

Review

Oceanographic Buoys for Marine Monitoring: A Review of Instrumentation, Applications, and Emerging Technologies

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Abstract

Oceanographic buoys are essential platforms for marine observation, supporting real-time monitoring, climate studies, operational oceanography, coastal management, and offshore activities. This review maps the scientific literature on oceanographic buoys and identifies the main research sectors that structure the field. A Scopus search using TITLE-ABS-KEY((oceanographic OR metocean OR “ocean observing” OR “ocean observation”) AND (buoy OR buoys)) retrieved 1876 documents published between 1938 and 2026. The records were processed using a network-based sector detection and visualization workflow. Five thematic sectors were identified: platform engineering, sensors, moorings, and autonomous systems; marine wind, waves, metocean, and offshore energy applications; physical oceanography, sea-surface temperature (SST), currents, and environmental variability; coastal and ocean observing networks and operational services; and drifting buoys, floats, and global ocean datasets. The results show that buoy research has evolved from isolated measurement systems to integrated observing infrastructures that combine in situ sensing, satellite validation, autonomous operation, telemetry, and decision-support services. By linking bibliometric structure and thematic interpretation, this review provides a sector-based map showing where scientific observation, engineering design, operational services, and autonomous technologies converge.

Keywords: autonomous platforms; marine monitoring; metocean; ocean observing systems; oceanographic buoys; sensors; thematic sector analysis; wave energy



Academic Editor: João Miguel Dias

Received: 27 May 2026

Revised: 11 July 2026

Accepted: 13 July 2026

Published: 14 July 2026

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1. Introduction

Oceanographic observation is essential for understanding marine processes, supporting climate studies, improving coastal management, and enabling operational decision-making in offshore and coastal environments [1]. The ocean is a highly dynamic system in which physical, chemical, biological, and meteorological variables interact over a wide range of spatial and temporal scales. Continuous and reliable measurements are therefore required to characterize sea-state conditions, water-column variability, air–sea interactions, ecosystem dynamics, and extreme events [2]. In this context, oceanographic buoys have

become one of the most relevant platforms for in situ marine monitoring, as they can provide long-term observations under real environmental conditions and in locations where ship-based campaigns or fixed coastal stations are insufficient [3,4].

Despite their relevance for marine observation, the scientific literature on oceanographic buoys remains highly heterogeneous and fragmented across several disciplines, including physical oceanography, marine engineering, environmental monitoring, remote sensing, telecommunications, sensor development, operational oceanography, and coastal management [5,6]. As a result, existing studies often focus on specific applications or technological aspects, such as wave measurement [7], drifting-buoy trajectories [1], water-quality sensors [8], telemetry systems [9], or early-warning networks [10]. This dispersion makes it difficult to obtain an integrated view of the field, identify the dominant research areas, and determine the main technological and methodological challenges currently shaping the development of oceanographic buoys.

Oceanographic buoys are used in a wide variety of applications, including metocean monitoring, wave and current measurements, sea-surface temperature and salinity observations, water-quality assessment, tsunami and storm-surge warnings, aquaculture monitoring, offshore renewable-energy assessment, and climate-related studies [4]. Depending on their configuration and deployment strategy, these platforms may operate as moored buoys, drifting buoys, profiling systems, or integrated nodes within broader ocean observing networks [11]. Their value lies not only in acquiring environmental data but also in their capacity to support real-time monitoring, early-warning systems, numerical model validation, and decision-support tools for maritime activities [12].

In recent decades, the development of oceanographic buoys has evolved from conventional measurement platforms toward increasingly autonomous, connected, and sensor-rich systems [5]. Advances in marine instrumentation, embedded electronics, low-power data acquisition, satellite and wireless communications, energy management, and data-processing techniques have expanded the capabilities of buoy-based monitoring [8]. Modern buoy systems can integrate multiple sensors, acquire high-frequency time series, transmit data in near real time, and operate for extended periods with limited maintenance [13]. At the same time, the marine environment imposes demanding technical constraints, including corrosion, biofouling, mechanical stress, power autonomy, sensor drift, calibration stability, and data-quality assurance [14,15].

A structured review of the literature is therefore necessary to clarify the scientific landscape of oceanographic buoy research. Previous reviews have addressed broader ocean-observation technologies, the historical development of observing systems, or specific operational and application domains. In contrast, this review provides a Scopus-based sector map of 1876 records focused specifically on oceanographic buoy research and interprets how scientific, operational, and engineering dimensions interact across the field. Rather than providing a purely bibliometric description, this review aims to synthesize the main research lines by combining a broad literature search with thematic sector detection. This approach enables the organization of a large body of publications into coherent research areas and the development of a critical analysis of the applications, measurement variables, technological solutions, and limitations associated with buoy-based ocean observation. In this manuscript, the term sector refers to the organization of the literature into thematic sectors derived from the Scopus document-similarity network. The word sector does not refer to an economic, industrial, or institutional sector. Instead, it denotes a group of publications that share similar terminology, applications, platform types, measured variables, or research objectives.

The scientific contribution of this review is threefold. First, it provides a sector-based map of 1876 Scopus-indexed publications on oceanographic buoy research, enabling the

field's main thematic areas to be identified reproducibly. Second, it interprets these sectors from technical and operational perspectives, linking buoy applications to instrumentation, platform engineering, observing networks, drifting systems, and global ocean datasets. Third, it identifies cross-sector trends and future requirements related to autonomy, interoperability, data quality, and integration with multi-platform ocean-observing systems.

Based on this contribution, the specific objectives of the review are:

- Identify the main thematic sectors within oceanographic buoy research;
- Analyze the principal applications and measured variables associated with each sector;
- Examine the technological components involved in buoy-based monitoring, including sensors, data acquisition, communication, and energy supply;
- Discuss current limitations and future trends in the development of autonomous and intelligent buoy systems.

By providing this thematic synthesis, the article aims to support researchers and practitioners involved in the design, deployment, and use of oceanographic buoy platforms for environmental, operational, and scientific applications.

The remainder of the paper is organized as follows. Section 2 describes the Scopus search strategy, data preparation, similarity network construction, sector detection, and the visualization workflow. Section 3 presents the corpus structure, the five detected thematic sectors, and the highly cited representative studies associated with each sector. Section 4 discusses the meaning of the detected sectors, cross-sector trends, future perspectives, and methodological limitations. Finally, Section 5 summarizes the main conclusions and implications for future oceanographic buoy research.

