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# Trends and innovations in ocean mesoscale eddy studies via satellite observation: a bibliometric review

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Ocean mesoscale eddies play a crucial role in global ocean circulation, heat transport, and biogeochemical processes. Satellite altimetry has become a foundation in observing and analyzing these dynamic phenomena, offering high-resolution, global coverage of sea level anomalies. This bibliometric review investigates the trends and innovations in mesoscale eddy research using satellite altimetry data over the past decades. Based on Web of Science, VOSviewer, and CiteSpace, we analyze publication growth, geographical and institutional contributions, keyword co-occurrence, and citation networks. Key innovations such as advanced data assimilation, multi-satellite collaboration, and integration with machine learning models are highlighted. Finally, we discuss future opportunities of next-generation altimetry missions like SWOT for mesoscale eddy dynamics. This review serves as a comprehensive guide for researchers exploring mesoscale eddies and satellite-based ocean observations.

KEYWORDS

**mesoscale eddies, satellite observation, bibliometric analysis, web of science (WOS), VOSviewer**

## 1 Introduction

Oceanic mesoscale eddies are ubiquitous, with scales typically ranging from tens to hundreds of kilometers (Chelton et al., 2007, 2011), and lie between large-scale circulation and smaller-scale processes, such as submesoscale dynamics and microscopic turbulence. Their life cycles can range from several days to months (Chelton et al., 2011), and in summer, enhanced upper-ocean stratification can increase the stability of small (often short-lived) eddies, leading to a seasonal peak in their occurrence (Chen and Han, 2019). These eddies play a crucial role in the oceanic energy cascade, transferring energy from large-scale motions to smaller-scale turbulence (Evans et al., 2022). Additionally, they also play an important role in the ocean, especially in ocean circulation (Zhang Z. et al., 2014), material and energy exchange (Xia et al., 2022), climate change (Beech et al., 2022), and marine ecosystems (Mikaelyan et al., 2020).

The generation of oceanic mesoscale eddies is closely associated with various fluid dynamic processes. Common formation mechanisms include disturbances in ocean circulation (Ji et al., 2018), wind stress forcing (Chi et al., 1998), and interactions between ocean currents and topographic features (Heywood et al., 1996). These processes influence temperature-salinity distributions, vertical mixing, and air–sea interactions (Dong et al., 2025). Oceanic mesoscale eddies are generally divided into two categories: anticyclonic eddies and cyclonic eddies. In the Northern Hemisphere, Anticyclonic eddies rotate clockwise and often lead to local seawater downwelling, which alters the vertical distribution of oceanic heat by enhancing the barrier layer and suppressing upward heat flux (He et al., 2020). Cyclonic eddies rotate anticlockwise and are typically associated with upward water movements, influencing vertical mixing of water (Liu et al., 2017). The rotation direction pattern is reversed in the Southern Hemisphere.

Early oceanographic research primarily focused on large-scale flow patterns such as thermohaline circulation and large ocean currents, with limited focus on mesoscale eddy structures (Wyrtki, 1961). This began to change in the 1950s, as advancements in ocean observation technologies (e.g., ship-based surveys) enabled scientists to detect smaller, rotating features in the ocean (Fuglister and Worthington, 1951). These eddies, much smaller than basin-scale circulations, exhibited strong rotational dynamics and were soon recognized as playing an active role in ocean processes. By the 1980s, continued improvements in observation techniques—including ship-based surveys, buoy monitoring, and the emergence of satellite remote sensing—allowed for widespread detection of mesoscale eddies (Fu et al., 2010). Researchers observed that these eddies often formed near the boundaries of large-scale circulations, at turning points of ocean currents, or under topographic influence, and exhibited distinct dynamic and thermodynamic characteristics (Chelton et al., 2011; McWilliams, 1985). With the rise of numerical modeling in the late 20th century, oceanographers gained powerful tools to simulate the formation, evolution, and dissipation of mesoscale eddies (Holland, 1978). These studies revealed the critical roles eddies play in modulating ocean circulation, enhancing vertical and horizontal mixing, and contributing to material and heat transport, the carbon cycle, and climate change. In the 21st century, high-resolution satellite remote sensing has further advanced the global monitoring of mesoscale eddies (Fu et al., 2023; Gurova and Chubarenko, 2012; Kubryakov et al., 2021). Modern research now integrates dynamic, thermodynamic, and biogeochemical perspectives, exploring how eddies influence climate systems, the marine carbon cycle, and ecosystem variability (Mikaelyan et al., 2020).

To trace the evolution of a specific discipline, researchers often conduct large-scale literature analyses and topic-focused reviews based on extensive collections of research articles. However, this traditional review method usually takes a long time to read the literature and is difficult to reveal the development process quantitatively and systematically, with conclusions lacking objectivity. In contrast, bibliometrics is an effective tool for analyzing the development trends of a discipline. It integrates mathematics, statistics, and bibliometrics and provides a macro-to-micro analysis of research content (Chen et al., 2010; Zhong et al., 2023). Numerous studies have used bibliometric methods to analyze the progress of satellite remote sensing technology in surface water bodies (Huang et al., 2023), forest fires (Santos et al., 2021), the cryosphere (Yu et al., 2023), oceans (Wang et al., 2022), etc., but so far, no bibliometric analysis has systematically studied the development of satellite remote sensing-based research on oceanic mesoscale eddies.

Therefore, this study employs VOSviewer and CiteSpace to conduct bibliometric analysis of literature on satellite remote sensing technology in monitoring oceanic mesoscale eddies, aiming to systematically analyze recent research progress and future directions. The main work of this paper includes: (1) analyzing the number and trends of publications in the Web of Science database; (2) identifying highly collaborative countries and authors; (3) identifying highly cited journals, authors, and articles; (4) clustering and burst analysis based on keyword co-occurrence in the literature; (5) analyzing the development of research hotspot topics. This paper summarizes the existing literature and systematically reveals the development and changing patterns of research on oceanic mesoscale eddies using remote sensing technology, providing guidance and references for further research.

