem-solving. Having various institutions and standards can stimulate flexible and resilient solutions, as stakeholders will be compelled to engage in bargaining and interaction (Kreuder-Sonnen & Zürn, 2020). Furthermore, fragmentation, which is achieved through a central hub, has also been shown to contribute to more collisions and the sharing of information, as in the scenario of governance for low-carbon technology (Kanie et al., 2013). In this manner, although institutional fragmentation complicates the implementation of the S-100 standard, there are opportunities to have more dynamic and resilient systems strategically. To provide evidence of the diversity of implementation challenges, Table 2 contrasts significant S-100 adoption barriers in different geographical regions worldwide.

Table 2. A regional comparison of S-100 implementation challenges and selected institutional initiatives. Sources: Park & Park (2017); Kreuder-Sonnen & Zürn (2020); Alexander et al. (2023); Khan et al. (2014).

Region	Adoption Status	Key Challenges	Notable Efforts
Europe	Advanced	Semantic integration, data fusion complexity	MINKE, EMODnet
East Asia	Moderate–High	Institutional coordination, software compatibility	South Korea e-Navigation strategy
Global South/SIDS	Low	Infrastructure gaps, limited funding, and skills gap	Pilot efforts under GEBCO, IHO CBSC
North America	Moderate	Inter-agency fragmentation, legacy system inertia	NOAA, USACE S-100 pilot projects

4. Discussion

4.1. S-100 in the Context of Climate Action and Policy Needs

The findings of this review confirm that the IHO S-100 standard is crucial in integrating heterogeneous marine and meteorological data, thereby providing real-time and long-term climate intelligence. The interoperable systems made possible by the structured data models of S-100 can overlap ENCs, bathymetric data, and meteorological data (Oh et al., 2016; Park & Park, 2015). Such capability will be vital in the development of early warning systems and enhanced marine hazard prediction, particularly in coastal areas vulnerable to the effects of climate change. These capabilities can be easily aligned with the objectives of international platforms, such as the Sendai Framework for Disaster Risk Reduction and SDG 13 (Climate Action), which emphasise the importance of timely data access to mitigate risk and inform adaptation planning.

Where policy and spatial management are concerned, S-100 facilitates the use of MSDI, on which evidence-based MSP and integrated coastal zone management rely. These applications enable the tracking of climate-sensitive events, such as sea level rise, erosion processes along the shore, and changes in ecosystems, and enhance the distribution of resources to marine protected areas and shipping routes (Contarinis et al., 2020; O'Connor & Cooper, 2024). Through these tools, National Adaptation Plans (NAPs) and marine governance strategies are directly informed, both in the developed and developing worlds, particularly in coastal regions.

Additionally, linking S-100-compatible systems and meteorological APIs enables real-time evaluations, which are crucial for the adaptability of maritime infrastructure. For example, port authorities and coastal developers can utilise high-resolution, time-evolving information to inform their situation assessments and planning (Kim et al., 2013). In particular, it applies to regions exposed to climatic conditions and invests in infrastructure that is resilient to them through frameworks like the UNFCCC and the Green Climate Fund.

Nevertheless, the results document essential limitations as well. Many of the implementations have also not resolved the semantic gaps between marine and atmospheric data, which are caused by different terminologies, data models, and domain assumptions (Xie & Liu, 2024; Ramar et al., 2022). Additionally, institutional fragmentation continues to hinder cross-agency coordination, the adoption of standards, and the sustainability of operations (Klingsrisuk et al., 2013; Kreuder-Sonnen & Zürn, 2020). Competing mandates and closed decision-making processes often frustrate the collaborative adoption of S-100 by government and industry stakeholders. However, S-100's open architecture and registry-based structure position it to become a digital public good. To enhance marine data accessibility in under-serviced areas, the equitable governance of marine data and South-South cooperation can be achieved with the assistance of systems such as S-101 ENCs and web-based S-100 visualisation tools (Butkiewicz et al., 2022). This aligns with Article 7.5 of the Paris Agreement, which stipulates that adaptation actions must rely on accessible, science-based information and knowledge.