2. Materials and Methods

2.1. Data Source and Search Strategy

The bibliographic corpus was retrieved from Scopus on 21 May 2026 using the search equation TITLE-ABS-KEY((oceanographic OR metocean OR "ocean observing" OR "ocean observation") AND (buoy OR buoys)). The search was designed to capture studies that explicitly combine buoy platforms with oceanographic, metocean, or ocean-observing terminology. The search returned 1876 records. No additional limits by year, document type, source title, or subject area were applied, thereby retaining the field's full historical and thematic scope.

To assess the precision of the broad Boolean query, a title and abstract relevance screening was performed on a random sample of 100 records from the corpus. Records were classified as directly relevant, indirectly relevant, or tangential/possible false positives. The screening identified 53 directly relevant records, 35 indirectly relevant records, and 12 tangential or possible false-positive records, indicating that 88% of the sampled records were directly or indirectly connected to buoy-based observation, buoy data, drifters/floats, moorings, or related ocean observing networks.

2.2. Data Preparation

For each record, the available bibliographic information was exported, including title, abstract, authors, source title, year of publication, document type, DOI, Scopus identifier, citation count, and subject descriptors. The textual fields were standardized before analysis by applying basic cleaning procedures, harmonizing repeated word forms, and removing terms of low thematic value. This preprocessing reduced noise while preserving the corpus's main scientific and technical vocabulary.

2.3. Similarity Network and Thematic Sectors

The similarity-network workflow was implemented in Python 3.12.13 using pandas 3.0.1 and numpy 2.3.5. Textual information from titles, abstracts, and subject-area descriptors was transformed into a TF-IDF document representation. Term frequencies were log-scaled, multiplied by inverse document frequency, and L2-normalized. Terms were retained when they appeared in at least four documents and in no more than 55% of the corpus, and the vocabulary was limited to the 2500 most informative terms. Document similarity was then calculated using cosine similarity. A sparse document-similarity network was built by retaining up to the eight strongest links per document when cosine similarity was at least 0.12, producing 10,811 weighted edges among 1876 nodes. Sector assignment was performed using spherical k-means with 5 clusters, a fixed initialization seed, and a maximum of 80 iterations. The resulting node table, edge list, and GraphML (XML 1.0) file were exported for visualization and inspection. Because sector assignment was obtained using spherical k-means rather than a modularity-based community detection algorithm, no Louvain, Leiden, or resolution/gamma parameter was used.

The five-sector solution was retained after comparing neighboring resolutions and inspecting the thematic coherence of the resulting clusters. Four clusters produced a broader structure but merged the drifting-buoy, float, and global-dataset literature with the physical-oceanography and SST domain. Six clusters produced only a marginal increase in network modularity but fragmented the physical-oceanography domain into narrower subgroups. The five-sector solution was therefore selected as a macro-sector resolution that balanced quantitative network separation with thematic interpretability.

Sector labels were assigned after reviewing the dominant terms, representative titles, publication sources, publication years, and highly cited studies in each group. The final classification contained five thematic sectors: platform engineering, sensors, moorings, and autonomous systems; marine wind, waves, metocean, and offshore energy applications; physical oceanography, sea-surface temperature (SST), currents, and environmental variability; coastal and ocean observing networks and operational services; and drifting buoys, floats, and global ocean datasets. All 1876 records were assigned to one of these sectors. In this context, a thematic sector is defined as a cluster of publications with shared textual similarity and coherent scientific or technological content, rather than as an economic or institutional sector.

The computational sector assignment was not manually modified after clustering. Manual review was used only to assign meaningful sector labels and to check the thematic coherence of dominant terms, representative titles, publication sources, and highly cited records within each sector. This review was conducted by the authors involved in methodology and formal analysis, and disagreements in sector naming or interpretation were resolved by consensus. Because individual records were not manually reclassified, no inter-annotator agreement statistic was calculated for record-level assignment.

2.4. Visualization and Interpretation

The network and sector assignments were exported as node and edge tables and as a GraphML file for reproducible visualization. The thematic sector map was generated from the document-similarity network and used to support the qualitative interpretation of the sector structure. Total citation counts from Scopus were used to identify historically visible representative publications within each sector. To reduce the age bias inherent in total citation counts, a citation rate indicator was also calculated as citations per year, using the formula: citation count / (2026 – publication year + 1). This normalized indicator was reported alongside total citations in the sector tables.

In contrast, source-title information was used to compare the publication outlets associated with each research area. The processed corpus, node table, edge list, sector assignments, and tables of highly cited representative articles were retained as Supplementary Materials to ensure reproducibility. The complete methodological workflow is summarized in Figure 1.

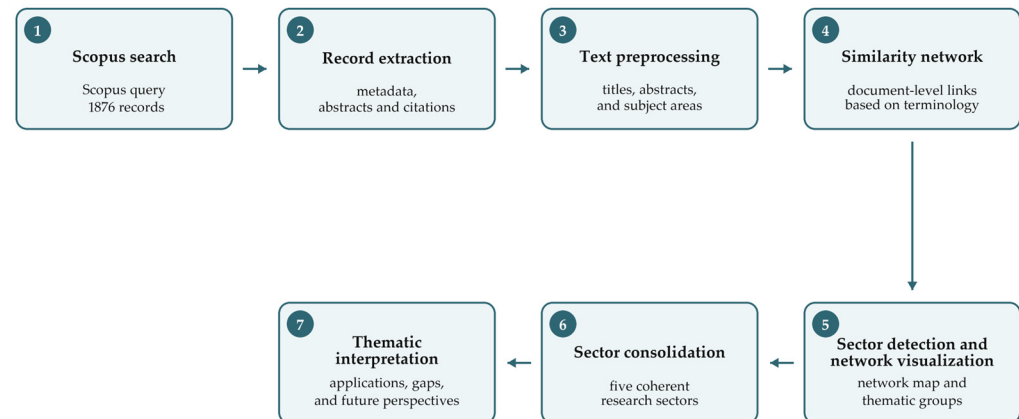


Figure 1. Methodological workflow used to retrieve, process, visualize, consolidate, and interpret the Scopus corpus.