## 2 Data source and method

### 2.1 Data acquisition

To track the development and dynamics of this research field globally, we selected the Science Citation Index-Expanded (SCI-E) from the Web of Science (WOS) core collection as our literature data source. After multiple adjustments to the relevance and completeness of the search results, we finally used the following search query: TS=("ocean*" or "sea*") AND TS=("mesoscale edd*" or "mesoscale vortex*") AND TS=("satellite*" or "altimeter*" or "remote sensing" or Jason-1 or Jason-2 or Jason-3 or TOPEX/Poseidon or ERS-1 or ERS-2 or ENVISAT or Saral or ICESat or ICESat-2 or CryoSat-2 or Sentinel-3 or Sentinel-6 or GEOSAT or GFO or HY-2 or Haiyang-2 or SWOT) AND PY = (1977-2024). The types of literature selected were research papers and review articles, which were further exported as (full records and cited references) in plain text format. Each record contains the author, title, keywords, journal, source file, abstract, and cited references. After preliminary screening and analysis, we retained 1681 research papers and reviewed articles for subsequent data analysis. Figure 1 illustrates the data processing and analysis workflow of this study.

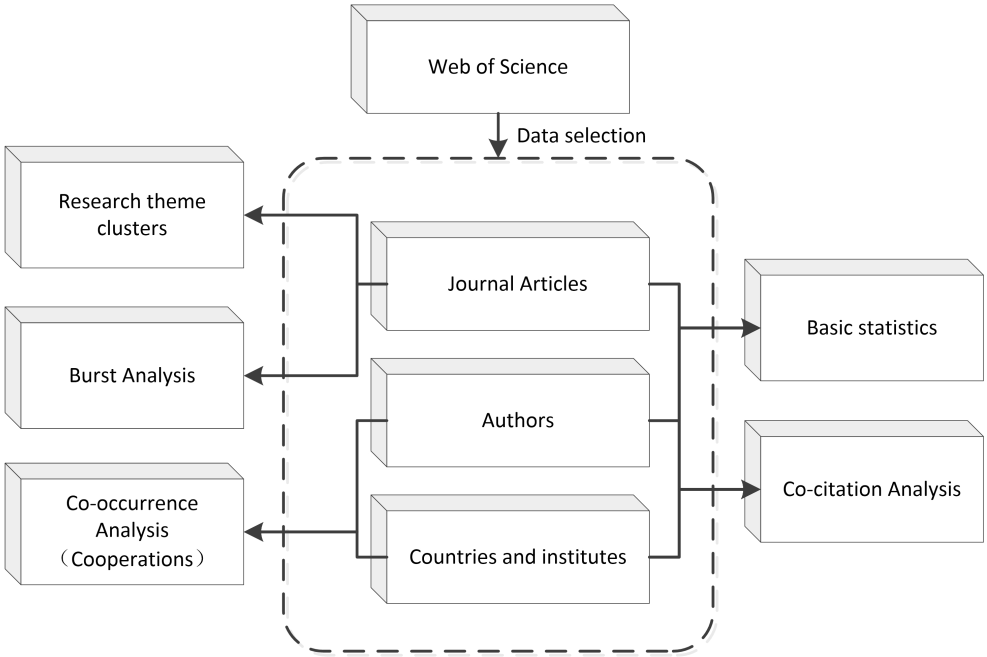


FIGURE 1
Data acquisition and processing workflow in this study.

## 2.2 Methodology

Bibliometric methods are used to quantitatively analyze the significance of published literature in a specific research discipline. Firstly, we used Histcite 12.03.07 software developed by Eugene Garfield (2009) to preprocess the literature. Co-occurrence analysis was conducted using VOSviewer 1.6.18, a platform primarily focused on literature data, which uses "network data" to build relationships and perform visual analysis of knowledge units in the literature. It can generate scientific knowledge maps to display the structure, evolution, and collaboration relationships of a knowledge domain (Van Eck and Waltman, 2010). In addition, CiteSpace 6.1 R2, a Java-based co-citation network analysis and visualization platform developed by Dr. Chen at Drexel University (Chen, 2006), was used for analysis. For the large amount of research literature, we implemented keyword co-occurrence and burst analysis. The keywords of each paper reflect its research topic, and there are certain relationships between different keywords. Generally, the more co-occurring terms found in the literature, the higher the correlation between two topics (Li et al., 2021). High-frequency keywords represent the hot research topics. In addition, different keyword groups are marked with distinct research identifiers in VOSviewer, the size of each cluster represents its relative contribution to the keyword group, while the thickness of the connecting lines between clusters indicates the strength of interaction. The keyword citation burst analysis indicates that the number of citations of articles changes drastically within a short period, and it is a useful method to explore research trends (Chen, 2017). Kleinberg's burst detection algorithm was used to identify bursts that represent the cutting-edge of research, extracting burst nodes from large data sets (Kleinberg, 2002).

# 3 Results

## 3.1 Statistics of publications by countries, research institutions and researchers

According to records from the WOS database, research on oceanic mesoscale eddies began as early as around 1977. Over the course of 47 years, the number of publications has steadily increased, which can be divided into three distinct periods (Figure 2).

The first period (1977-1991): Before the widespread use of large-scale satellite remote sensing for mesoscale eddies, less than one paper were published annually. During this time, researchers primarily studied the location, physical properties, and structural characteristics of mesoscale eddies through field observations. For example, Johannessen et al. (1989) combined acoustic Doppler current profiler (ADCP), towed and profiling CTD, and satellite infrared data to investigate the three-dimensional velocity and thermohaline structure of mesoscale eddies in Norwegian coastal currents.