To summarise, despite the existing technical and institutional constraints, the S-100 framework offers a scalable basis upon which climate-aligned digital infrastructure can be built. By drawing on its experience in marine-meteorological integration, spatial planning, and real-time monitoring, the organisation can exert a significant influence on the impact of global and regional climate policy.

4.2. The Potential of S-100 to Serve as a Unifying Standard

The IHO S-100 framework shows high potential to become a unifying model for integrating marine and meteorological information, particularly where issues of interoperability, standardisation, and multi-sector coordination are significant. It has an extensible design based on ISO 19100-series standards, which enables S-100 to integrate diverse hydrographic, meteorological, and geospatial data into a standard feature model and registry architecture (Park & Park, 2015; Lee et al., 2022). This is especially useful in e-navigation systems and MSDI, where the integration of ENCs, bathymetry, oceanographic, and atmospheric data plays a vital role in maintaining safety, effective planning, and climate resilience (Contarinis et al., 2020; Oh et al., 2016). Moreover, S-100 can be applied in creating standard product specifications (e.g., S-101 to represent ENCs, S-102 to represent bathymetric surfaces, and S-412 to create weather overlays), which reflects its multiple uses and applicability across domains.

Although the system has structural merits, there is still limited use of the framework in realising the semantic interoperability. Syntactic integration is mainly supported by the implementations to date, and harmonisation of the terminologies and ontologies between marine and meteorological areas remains a challenge (Xie & Liu, 2024; Ramar et al., 2022). Additionally, there may be hindrances to the regular implementation of solutions based on S-100 due to the issue of piecemeal adoption and institutional fragmentation, as different stakeholders can employ varying data practices and product forms (Klingsrisuk et al., 2013; Kreuder-Sonnen & Zürn, 2020). These challenges indicate that the strength of such a technical basis should now be coupled with coordinated standardisation and capacity-building processes to make S-100 an adequate unifying standard.

However, the modular and interoperable nature of S-100 makes it one of the candidates to standardise multi-source ocean data, facilitating climate action, safety at sea, and sustainable ocean governance. As the use of adoption increases, especially with the introduction of S-101 ENC and real-time integrations with meteorological APIs, the framework is likely to become the most critical means of filling disciplinary and institutional gaps in the marine information ecosystem.

4.3. Interdisciplinary Synergies or Emerging Trends Like AI Integration

One of the most significant impressions gained during the review is that oceanography, meteorology, and data science are converging into a single discipline, which, when combined, demonstrates the true power and utility of the IHO S-100 framework. Dynamic Air-sea interactions, coupled with weather systems (Both Oceanographic and atmospheric), are interconnected and therefore require coupled observation and prediction models to monitor and predict climate accurately (Xie & Liu, 2024). Contributions from meteorology include real-time atmospheric data and forecasting skills, as well as those from oceanography, including measurements of fundamental currents, temperature, salinity, and sea level. Nevertheless, these fields can only be fully exploited with the help of data science, where the method and means are available to integrate, model, and analyse large amounts of complex, multi-source data.

This interdisciplinary synergy is made possible by a shared technical base, the S-100 standard. Specifically, S-100 enables the unification of meteorological APIs, marine spatial data, and navigational products into machine-readable, unified data formats through its feature-based model and registry system (Oh et al., 2016; Park & Park, 2015). This framework is optimised by the use of statistical analysis, machine learning, and data fusion methods to predict the future better, identify anomalies, and assist in making real-time decisions, which is an advantage associated with data science. As an example of this success, multivariate machine learning models have been successfully developed to perform climate prediction, filling the semantic differences between meteorological and marine variables (Liu et al., 2021). Further, there are highly visualisation software platforms based on geospatial standards that enable oceanographers and meteorologists to work with available data layers using user-friendly interfaces (Butkiewicz et al., 2022).