3. Results

3.1. Corpus and Similarity Network

The Scopus search retrieved 1876 publications related to oceanographic buoys. The corpus covers a broad temporal range, from early studies on buoy-based measurements and moored instrumentation to recent work on autonomous platforms, satellite validation, intelligent monitoring, metocean applications, and offshore energy systems. The similarity network contained 1876 nodes and 10,811 weighted edges, with a network density of 0.0061 and an average degree of 11.5. Node degrees ranged from 4 to 34 links, and edge weights, corresponding to cosine similarity values, ranged from 0.120 to 1.000. Sector detection produced five macro sectors, with sizes ranging from 200 to 504 publications. The weighted modularity of the five-sector partition was 0.497; comparison with neighboring resolutions showed modularity values of 0.478 for four sectors and 0.501 for six sectors, indicating that the six-sector solution produced only a small quantitative gain while reducing interpretability. Figure 2 shows the thematic sector map used to interpret the corpus, where nodes represent publications, edges represent textual similarity between publications, colors indicate the five consolidated thematic sectors, and node size is proportional to document degree.

The five consolidated sectors are summarized in Table 1. For each sector, the table reports the number of documents, the publication-year range, the median publication year with interquartile range, and the main thematic focus inferred from the most frequent terms and representative titles. This summary provides the basis for the sector-by-sector analysis developed in the following subsections.

The temporal distribution indicates that the field is concentrated in the recent literature rather than evenly distributed across the full historical range. Although the corpus spans 1938–2026, 1652 of the 1876 records were published from 1990 onward. Records published in 2026 and indexed in Scopus up to the retrieval date of 21 May 2026 were included in the sector-detection network and in all downstream statistics. Annual output increased especially after the early 2000s, reaching 96 records in 2025; the lower value for 2026 reflects the partial publication year at the time of retrieval. This temporal pattern supports the interpretation that oceanographic buoy research has expanded alongside the development

of satellite validation, operational observing systems, autonomous platforms, and offshore energy applications.

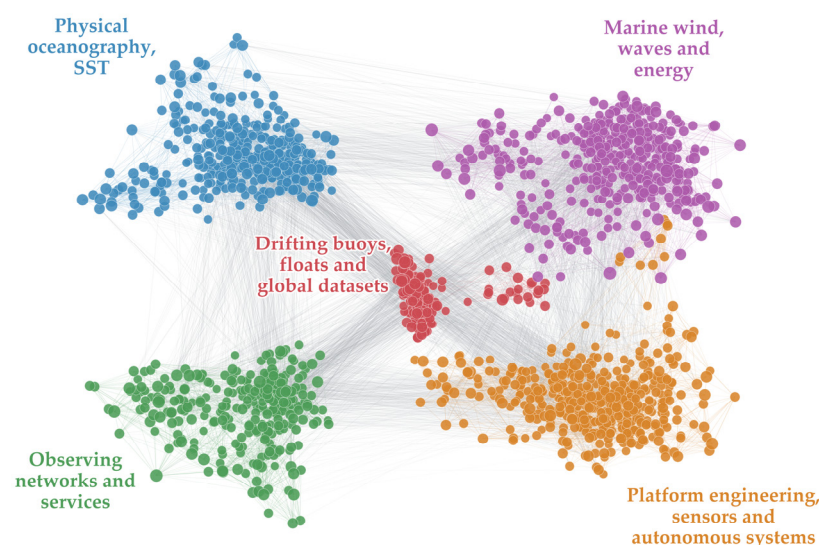


Figure 2. Thematic sector map generated from the Scopus document-similarity network. Each node represents one Scopus record, node color indicates the consolidated thematic sector, and node size is proportional to document degree, ranging from 4 to 34 links. Edges represent cosine-similarity links between records; edge weights ranged from 0.120 to 1.000 and are provided in the Supplementary Materials file *scopus_oceanographic_buoy_edges.csv*. Edges are displayed with uniform low opacity to improve the readability of the global network structure.

Table 1. Thematic sectors detected in the Scopus corpus, including document counts, publication-year ranges, median publication year, interquartile range, and main thematic focus.

Sector	Doc.	Years	Median Year (IQR)	Focus
Platform engineering, sensors, moorings, and autonomous systems	504	1938–2026	2010 (1996–2018)	Sensors, mooring design, power supply, underwater communication, autonomous platforms, acoustic systems, and platform integration.
Marine wind, waves, metocean, and offshore energy applications	433	1968–2026	2017 (2007–2023)	Wind speed, wave height, sea-state parameters, metocean hindcasts, offshore engineering, and wave-energy or offshore-energy applications.
Physical oceanography, SST, currents, and environmental variability	419	1945–2026	2012 (2002–2020)	Sea-surface temperature, currents, satellite validation, coastal variability, air–sea interaction, and environmental ocean observations.
Coastal and ocean observing networks and operational services	320	1963–2025	2009 (2004–2016)	National and regional observing systems, coastal monitoring networks, operational oceanography, real-time services, and public data infrastructures.
Drifting buoys, floats, and global ocean datasets	200	1958–2026	2005 (1996–2017)	Drifting buoys, drifter data archives, profiling floats, global ocean datasets, data assimilation, and large-scale ocean-observing programs.

The most frequent publication sources support the thematic interpretation of the detected sectors. “Oceans Conference Record” (IEEE) was the most frequent source in

the platform-engineering sector (52 documents), the coastal and ocean observing networks sector (44 documents), and the drifting-buoy/global-dataset sector (18 documents). “*Ocean Engineering*” (Elsevier) and the “OMAE conference series” (American Society of Mechanical Engineers) were the most frequent sources in the wind, waves, metocean, and offshore energy sectors, with 30 documents each. “*Journal of Oceanography*” (Springer) was the most frequent source in the physical oceanography, SST, currents, and environmental variability sector, with 29 documents. Because the “Oceans Conference Record” (IEEE) series appeared among the most frequent sources across several sectors, an additional sensitivity check was performed by excluding conference papers and conference reviews, retaining only article and review records. This restricted subset contained 1054 records, and all five sectors remained represented: platform engineering, sensors, moorings, and autonomous systems (230 records); marine wind, waves, metocean, and offshore energy applications (259 records); physical oceanography, SST, currents, and environmental variability (346 records); coastal and ocean observing networks and operational services (110 records); and drifting buoys, floats, and global ocean datasets (109 records). This check indicates that the five-sector structure was not driven solely by conference literature. However, the platform-engineering and coastal/operational-network sectors were more strongly represented in conference proceedings than in the other sectors. The recurrence of the OCEANS series should therefore be interpreted as evidence of its role as a broad venue for applied ocean-observing technology, rather than as evidence that the detected sectors are merely artifacts of conference indexing.