The second period (1992-2007): This period saw a significant shift with the launch of altimetry satellites such as ERS-1 and TOPEX/Poseidon, marking the beginning of a new phase in mesoscale eddy research. In the early stages of satellite deployment, researchers focused on improving the accuracy of

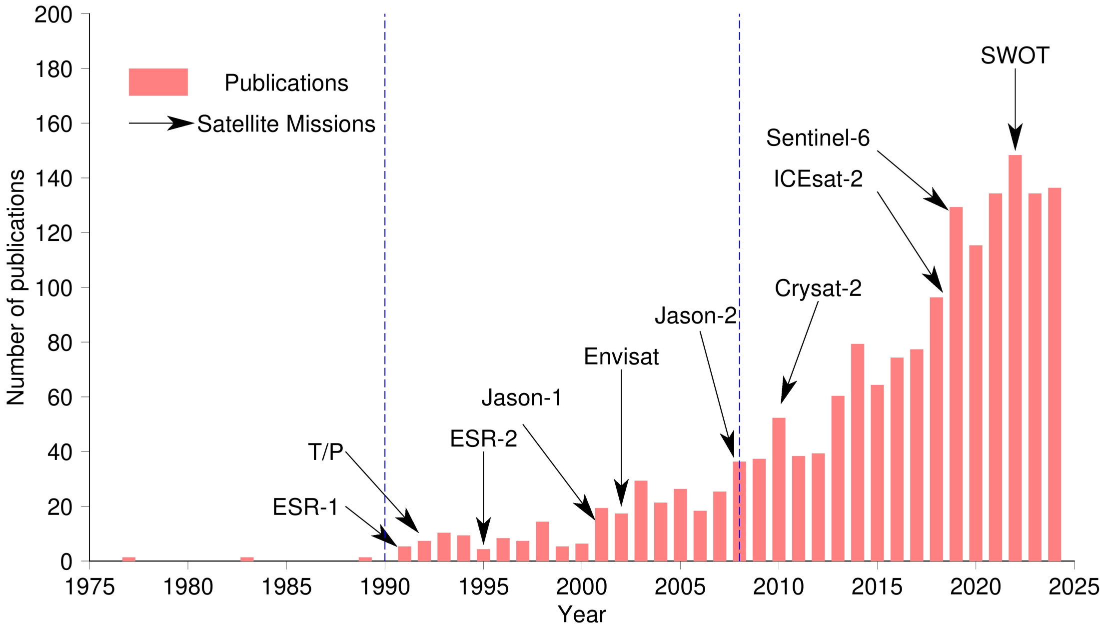


FIGURE 2
Annual number of publications on ocean mesoscale eddy research via remote sensing, with the blue dashed lines delineating the three development stages.

sea surface height constructed from single and multi-satellite altimetry missions (Greenslade et al., 1997; Le Traon and Ogor, 1998), laying the foundation for subsequent oceanographic applications. Satellite altimetry rapidly developed during this phase. Nystuen and Andrade (1993) used Geosat Exact Repeat Mission (ERM) altimetry data collected during 1987–1988 to detect and track mesoscale sea surface height anomalies. Glorioso et al. (2005) highlighted the potential of using continuous real-time satellite altimetry to detect and monitor mesoscale phenomena and understand regional circulation. Due to the deployment of exploratory satellites such as ERS-2, Jason-1, and Envisat, an average of 15 papers were published annually.

The third period (2008-present): This period was characterized by rapid advancements in mesoscale eddy research, largely driven by the launch of satellites such as Jason-2 and CryoSat-2. The average annual publication increased to 85 papers. Many studies emphasized the fusion of data from multiple satellites to improve observational accuracy. For instance, Dibarboure et al. (2012) combined CryoSat-2 data with other radar altimetry datasets to enhance the resolution of multi-mission gridded sea surface height anomaly products for the Gulf Stream. In addition, from 2018 to the present, this phase has witnessed further progress with the launch of high spatial resolution satellites such as ICESat2, Sentinel-6, and SWOT, significantly advancing the field. The complementary capabilities of different satellites have enhanced the ability of altimetry to monitor mesoscale eddies (Peng et al., 2024). Moreover, the recently launched SWOT satellite, with its higher spatial resolution, enables the detection of finer structures and dynamic evolution processes of larger submesoscale eddies (~10 km or greater) (Zhang Z. et al., 2024; Du and Jing, 2024).

A further statistical analysis of publications on mesoscale eddy research using remote sensing, categorized by countries, research institutions, and publishing journals, indicates that the top five countries in terms of publications are the United States (625 publications), China (542 publications), France (247 publications), Japan (93 publications), and Australia (91 publications). Notably, although China ranks second in publication volume, its citation count is just comparable to that of France, despite France's publication volume being only half of China's (Figure 3a). At the institutional level, four of the top ten institutions are from China, with the Chinese Academy of Sciences leading (217 publications), followed by Ocean University of China (130 publications), the University of Chinese Academy of Sciences (88 publications), and the Ministry of Natural Resources of China (78 publications). From the perspective of academic journals, the Journal of Geophysical Research: Oceans is the leading journal in terms of publication volume (341 publications) and citation count (11,851). Other important journals include the Journal of Physical Oceanography (99 publications, 6,385 citations) and Geophysical Research Letters (91 publications, 3,542 citations) (Figure 3b). Reading these specialized journals is essential for staying updated on the latest advancements in mesoscale eddy research using remote sensing methods.