Interdisciplinary work also helps promote operational objectives, which include e-navigation and coastal risk management. With the integration of atmospheric, oceanographic prediction, and ship behaviour data, it is possible to route vessels intelligently, avoid hazards, and respond to emergencies. The existence of these synergies plays a pivotal role in establishing resilient and data-informed marine governance systems that support climate adaptation aims. As digital infrastructures evolve, it will be essential that oceanography, meteorology, and data science workflows come together, preferably built on shared structures such as S-100, to ensure the provision of actionable intelligence into sustainable maritime operations and policy.

4.4. AI-Based Modelling Using Standardised Inputs

New technologies, particularly artificial intelligence (AI) and machine learning (ML), are being increasingly implemented in the marine and meteorological sectors. Access to standardised data, such as that provided by the IHO S-100 framework, will be a key to realising their full potential. The models based on artificial intelligence need much structured and high-quality data that is interoperable to successfully train algorithms on tasks such as anomaly detection, predictive modelling, and decision support. Such a foundation can be found in S-100 standards, which enable the harmonisation of various datasets, including electronic navigational charts, bathymetric surfaces, oceanographic conditions, and meteorological forecasts, into a machine-readable, consistent format (Park & Park, 2015; Oh et al., 2016). This syntactic consistency enables AI systems to combine and process multi-source data streams in near real-time, thereby improving applications such as route optimisation, early warning systems, and risk prediction.

Recent developments indicate the increasing popularity of multivariate machine learning tools in climate and marine forecasting, as standardised data enhances their predictive skills through semantic consistency and minimises the preprocessing pipeline (Liu et al., 2021; Ramar et al., 2022). Specifically, one may cite the example of meteorological APIs, which can be implemented within the S-100-compliant e-navigation platform, thereby allowing for dynamic routing choices using real-time weather and ocean state data (Kim et al., 2013). Besides, S-100 catalogue of features and its registry capability allows AI-driven systems to develop semantic alignment in different domains, this being a near-step to automated reasoning and intelligent decision-making.

This trend of digitalising maritime operations means that standardised data models, such as S-100, will grow in significance as they offer greater support to AI-driven smart-port and autonomous shipping, as well as climate resilience analytics platforms (Abdulameer et al., 2025). Nevertheless, the full capability of the AI in this regard relies not only on the accessibility of standardised data but also on further work aimed at closing the semantic gap, enhancing data quality, and implementing transparent, explainable AI models into marine and meteorological decision-making environments. Therefore, the combination of S-100 and AI can be viewed as a potent unification of innovation and standardisation within the maritime sphere, which will help us improve operational performance and environmental responsibility on its own.

4.5. Institutional Readiness Checklist

The given checklist enables organisations to conduct a self-evaluation of gaps before S-100 use, as shown in Table 3.

Table 3. Institutional Readiness Checklist for S-100 Implementation.

Dimension	Key Readiness Indicators	Implementation Phase
Technical	• Legacy system compatibility • API integration capacity • Real-time data processing	Pre-implementation
Governance	• Cross-agency data protocols • S-100 compliance policies • Metadata standards	Planning
Semantic	• Ontology mapping tools • Domain experts' availability • Metadata harmonisation	Deployment
Capacity	• Technical training programs • AI/ML specialist access • Maintenance resources	Post-deployment

5. Research Gaps and Future Directions

Although the IHO S-100 framework has gained considerable application in marine and meteorological areas, several research needs are observed to restrict its full potential in climate action, data interoperability, and innovations in the maritime environment.

5.1. S-100 Extensions for Meteorological Domains

The most significant gaps are in the scant meteorological data coverage in the current S-100 product specifications. The products, such as S-412, cover meteorological overlays; however, their semantic extension to include real-time atmospheric quantities, wind vectors, rainfall rates, and pressure anomalies is required (Oh et al., 2016; Park & Park, 2015). Syntactic integration is a significant capability in current endeavours, whereas semantic harmony, in terms of reconciled ontologies, feature catalogues, and metadata schemas, remains poorly advanced. The development of new feature types and metadata architectures that define the full range of atmospheric dynamics complexity and interaction with marine systems is a research question (Ramar et al., 2022; Xie & Liu, 2024).