Citation accumulation by source provides a complementary perspective to publication frequency. In the physical oceanography, SST, and environmental variability sector, the journal “*Journal of Oceanography*” (Springer) received the most citations, with 882 citations across 27 documents. In the marine wind, waves, metocean, and offshore energy applications sector, the “*Journal of Atmospheric and Oceanic Technology*” (American Meteorological Society) was the most-cited source, with 1065 citations across 14 documents. In the coastal and ocean observing networks and operational services sector, “*Journal of Geophysical Research—Oceans*” (American Geophysical Union) received the most citations. However, this result was driven by a single highly cited publication with 927 citations. In the platform engineering, sensors, moorings, and autonomous systems sector, “*Applied Optics*” (Optica Publishing Group) was the most-cited source, with 559 citations across three documents. Finally, in the drifting buoys, floats, and global ocean datasets sector, the “*Journal of Atmospheric and Oceanic Technology*” (American Meteorological Society) had the highest citation count, with 676 citations across eight documents. These results indicate that the most frequent and most cited publication sources do not always coincide, suggesting that sector visibility is shaped by both sustained publication activity and a smaller number of highly influential papers.

3.2. Platform Engineering, Sensors, Moorings, and Autonomous Systems

The largest sector comprises 504 documents and focuses on the engineering systems that enable buoy-based observation. Frequent terms include sensor, mooring, monitoring, surface, water, design, current, platform, power, underwater, communication, acoustic, measurement, and energy. Representative studies address wireless sensor networks for marine monitoring, biofouling protection, unmanned marine platforms, autonomous Lagrangian floats, and optical or moored observatory systems [16–18].

Table 2 summarizes highly cited representative publications in this sector, covering marine sensor networks, biofouling protection, unmanned vehicle platforms, autonomous floats, optical buoy calibration, mooring design, AUV navigation, and power/data transmission for moored observing systems.

Table 2. Ten highly cited representative articles in the platform engineering, sensors, moorings, and autonomous systems sector, including total Scopus citations and citations per year.

Rank	Title	Source	Year	Cit.	Cit./Year
1	Applications of wireless sensor networks in marine environment monitoring: A survey [16]	<i>Sensors Switzerland</i>	2014	369	28.4
2	Biofouling protection for marine environmental sensors [17]	<i>Ocean Science</i>	2010	237	13.9
3	Marine environmental monitoring with unmanned vehicle platforms: Present applications and future prospects [18]	<i>Science of the Total Environment</i>	2023	205	51.2
4	Performance of autonomous Lagrangian floats [19]	<i>Journal of Atmospheric and Oceanic Technology</i>	2003	144	6.0
5	Calibration of SeaWiFS. I. Direct techniques [20]	<i>Applied Optics</i>	2001	118	4.5
6	The BOUSSOLE Buoy—A new transparent-to-swell taut mooring dedicated to marine optics: Design, tests, and performance at sea [21]	<i>Journal of Atmospheric and Oceanic Technology</i>	2008	85	4.5
7	Initial results from the Bermuda Testbed Mooring program [22]	<i>Deep Sea Research Part I Oceanographic Research Papers</i>	1998	82	2.8
8	PARADIGM: A buoy-based system for AUV navigation and tracking [23]	Oceans Conference Record IEEE	2000	48	1.8
9	Coastal oceanography using a small AUV [24]	<i>Journal of Atmospheric and Oceanic Technology</i>	2001	44	1.7
10	Power feeding and data-transmission system using magnetic coupling for an ocean observation mooring buoy [25]	<i>IEEE Transactions on Magnetics</i>	2007	44	2.2

3.3. Marine Wind, Waves, Metocean, and Offshore Energy Applications

The second sector contains 433 documents and groups studies related to wave height, wind speed, significant wave height, offshore conditions, metocean hindcasts, floating-platform motion, and marine renewable-energy applications. Representative studies include altimeter-derived wind and wave datasets, floating wind-wave energy systems, multiplatform wind-wave calibration, wave-energy resource assessments, and sea-state monitoring using coastal GNSS-R [26–28].

Table 3 lists highly cited representative publications in this sector, which cover calibrated satellite wind-wave datasets, offshore energy systems, altimeter calibration, wave-energy resource assessment, oceanographic modeling winds, GNSS-R sea-state monitoring, air–sea interaction buoys, and self-powered sensor-buoy concepts.

Table 3. Ten highly cited representative articles in the marine wind, waves, metocean, and offshore energy applications sector, including total Scopus citations and citations per year.

Rank	Title	Source	Year	Cit.	Cit./Year
1	33 years of globally calibrated wave height and wind speed data based on altimeter observations [26]	<i>Scientific Data</i>	2019	269	33.6
2	Dynamic response and power performance of a combined Spar-type floating wind turbine and coaxial floating wave energy converter [27]	<i>Renewable Energy</i>	2013	257	18.4

Table 3. Cont.

Rank	Title	Source	Year	Cit.	Cit./Year
3	Joint calibration of multiplatform altimeter measurements of wind speed and wave height over the past 20 Years [28]	<i>Journal of Atmospheric and Oceanic Technology</i>	2009	195	10.8
4	Assessment of wave energy resources in Hawaii [29]	<i>Renewable Energy</i>	2011	163	10.2
5	Assessment of wind quality for oceanographic modeling in semi-enclosed basins [30]	<i>Journal of Marine Systems</i>	2005	159	7.2
6	Sea-state monitoring using coastal GNSS-R [31]	<i>Geophysical Research Letters</i>	2004	149	6.5
7	ASIS-a new Air-Sea Interaction Spar buoy: Design and performance at sea [32]	<i>Journal of Atmospheric and Oceanic Technology</i>	2000	133	4.9
8	Design of oscillating-water-column wave energy converters with an application to self-powered sensor buoys [33]	<i>Energy</i>	2016	99	9.0
9	Oceanic internal tides: Observations, analysis and modeling: A global view [34]	<i>Oceanic Internal Tides Observations Analysis and Modeling A Global View</i>	2018	91	10.1
10	HF radar data quality requirements for wave measurement [35]	<i>Coastal Engineering</i>	2011	88	5.5

3.4. Physical Oceanography, Sea-Surface Temperature, Currents, and Environmental Variability

The third sector comprises 419 documents and focuses on physical oceanography, sea-surface temperature, currents, satellite validation, coastal variability, and environmental ocean observations. Frequent terms include surface, temperature, current, observation, water, sea surface, measurement, satellite, coastal, region, variability, speed, product, and wind speed. Representative studies address tropical observing systems, ocean heat budget closure, satellite wind vector validation, vicarious calibration, SST datasets, and moored climate arrays [36–38].