## 3.2 Collaboration analysis

A network and co-citation analysis of researchers contributing to published literature can identify the more influential scholars in the field of mesoscale eddy studies using satellite observations. The top five authors with the highest number of publications are Qiu B. (48), Chen

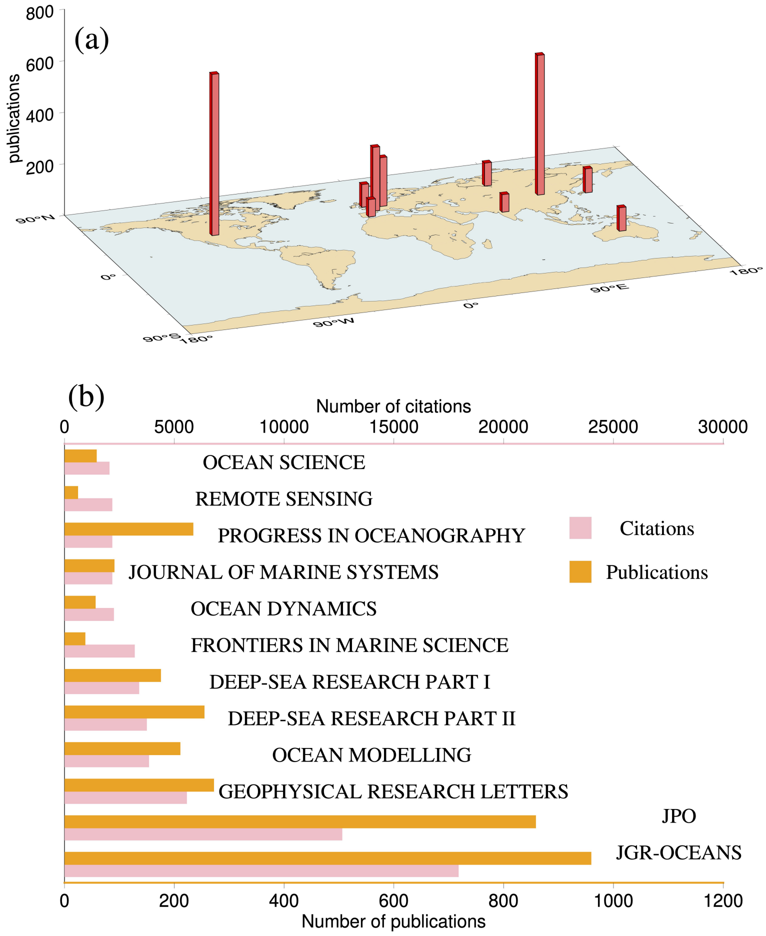


FIGURE 3
**(a)** Geographic distribution of the top 10 countries by number of publications; **(b)** Number of publications (orange) and citations (pink) in leading journals publishing mesoscale eddy research.

G. (38), Dong C.M. (30), Wang D.X. (26), and Chaigneau A (24). Further analysis of authors whose papers have been cited more than 50 times revealed a co-citation network consisting of six major scholar clusters (Figure 4). The top five authors ranked by citation count are Chelton D.B. (1609), Qiu B (760), McGillicuddy D.J. (744), Chaigneau A (542), and Gaube P (521). Interestingly, Chinese researchers rank high in publication quantity but not proportionally in citation count, which reflects their lower international influence compared to these leading scholars.

A further analysis was conducted to examine the key research areas pursued by prominent scholars in mesoscale eddy studies. Firstly, Professor Chelton D.B. from the Department of Oceanography at Oregon State University is a renowned oceanographer specializing in mesoscale ocean dynamics and satellite altimetry for oceanographic measurements. His work significantly contributes to understanding ocean circulation, mesoscale eddies, and their role in the climate system, especially in satellite remote sensing and ocean dynamics, making his research widely cited. Secondly, Bo Qiu, a prominent oceanographer at the University of Hawaii, specializes in ocean dynamics, particularly western boundary currents, mesoscale and submesoscale eddies, and their roles in large-scale ocean circulation and decadal climate variability. His work emphasizes tropical air-sea interactions and the impact of ocean circulation on climate change, employing numerical models and observational data to explore the complex feedback mechanisms between the ocean and the atmosphere. Thirdly, Professor David J. McGillicuddy from the Woods Hole Oceanographic Institution is a leading American oceanographer with expertise in marine biogeochemistry, ocean circulation, phytoplankton ecology, and the oceanic carbon cycle. His research has greatly contributed to understanding ocean ecosystem dynamics, nutrient distribution, and the relationship between ocean climate and biological productivity. His work on mesoscale eddies highlights their impact on marine biological productivity and their role in global climate systems through complex air-sea interactions. Next, Professor Chaigneau A. from the University of Santiago, Chile, is a marine physicist whose research focuses on ocean circulation, mesoscale eddies, and physical oceanography. His work, particularly in monitoring and analyzing ocean eddies using satellite remote sensing, has had a broad impact on oceanographic studies. Last but not least, Professor Gaube P. from the University of California, Santa Barbara,