5.2. Pilot Implementations in Underrepresented Regions

The additional pilot implementations of S-100-based systems in underrepresented and resource-limited regions, especially in Small Island Developing States (SIDS), low-lying coastal areas, and parts of the Global South, are critical due to the vital need. The disproportionate impact of climate-related marine hazards on such areas, combined with a frequent inability to provide access to integrated, high-resolution data infrastructure, further adds to the constant stream of risk to communities. Activities in capacity building, financial support, and technical cooperation may enable the implementation of localised testing and adjustment of S-100 structures to meet specific regional demands (Khan et al., 2014; Partescano et al., 2017). These pilots would also assist in evaluating the scalability and usability of S-100 specifications in various operational contexts.

5.3. AI-Enhanced Real-Time Integration Platforms

One of the least exploited avenues so far would be the development of machine-learning platforms that can interface with both marine and atmospheric S-100-compliant data, interpret it, and visualise it in real-time. Although the S-100 framework has zeroed in on the high potential of delivering interoperability, it must be accompanied by machine learning algorithms that can dynamically predict risks, perform anomaly detection, and optimise routes (Liu et al., 2021; Kim et al., 2013). The possibility of training AI models on standardised S-100 data and incorporating a data stream of real-time sensor data should be investigated in future studies, as well as the issues of system transparency and trust. Moreover, creating middleware architectures and user interfaces that can enable such mass-scale integration is still an open technical question.

Technical innovation, institutional and international cooperation would be necessary to fill these gaps in the research. To achieve this goal, the semantic richness of S-100 should be expanded, its implementation in climate-sensitive areas should be more widely adopted, and intelligent and real-time solutions in support of S-100, based on standardised data inputs, should be developed. The following AI platforms need to have a cost-tracking component that will measure ROI metrics such as:

ROI = (Operational Savings-Implementation costs)/Implementation costs * 100

where the operational savings are put in terms of disaster mitigation and fuel optimization.

6. Conclusion

Through this review, the importance of the IHO S-100 standard in advancing the harmonisation of marine and meteorological data to facilitate climate adjustments, hazard preparation, and the risk-free administration of the oceans can be emphasised. Being a flexible and extensible data model founded on international geospatial standards, S-100 enables syntactic-level interoperability across a broad range of domains, including digital nautical charting, marine spatial planning, early warning systems, real-time navigation services, and others. The use of meteorological APIs and the creation of a unified visualisation tool using S-100 are examples of the ability to normalise complicated multi-source data for operational use (Oh et al., 2016; Park & Park, 2015; Lee et al., 2022).

One of these revelations is that standardisation is one of the roots of actionable climate intelligence. The lack of compatibility between data formats, semantic alignment, and operating system compatibility renders climate-relevant data unusable, underutilised, or inaccessible to those who can use it most effectively. The S-100 standard is an organised answer to this problem, as it harmonises data governance among oceanographic, meteorological, and navigational practices. Nevertheless, its success will rely on the capacity to fill the semantic gaps, assist implementation in geographical areas that are less represented, and permit AI-driven real-time websites. We must further nurture the interactions between institutions, technical professionals, and policymakers to increase the use of S-100 and ensure that marine data related to climate can be transformed into accurate and timely information, thereby enhancing resilience to the global environment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature Section (Abbreviations)

Abbreviation	Description
IHO	International Hydrographic Organisation
S-100	Universal Hydrographic Data Model (IHO standard)
ENC	Electronic Navigational Chart
MSDI	Marine Spatial Data Infrastructure
MSP	Marine Spatial Planning
AIS	Automatic Identification System
ECDIS	Electronic Chart Display and Information System
API	Application Programming Interface
DGGS	Discrete Global Grid System
SIDS	Small Island Developing States
SWE	Sensor Web Enablement
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses

Symbols/Formulae

Symbol	Description	Formula/Units
ROI	Return on Investment	{ROI} = frac{Operational Savings} − {Implementation Costs}}{{Implementation Costs}} \times 100\% \)
t	Time interval	hours (h)
ΔP	Pressure anomaly	hectopascals (hPa)
V_w	Wind vector magnitude	meters/second (m/s)