Table 4 summarizes highly cited representative publications in this sector, which cover tropical observing systems, air–sea fluxes, satellite wind and ocean-color validation, SST products, moored climate arrays, coastal cyclone interactions, and buoy-based comparisons with surface-flux products.

Table 4. Ten highly cited representative articles in the physical oceanography, SST, currents, and environmental variability sector, including total Scopus citations and citations per year.

Rank	Title	Source	Year	Cit.	Cit./Year
1	The Tropical Ocean-Global Atmosphere observing system: a decade of progress [36]	<i>Journal of Geophysical Research—Oceans</i>	1998	927	32.0
2	New insights into the ocean heat budget closure problem from analysis of the SOC air–sea flux climatology [37]	<i>Journal of Climate</i>	1999	320	11.4
3	Evaluation of wind vectors observed by QuikSCAT/SeaWinds using ocean buoy data [38]	<i>Journal of Atmospheric and Oceanic Technology</i>	2002	319	12.8
4	Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry [39]	<i>Applied Optics</i>	2007	315	15.8

Table 4. *Cont.*

Rank	Title	Source	Year	Cit.	Cit./Year
5	An Ensemble Data Set of Sea-Surface Temperature Change From 1850: The Met Office Hadley Centre HadSST.4.0.0.0 Data Set [40]	<i>Journal of Geophysical Research Atmospheres</i>	2019	240	30.0
6	A Pilot Research Moored Array in the Tropical Atlantic (PIRATA) [41]	<i>Bulletin of the American Meteorological Society</i>	1998	210	7.2
7	Stratified coastal ocean interactions with tropical cyclones [42]	<i>Nature Communications</i>	2016	191	17.4
8	Sea ice surface temperature product from MODIS [43]	<i>IEEE Transactions on Geoscience and Remote Sensing</i>	2004	180	7.8
9	An evaluation of above- and in-water methods for determining water-leaving radiances [44]	<i>Journal of Atmospheric and Oceanic Technology</i>	2002	173	6.9
10	A comparison of ECMWF, NCEP-NCAR, and SOC surface heat fluxes with Moored Buoy measurements in the subduction region of the Northeast Atlantic [45]	<i>Journal of Climate</i>	2001	109	10.5

3.5. Coastal and Ocean Observing Networks and Operational Services

The fourth sector contains 320 documents and focuses on coordinated observing infrastructures, operational oceanography, coastal monitoring networks, national programs, real-time services, and public environmental information platforms. Representative studies include Deepwater Horizon observing support, PIRATA and NDBC programs, operational monitoring in the Aegean Sea, Mediterranean HF radar coordination, tsunami observing requirements, coastal mooring recommendations, and data-quality procedures for operational networks [46–48].

Table 5 summarizes highly cited representative publications in this sector, which cover sustained observing systems, emergency response, operational forecasting, HF radar networks, tsunami warning requirements, coastal mooring networks, data-quality procedures, and fixed-point observatory networks.

Table 5. Ten highly cited representative articles in the coastal and ocean observing networks and operational services sector, including total Scopus citations and citations per year.

Rank	Title	Source	Year	Cit.	Cit./Year
1	Science in support of the Deepwater Horizon response [46]	<i>Proceedings of the National Academy of Sciences of the United States of America</i>	2012	123	8.2
2	PIRATA: A Sustained Observing System for Tropical Atlantic Climate Research and Forecasting [47]	<i>Earth and Space Science</i>	2019	89	11.1
3	Programs of the National Data Buoy Center [48]	<i>Bulletin American Meteorological Society</i>	1992	70	2.0
4	Operational monitoring and forecasting for marine environmental applications in the Aegean Sea [49]	<i>Environmental Modeling and Software</i>	2006	67	3.2
5	Toward an integrated HF radar network in the Mediterranean sea to improve search and rescue and oil spill response: The TOSCA project experience [50]	<i>Journal of Operational Oceanography</i>	2015	59	4.9

Table 5. Cont.

Rank	Title	Source	Year	Cit.	Cit./Year
6	Ocean observations required to minimize uncertainty in global tsunami forecasts, warnings, and emergency response [10]	<i>Frontiers in Marine Science</i>	2019	54	6.8
7	Coastal mooring observing networks and their data products: Recommendations for the next decade [2]	<i>Frontiers in Marine Science</i>	2019	45	5.6
8	Data quality check procedures of an operational coastal ocean monitoring network [51]	<i>Ocean Engineering</i>	2007	39	1.9
9	The RITMARE italian fixed-point observatory network (IFON) for marine environmental monitoring: A case study [52]	<i>Journal of Operational Oceanography</i>	2016	38	3.5
10	Overview of ocean based buoys and drifters: Present applications and future needs [53]	Oceans Conference Record IEEE	2001	36	1.4

3.6. Drifting Buoys, Floats, and Global Ocean Datasets

The fifth sector comprises 200 documents and covers drifting buoys, drifter archives, profiling floats (including Argo profiling floats), global ocean datasets, data assimilation, satellite-related products, and large-scale observing programs. Representative studies include operational multivariate data assimilation, Gulf and Strait of Hormuz physical oceanography, ICOADS, WOCE-TOGA drifter quality control, ice-tethered profilers, COADS marine surface fluxes, surface-drifter applications, and SST observational requirements [54–56].

Table 6 summarizes highly cited representative publications in this sector, which cover data assimilation, historical marine climate records, global drifter datasets, ice-tethered profilers, surface-drifter applications, SST observing requirements, dynamic topography, and oil-spill modeling.

Table 6. Ten highly cited representative articles in the drifting buoys, floats, and global ocean datasets sector, including total Scopus citations and citations per year.

Rank	Title	Source	Year	Cit.	Cit./Year
1	Operational multivariate ocean data assimilation [54]	<i>Quarterly Journal of the Royal Meteorological Society</i>	2006	638	30.4
2	Physical oceanography of the Gulf, Strait of Hormuz, and the Gulf of Oman-Results from the Mt Mitchell expedition [57]	<i>Marine Pollution Bulletin</i>	1993	625	18.4
3	ICOADS Release 3.0: a major update to the historical marine climate record [58]	<i>International Journal of Climatology</i>	2017	368	36.8
4	Quality control and interpolations of WOCE-TOGA drifter data [55]	<i>Journal of Atmospheric and Oceanic Technology</i>	1996	350	11.3
5	Automated ice-tethered profilers for seawater observations under pack ice in all seasons [59]	<i>Journal of Atmospheric and Oceanic Technology</i>	2008	221	11.6
6	COADS Release 2 data and metadata enhancements for improvements of marine surface flux fields [60]	<i>Physics and Chemistry of the Earth</i>	1998	213	7.3
7	Advances in the Application of Surface Drifters [56]	<i>Annual Review of Marine Science</i>	2017	190	19.0

Table 6. Cont.