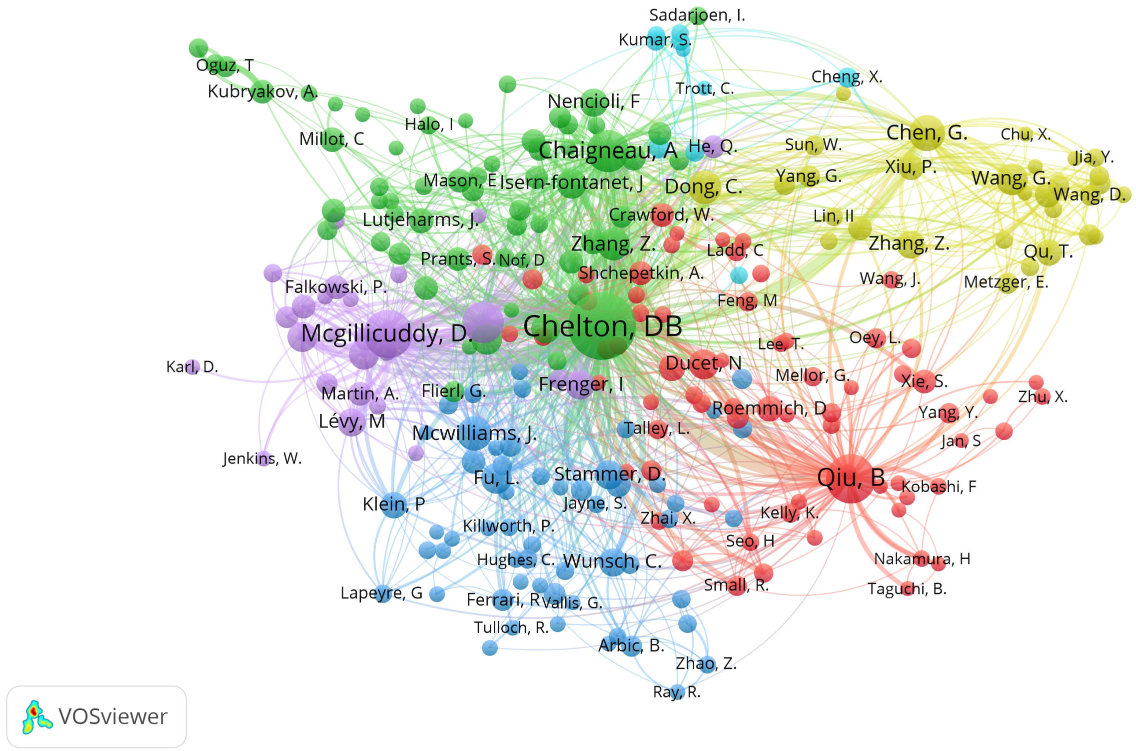


FIGURE 4
A co-citation network of authors whose papers on satellite remote sensing in the field of ocean mesoscale eddies have been cited more than 50 times, identifying a total of 252 authors.

specializes in marine physics and ocean sciences. His research areas include ocean circulation, eddies, and ocean-atmosphere interactions. Gaube has made significant contributions to understanding mesoscale eddies, particularly in analyzing their structure and dynamics through satellite remote sensing data. His studies have advanced knowledge of the role of mesoscale eddies in ocean dynamics, material transport, and climate change.

In addition, we analyzed the co-occurrence network of international collaboration among different countries in mesoscale eddy, which helps to understand the cooperative relationships between countries (Figure 5). For the co-occurrence network of international collaboration among different countries, each node represents a country, with the size of the node indicating its frequency of collaboration or influence in this research area. The lines between nodes represent the strength of collaborative relationships between countries, while colors are used to distinguish different collaborative groups or communities. Finally, five major research clusters have formed in the international study of mesoscale eddies in remote sensing (Table 1), with it being evident that the United States, China, and France are the most influential countries in this field. Their nodes are significantly larger, indicating their central role in mesoscale eddy studies and their extensive participation in international collaborations. Among them, the collaboration network between the United States and China is the densest, demonstrating that they are at the core of international research cooperation, maintaining strong connections with other countries. France also occupies a central position in European research networks, maintaining strong collaborative ties with countries such as Germany, the United Kingdom, Italy, and Spain. Additionally, our results highlight the collaboration characteristics of other countries. For instance, countries such as Australia, South Africa, India, and Japan, although represented by smaller nodes, maintain direct collaborative relationships with the United States and China. Collaboration among European countries is highly interconnected, forming a network centered on France. In contrast, some countries, such as New Zealand, Israel, and Brazil, have smaller nodes and fewer connections, indicating that they occupy a relatively peripheral position in international collaborations within this field. Overall, the international collaboration patterns in remote sensing-based mesoscale eddy studies, with the United States, China, and France serving as leading contributors. Research institutions worldwide are closely cooperating. In the future, with advancements in technology and enhanced data sharing, other countries are likely to strengthen their collaborations with these core nations, further promoting global research in this field.

## 3.3 Keywords burst analysis

Keywords highlight the main focus of academic articles, and keyword bursts refer to significant changes in the frequency of these words' appearances during specific time periods. Keywords burst can uniquely reveal future trends and states in the field. In CiteSpace, keyword burst analysis is implemented based on the