Rank	Title	Source	Year	Cit.	Cit./Year
8	Observational needs of sea-surface temperature [61]	<i>Frontiers in Marine Science</i>	2019	186	23.2
9	The new CNES-CLS18 global mean dynamic topography [62]	<i>Ocean Science</i>	2021	141	23.5
10	MEDSLIK-II, a Lagrangian marine surface oil spill model for short-term forecasting-Part 2: Numerical simulations and validations [63]	<i>Geoscientific Model Development</i>	2013	137	9.8

4. Discussion

4.1. Interpretation of the Detected Research Sectors

The sector structure identified in this review indicates that oceanographic buoy research is organized around three complementary dimensions. The first dimension is scientific and operational: buoys provide sustained in situ observations for physical oceanography, SST assessment, satellite validation, forecasting, and coastal services [10,36,61]. The second dimension is technological: buoy performance depends on sensors, moorings, power supply, data acquisition, telemetry, antifouling, calibration, and autonomous operation [16–18]. The third dimension is infrastructural: drifting buoys, profiling floats, global datasets, and operational networks connect individual instruments to large-scale ocean-observing systems [2,58,64].

4.1.1. Platform Engineering, Sensors, Moorings, and Autonomous Systems

The platform-engineering sector shows that the technological core of buoy research has shifted from individual sensors to fully autonomous observing platforms. Wireless marine sensor networks and unmanned monitoring platforms illustrate this shift from isolated measurement devices to integrated systems that combine sensing, control, telemetry, and deployment logistics [16,18]. Studies also show that this technological shift includes dedicated development of current meters and ADCP-based improvements for buoy-mounted measurement stations, reinforcing the need to evaluate the sensor and buoy platform as a coupled measurement system [65,66].

The main technical gap is not simply the availability of better sensors, but the reliability of the complete platform under real marine conditions. Biofouling, sensor drift, calibration stability, underwater communication, mooring loads, and power/data transmission can all degrade the value of otherwise high-quality measurements [17,25,67].

This sector, therefore, reveals an engineering tension between functional complexity and long-term robustness. Newer designs that combine buoy nodes, benthic nodes, electro-optical-mechanical cables, and autonomous vehicle platforms point toward more capable systems. Still, they also increase the number of failure points that must be validated before long deployments [4,18].

For future buoy systems, evaluation should be performed at the platform level. Reliability, maintainability, interoperability, energy autonomy, antifouling, and traceable calibration should be considered together, rather than treated as independent design problems [68,69].

4.1.2. Marine Wind, Waves, Metocean, and Offshore Energy Applications

The marine wind, waves, metocean, and offshore energy sectors link buoy-based monitoring to the characterization of wind-wave climates, offshore design conditions, marine operations, and renewable energy resources. Buoy and altimeter datasets are used

to create calibrated wind and wave records, while metocean datasets support offshore wind simulation and engineering assessment [26,28,70].

Studies use buoy observations to evaluate tropical-cyclone wave reanalysis products and GNSS-R wind-speed retrievals, confirming the role of buoys as reference data for wind and wave products [71,72]. Other contributions compare buoy observations with alternative sea-state estimation approaches, including land-recorded seismic estimates of significant wave height and neural-network estimates derived from measured ship motions [73,74].

The main tension in this sector is the need to translate point-based or sparse in situ observations into robust design information. Offshore engineering and marine-energy applications require estimates of extreme conditions and uncertainty, but buoy records may be limited by location, deployment duration, sensor response, and local exposure [75,76]. This issue is also relevant for offshore buoy-related structures, where wave loading and mooring configuration can influence the dynamic response of hoses, anchor chains, and floating systems [77,78].

The inclusion of wave-energy and floating offshore-energy studies shows that buoy-like platforms are no longer used only as passive observing devices. They increasingly support resource assessment, device validation, and floating-structure design in the blue-energy sector [27,29,79].

Future work in this sector should therefore focus on uncertainty-aware wind-wave datasets, comparable buoy records, and stronger integration among buoy observations, satellite products, hindcasts, and offshore energy models. This is especially important where operational decisions depend on reliable sea-state forecasts and where renewable-energy projects require defensible metocean evidence [80,81].

4.1.3. Physical Oceanography, SST, Currents, and Environmental Variability

The physical oceanography sector confirms that buoys remain reference platforms for ocean variability, air–sea interaction, SST, currents, and satellite validation. Large-scale tropical arrays and moored climate systems show the continuing value of sustained in situ records for understanding ocean dynamics and climate variability [36,41,47].

The key contribution of this sector is the use of buoy observations as benchmark data for products generated elsewhere. Buoy records support SST validation, wind-vector evaluation, ocean heat budget analysis, satellite calibration, and assessment of environmental variability [37,38,61].

The main gap is in maintaining homogeneous, traceable long-term observations across heterogeneous platforms. This is particularly relevant when drifting and moored buoys are compared against satellite-derived products or used to build climate-quality datasets [82,83].

Future observing systems should therefore strengthen calibration continuity, metadata quality, sensor stability, and product-level validation. In this sector, buoy systems should be interpreted less as local instruments and more as reference infrastructure for multi-platform oceanography [61,84].

4.1.4. Coastal and Ocean Observing Networks and Operational Services

The coastal observing and operational services sector reflects the transition from individual buoy deployments to coordinated observing infrastructure. Regional networks, national data-buoy programs, ocean portals, HF radar coordination, and emergency-response observing systems show that buoy research increasingly depends on institutional data-service frameworks [48,50]. Operational observing systems provide a useful example of

this transition, since they combine fixed ocean-observing platforms, sensor integration, real-time transmission, and long-term system maintenance [13].

The value of buoys in this sector lies in their contribution to operational oceanography. Near-real-time observations support forecasts, warnings, maritime safety, emergency response, environmental surveillance, and public information systems [10,46,85]. Environmental-surveillance applications can also extend beyond standard physical variables, as shown by in situ radioactivity monitoring integrated into an ocean-observing platform in the North Aegean Sea [86].

The main tension is that operational networks must combine scientific flexibility with service reliability. A network can only support decision-making if data streams are continuous, quality-controlled, interoperable, and institutionally maintained [2,87,88].

This sector, therefore, shows that the future of buoy-based monitoring depends as much on governance and data infrastructure as on platform hardware. Standardized data flows, shared metadata, clear quality flags, and sustained maintenance are necessary if buoy observations are to remain usable in forecasting and decision-support chains [2,89].

For ocean-observing systems, this implies that buoys should be designed as nodes in an operational service architecture. The relevant unit of analysis is not only the buoy, but the full chain from sensor to telemetry, data portal, quality control, forecast system, warning product, and end user [90,91].

4.1.5. Drifting Buoys, Floats, and Global Ocean Datasets

The drifting-buoy, float, and global-dataset sector highlights the mobile and data-assimilation layers of buoy research. Unlike fixed moorings, drifters and profiling floats extend observing capacity across large spatial domains and help fill gaps in global ocean monitoring [56,61,92]. Argo profiling floats are especially relevant in this sector because they are among the most important examples of autonomous profiling-float technology applied to sustained global subsurface ocean observation, data assimilation, climate research, and operational oceanography [93–95].

The main contribution of this sector is not only additional coverage, but the transformation of mobile observations into quality-controlled datasets for climate, reanalysis, and forecasting. Historical marine climate records, drifter archives, and data-assimilation systems illustrate this role [54,55,58].

The main gap is the harmonization of heterogeneous drifting and profiling observations. Different sensors, sampling schemes, trajectories, deployment conditions, and quality-control procedures must be reconciled before these data can support robust assimilation or long-term environmental assessment [64,83].

Future ocean-observing systems should therefore treat fixed buoys, drifting buoys, profiling floats, gliders, satellites, and models as complementary components of a distributed measurement infrastructure. The strength of this sector lies in its ability to connect local in situ observations with basin-scale and global ocean products [61,96].

The smaller size of this sector (200 documents) should be interpreted cautiously. It may reflect a genuine concentration of drifter and float studies outside the core buoy terminology used in the search. Still, it may also result from the query design because terms such as float, drifter, or mooring were not used as primary search terms unless they co-occurred with buoy-related ocean-observing terminology.

4.2. Cross-Sector Trends in Oceanographic Buoy Research

Across sectors, the first major trend is the role of buoy observations as reference measurements for broader observing systems. This role appears in SST validation, altime-

ter wind-wave calibration, ocean heat-budget analysis, satellite wind retrieval, and data assimilation [26,38,61].

The second trend is the movement from isolated platforms toward integrated observing infrastructures. Coastal mooring networks, PIRATA, NDBC, IOOS, and global drifter programs show that buoy value increases when measurements are connected to standards, data portals, forecasts, and sustained institutional programs [2,47,48].

The third trend is the increasing complexity of platforms. Modern buoy systems combine heterogeneous sensors, onboard electronics, power management, telemetry, antifouling, moorings, and sometimes autonomous or intelligent data handling [4,16,18].

The fourth trend is the overlap between buoy research and remote sensing. Buoys are not isolated data sources; they provide ground-truth measurements for satellite SST, altimetry, scatterometer winds, radar-derived wave products, and multi-platform ocean products [28,80,82].

The fifth trend is interdisciplinarity. Oceanographic buoy research combines physical oceanography, marine engineering, operational services, renewable energy, electronics, communications, autonomous platforms, and data science. This breadth is a strength, but it also creates challenges for terminology, standardization, interoperability, and methodological consistency [11,68,97].

4.3. Future Perspectives and Challenges

Over the period covered by this review, several scientific and technical problems in oceanographic buoy research have matured. These include the transition from isolated buoy deployments to sustained observing networks, the use of buoy records for satellite validation and data assimilation, the development of global drifter and profiling-float datasets, and the implementation of real-time data services and quality-control procedures. However, these advances should not be interpreted as completely solved problems in all contexts. Long-term autonomy, biofouling, sensor drift, calibration stability, interoperability, and operation in extreme or remote environments remain active research challenges.

Several future perspectives emerge from the sector-based analysis. The first challenge is long-term autonomy, because many buoy applications require extended deployments with limited maintenance. Future systems will need more efficient power electronics, optimized sampling strategies, renewable energy harvesting, low-power communication protocols, and intelligent duty cycling [25,98,99]. Energy autonomy is therefore not only a battery management problem; it also motivates buoy designs driven by ocean thermal energy and other harvesting strategies to extend deployment duration [100].

A second challenge is sensor reliability. Marine sensors are exposed to corrosion, biofouling, mechanical stress, drift, calibration instability, and platform motion. Future systems should incorporate antifouling strategies, self-diagnostic functions, redundant measurements, traceable calibration, and automated quality control [17,101,102]. For wave-buoy applications, this also requires explicit treatment of measurement uncertainty during calibration, because calibration-device uncertainty propagates into the reliability of sea-state observations [103].

A third priority is interoperability. As buoy systems become part of larger observing infrastructures, standardization of data formats, metadata, calibration information, communication protocols, and quality flags will become increasingly important [68,89,97].

A fourth future direction is intelligent data processing. Machine learning-based gap filling, wave-height forecasting, uncertainty quantification, anomaly detection, and communication management can improve buoy-system efficiency and data reliability [104–106]. Numerical methods will also remain important in future buoy research. High-fidelity simulations, including CFD and DNS in specific fluid-mechanics problems, can support

platform design, hydrodynamic analysis, mooring assessment, wave–structure interaction studies, and sensor-placement decisions. However, these approaches cannot replace in situ buoy observations in ocean monitoring. Real measurements are still required for calibration, validation, data assimilation, satellite-product assessment, operational forecasting, and long-term environmental records. Numerical approaches should therefore be viewed as complementary tools that increase the value of buoy observations, rather than as substitutes for experimental and field-based monitoring.

A fifth challenge is integration with other observing platforms. Future monitoring will likely combine buoys, satellites, coastal radars, gliders, autonomous underwater vehicles, fixed observatories, drifting arrays, and numerical models. In this context, buoys can act as stable reference nodes within distributed observing systems [50,64,107]. Recent developments in polar buoys further show that integration challenges are expanding toward ecological and under-ice observations, where imaging, satellite telemetry, and robust polar operation must be combined on a single platform [108].