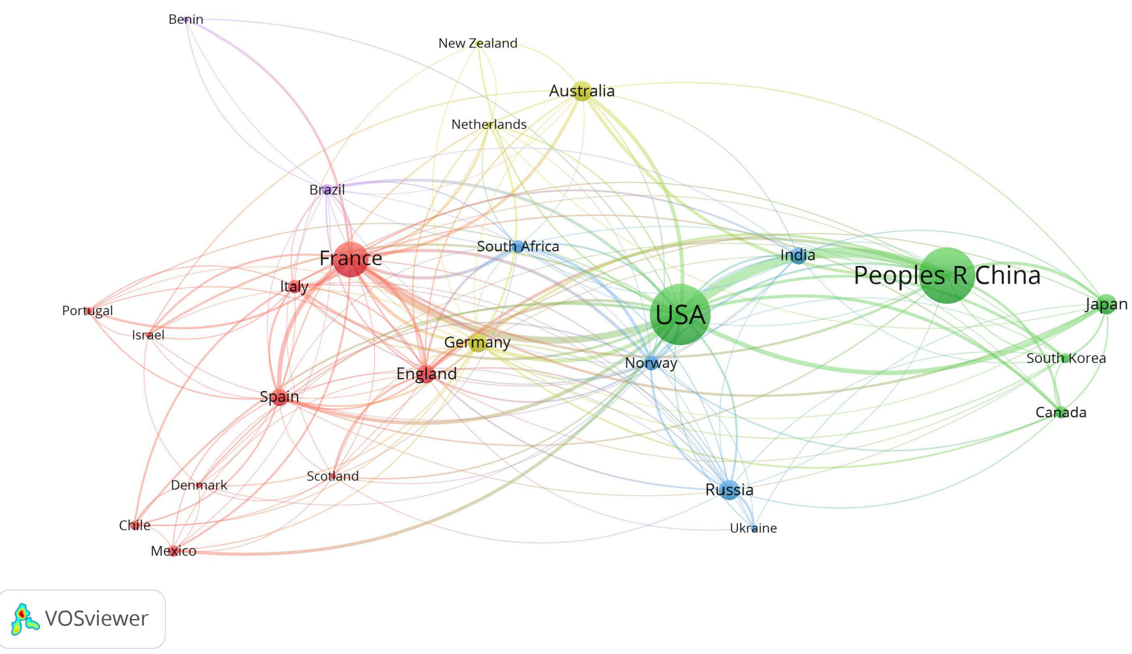


FIGURE 5
International collaboration in mesoscale eddy research.

TABLE 1 International collaboration in mesoscale eddy research.

| Clusters | Country |
|---|---|
| Green(5) | Canada, Japan, Peoples R. China, South Korea, USA |
| Blue(5) | India, Norway, Russia, South Africa, Ukraine |
| Yellow(4) | Australia, Germany, Netherlands, New Zealand |
| Purple(2) | Benin, Brazil |
| Red(10) | Chile, Denmark, England, France, Israel, Italy, Mexico, Portugal, Scotland, Spain |

burst detection algorithm proposed by Kleinberg (2002), which models temporal variations in keyword frequency to identify terms exhibiting significant bursts within large-scale datasets. However, certain keywords (such as "Oceanic Eddy") lack specific significance despite high frequency and are therefore manually excluded from the final analysis to enhance the clarity and relevance of the results. Figure 6 presents the citation bursts of 25 keywords from 1977 to 2024, reflecting not only the historical evolution of research hotspots but also potential future developments. The keywords cover a wide range of research themes, including physical oceanography, satellite observation technology, ecosystems, and artificial intelligence. Early keywords such as "North Atlantic" (1991–2008) and "Topex/Poseidon" (2003–2014) indicate that physical oceanography and satellite-based observation technologies were central focuses of the academic community during the initial period, closely tied to technological advancements at the time. After 2010, with the development of remote sensing, artificial intelligence, and computational simulation technologies, keywords such as "Sea Surface Height" (2020– 2024), "Deep Learning" (2020–2024), and "Simulation" (2011–2018) emerged as dominant research directions. Notably, recent burst keywords such as "Deep Learning" and "Primary Production" suggest a shift toward more detailed simulations of oceanic phenomena and ecosystem analyses, which suggests that researchers are increasingly turning to high-resolution observational data to gain a more detailed understanding of ocean dynamics and their influence on climate and ecosystems. Meanwhile, the appearance of keywords like "Western Boundary Currents" (2022–2024) and "Cyclonic Eddy" (2018– 2020) highlights an increasing emphasis on localized ocean dynamics and circulation features, potentially driving research on coupling regional ocean models with global climate models.

Furthermore, the continued prominence of keywords like "Sea Surface Height," "Western Boundary Currents," and "Deep Learning" suggests that these topics will remain central to future research, encouraging greater convergence of technological innovation and ocean science. Additionally, the emergence of ecology-related keywords in recent years, such as "Primary Production" and "Surface Chlorophyll," suggests that research on marine ecosystems and carbon cycles will attract increasing attention and see further development. This interdisciplinary trend reflects not only the scientific innovations enabled by technological progress but also the growing impact of global climate change and environmental challenges on academic study.

## 3.4 Keywords co-occurrence analysis

The keywords in the paper provide a high-level summary of its content. VOSviewer reveals important research themes through

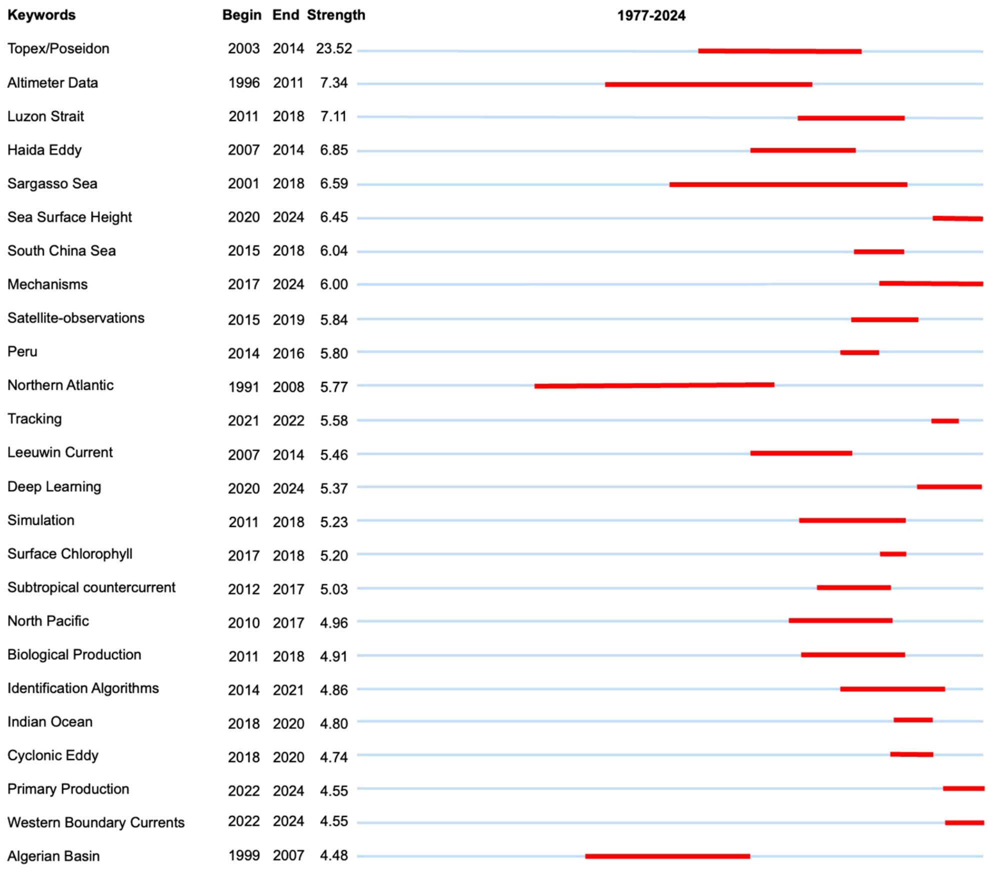


FIGURE 6
Distribution of the top 25 keywords sorted by burst intensity, sorted in descending order of keyword burst strength.

pairwise co-occurrence analysis of all keywords in the literature. By identifying the study regions from keyword co-occurrence analysis, the results shown in Figure 7a were obtained. Figure 7a illustrates the geographical distribution of research hotspots on mesoscale eddies based on keyword co-occurrence analysis. The results show that current research using satellite remote sensing is primarily concentrated in the Pacific Ocean (294 publications), Indian Ocean (102), Atlantic Ocean (191), and the Southern Ocean (100), reflecting a global focus on major ocean basins with high eddy kinetic energy. Among these regions, the Pacific Ocean stands out as the dominant hotspot, likely due to its extensive area, active western boundary currents, and prominent mesoscale variability. The South China Sea (202 publications) and the Luzon Strait (73 publications) also gain regional research interest, emphasizing the importance of monsoon-driven eddies and marginal sea dynamics in the western Pacific. Extensive research has been conducted in the high-latitude regions of the Pacific Ocean, particularly in the Bohai Sea, Yellow Sea, and East China Sea (26 publications), as well as the Sea of Japan (11), Sea of Okhotsk (6), Bering Sea (9), and Gulf of Alaska (15). In the Indian Ocean, the Bay of Bengal (63 publications) and Arabian Sea (46 publications) are key regions, consistent with their strong seasonal monsoon forcing and associated eddy activity. The Mediterranean Sea (60 publications) and the Mozambique Channel (25 publications) indicate focused studies in semi-enclosed basins and western boundary currents, respectively, while the Kuroshio Extension (224 publications) reflects interest in eddy–current interactions in the western North Pacific. However, research in the Arctic Ocean (17 publications) and the Beaufort Sea (5 publications) remains limited, likely due to sparse observational coverage and the challenges of remote sensing in polar regions. This distribution pattern highlights the uneven global research focus on mesoscale eddies, with an emphasis on dynamic regions driven by major currents, wind forcing, and complex topography. It also suggests opportunities for expanding research in underexplored areas such as the Arctic Ocean and high-latitude basins, where eddy dynamics may play critical roles under climate change.

Figure 7b presents the keyword co-occurrence network in remote sensing studies of oceanic mesoscale eddies, which reveals five distinct research clusters. In this network, the size of each node reflects the relative importance of a keyword, while the links between nodes represent co-occurrence relationships. The term “ocean mesoscale eddies” appears most frequently, with 1,151 occurrences and a total link strength of 5,271, confirming its central role in the field. Although the co-occurring keywords span a range of topics—such as detection techniques, biogeochemical processes, and energy transport— they are all directly associated with mesoscale eddy research. These results highlight the