Finally, cost and accessibility remain important. Low-cost and open-hardware buoy systems may expand monitoring capacity in coastal areas, developing regions, aquaculture zones, and educational contexts. Still, lower cost must not replace validation against reference systems [109,110]. Low-cost autonomous multifunctional buoys are a particularly relevant direction because they can combine current measurement, seawater parameter sensing, GPS tracking, local logging, and particle tracking on compact platforms [69].

4.4. Limitations of the Review

This review has several limitations. First, the analysis is based on Scopus. Although Scopus provides broad coverage of peer-reviewed scientific literature, the results remain influenced by database-specific indexing, source coverage, language coverage, and document-type selection [111,112].

Second, the search query was intentionally focused on TITLE-ABS-KEY((oceanographic OR metocean OR “ocean observing” OR “ocean observation”) AND (buoy OR buoys)). This strategy targets buoy-based ocean observation, but it may exclude studies that use alternative terms such as ocean observatory, marine platform, floating sensor platform, profiling float, or drifting platform, even if they do not explicitly use the selected terms. The relevance screening also confirmed that the broad search strategy retrieved a limited number of peripheral records. These cases mainly corresponded to studies in which the term “buoy” appeared in a secondary engineering, modeling, validation, or comparison context. Therefore, the corpus should be interpreted as a broad thematic map of buoy-related ocean-observing literature rather than as a manually filtered set of exclusively buoy-centered studies.

Third, the sector classification should be interpreted as a thematic synthesis rather than as a rigid taxonomy. Some publications naturally connect multiple sectors, such as wave measurement, renewable energy harvesting, satellite validation, autonomous telemetry, and data quality control. The sector boundaries are therefore useful for interpretation, but they should not be understood as strict disciplinary divisions.

Fourth, total citation counts were used to identify historically visible studies within each sector, and citations per year were added as an age-normalized complementary indicator. However, citation-based indicators still have limitations: they may favor established publication outlets, older research lines, and highly visible topics, while underrepresenting recent technological developments or applied contributions that have not yet had sufficient time to accumulate citations [113].

Fifth, the detected sectors depend on the document representation, the similarity network construction, the choice of five clusters, and the subsequent consolidation process.

Manual interpretation was necessary to assign meaningful labels and avoid excessive fragmentation. Still, sector-detection results are sensitive to text preprocessing, sparsification thresholds, the number of clusters, initialization, and labeling decisions [114].

5. Conclusions

This review organized scientific literature on oceanographic buoys using a Scopus-based sector-detection workflow. The analysis retrieved 1876 publications and produced a document-similarity network with 1876 nodes and 10,811 edges. The resulting thematic synthesis identified five main research sectors: platform engineering, sensors, moorings, and autonomous systems; marine wind, waves, metocean, and offshore energy applications; physical oceanography, SST, currents, and environmental variability; coastal and ocean observing networks and operational services; and drifting buoys, floats, and global ocean datasets. Thus, the contribution of this review is not only the identification of five sectors, but also the interpretation of how these sectors connect measurement needs, platform technologies, networked services, mobile observing platforms, and future observing-system requirements.

The corpus shows that oceanographic buoy research has evolved from individual measurement platforms toward integrated observing systems that combine in situ sensing, remote-sensing validation, real-time communications, autonomous operation, drifting platforms, profiling floats, and operational data services. Buoys remain central to marine monitoring because they provide continuous observations in dynamic environments and act as reference points for models, satellites, and global ocean datasets. The review also shows that several problems have matured, including real-time buoy telemetry, operational observing networks, satellite validation, data assimilation, and global drifting or profiling datasets. However, persistent challenges remain in autonomy, sensor reliability, biofouling control, calibration continuity, interoperability, and robust deployment under extreme marine conditions.

Future development should focus on improving long-term autonomy, reducing maintenance demands, standardizing data and metadata, increasing interoperability among observing networks, and incorporating intelligent data processing for anomaly detection and adaptive sampling. These directions are especially relevant for coastal resilience, offshore renewable energy, climate monitoring, marine safety, global ocean datasets, and sustainable management of ocean resources. This sector-based perspective can help researchers and system designers locate technological gaps and align future buoy development with integrated ocean-observing priorities.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse14141291/s1>, scopus_oceanographic_buoy_records_public_metadata.csv, complete Scopus metadata records used in the review; scopus_oceanographic_buoy_nodes.csv, node table with document identifiers, sector assignments, and network attributes; scopus_oceanographic_buoy_edges.csv, edge list of the document-similarity network; scopus_oceanographic_buoy_sectors.csv, sector-level summary; scopus_expanded_buoy_top10_cited_by_sector.csv, top-cited representative publications by sector; scopus_oceanographic_buoy_network.graphml, GraphML file of the document-similarity network; scopus_expanded_buoy_pipeline.py, Python script used for the Scopus-based sector-detection workflow; workflow_parameters.txt, workflow parameters; relevance_screening_random100_public.csv, random-sample relevance-screening file; README.md and MANIFEST.txt, documentation files describing the supplementary dataset.

Author Contributions: Conceptualization, F.P., N.R. and A.A.; methodology, F.P. and A.A.; software, F.P. and A.A.; formal analysis, F.P. and N.R.; investigation, F.P. and N.R.; resources, N.P., C.G., J.A.T., A.A. and M.I.S.; writing—original draft preparation, F.P. and N.R.; writing—review and editing, F.P., N.R., N.P., C.G., J.A.T., A.A. and M.I.S.; visualization, F.P. and N.R.; project administration, F.P.; funding acquisition, F.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was part of the CEIMAR25_I+D_01 project: “Calibration and Geospatial Analysis of Temporal Oceanographic Anomalies (C-GATA)”, funded by CEI-MAR.

Data Availability Statement: The processed metadata and reproducibility files used in this review are available in Zenodo at [<https://doi.org/10.5281/zenodo.21219345>]. The repository includes the sector-assignment table, node table, edge list with cosine-similarity weights, GraphML network, sector summaries, top-cited representative articles, random 100-record relevance screening, workflow script, and parameter file. The original Scopus search can be reproduced using TITLE-ABS-KEY((oceanographic OR metocean OR “ocean observing” OR “ocean observation”) AND (buoy OR buoys)), retrieved on 21 May 2026.

Acknowledgments: During the preparation of this manuscript, the authors used ChatGPT 5.5 (OpenAI) for language editing and to improve readability. The authors reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

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