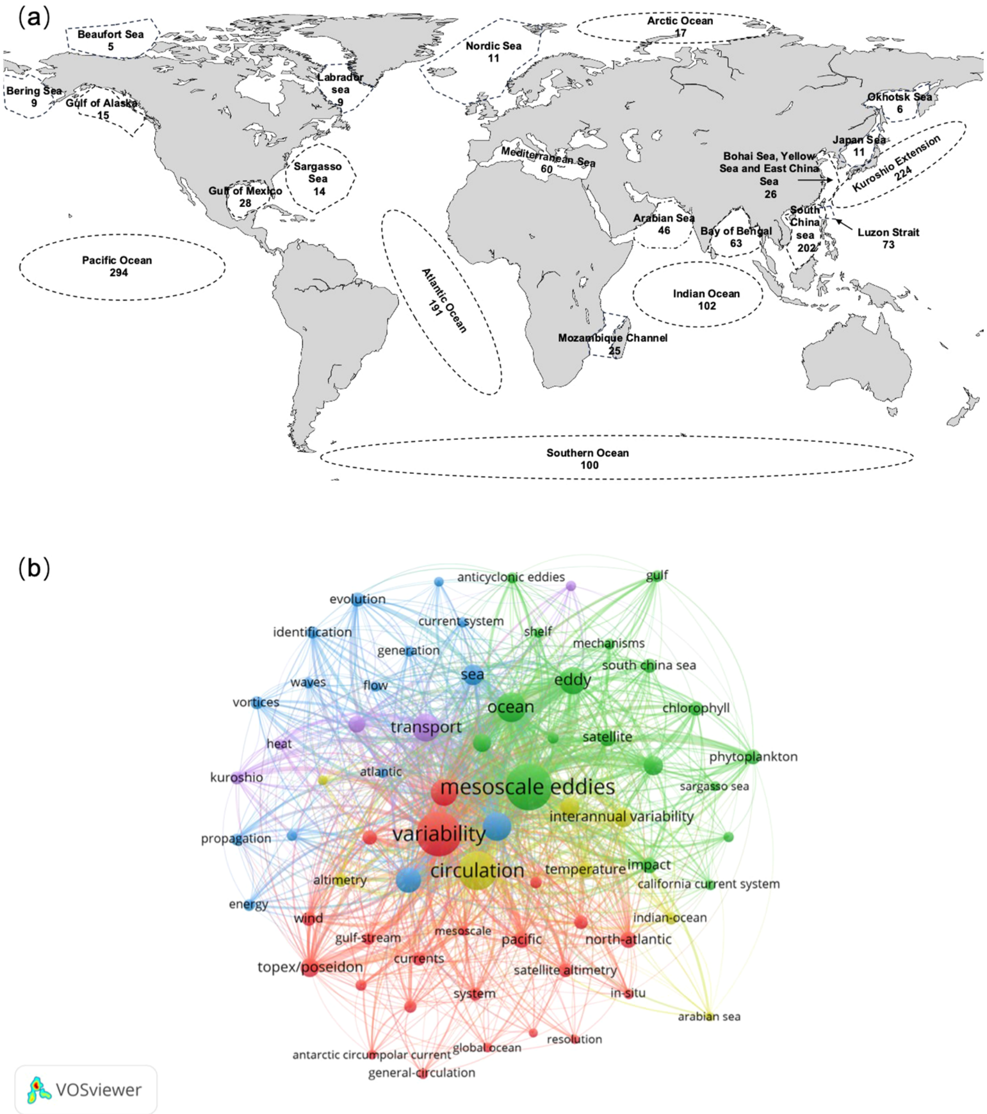


FIGURE 7
**(a)** Global distribution of research regions on oceanic mesoscale eddies based on keyword co-occurrence analysis. The dashed region represents identified study regions, and the numbers within each region indicate the number of publications. **(b)** Keyword co-occurrence network in remote sensing studies of oceanic mesoscale eddies, showing five major clusters (red, green, yellow, blue and purple clusters). Node size indicates keyword frequency, and the links represent co-occurrence strength.

multidisciplinary nature of the field and its integration with satellite remote sensing and ocean dynamics.

The five identified clusters represent distinct but related thematic areas. The red cluster includes keywords related to mesoscale eddies, satellite altimetry, ocean circulation, and wind fields. The green cluster features terms such as chlorophyll and photosynthesis. The yellow cluster involves circulation, interannual variability, and temperature. The blue cluster centers on remote sensing satellites, eddy energy evolution, and modeling. Finally, the purple cluster is associated with regional dynamics, including the Kuroshio and heat transport. In the following sections, we examine how remote sensing has been applied to mesoscale eddy research within each of these thematic clusters.

### 3.4.1 Investigating the generation mechanisms of mesoscale eddies using altimetry

The generation mechanisms of oceanic mesoscale eddies involve multiple physical processes, primarily resulting from the interactions among wind stress, topographic effects, boundary layer flows, thermohaline instability, nonlinear dynamical processes, tidal and wave effects, and large-scale circulation. Wind stress drives horizontal motion in the ocean's surface layer, and variations in wind fields induce shear in ocean currents, leading to eddy formation. Additionally, seafloor topographic features such as seamounts and ridges perturb ocean currents, further facilitating eddy generation (McWilliams, 2016; Qiu and Chen, 2010). The flow in the oceanic boundary layer is influenced by topography and thermohaline gradients, leading to the formation of boundary eddies (McWilliams, 1985; Haidvogel et al., 1991). Moreover, density instabilities arising from thermohaline differences in the ocean also contribute to eddy formation (McWilliams, 2016; Lapeyre and Klein, 2006). Nonlinear dynamical processes, such as the interaction between turbulence and rotational flows, play a crucial role in eddy formation (McWilliams, 1984; McGillicuddy, 2016). In certain regions, tidal effects and oceanic wave fluctuations can also promote eddy formation through their interactions with water mass movements (Zimmerman, 1981; Nidzieko, 2010). Furthermore, large-scale circulations, such as tropical and polar currents, influence the generation and evolution of eddies through their interactions with mesoscale flows (Zhang Z. et al., 2014; Qiu and Chen, 2005). Through the combined effects of these mechanisms, mesoscale eddies form across various spatial and temporal scales, exerting significant impacts on oceanic circulation, climate variability, and marine ecosystems.

Figure 8 illustrates the principal mechanisms involved in their formation and evolution. Specifically, wind stress curl and topographic forcing are recognized as key drivers of eddy generation. After formation, mesoscale eddies often exhibit an inverse energy cascade, whereby energy is transferred from smaller to larger spatial scales. These eddies subsequently interact with one another, and their energy is dissipated through eddy–eddy interactions, wind field suppression, frictional or viscous dissipation, loss of geostrophic balance, and boundary processes along the seafloor or continental slopes. According to Shang et al. (2013), the genesis mechanisms of mesoscale eddies can be broadly classified into two types: (1) the establishment of geostrophic-scale rotation, and (2) the development of geostrophic-scale sea surface height (SSH) or internal interface anomalies. The former is mainly governed by barotropic processes, such as wind stress curl input and horizontal shear-induced barotropic instability, which contribute kinetic energy to the eddy system. The latter involves the generation of available potential energy through baroclinic instability, manifested in anomalies of sea surface height or subsurface density interfaces.

## 3.4.2 The impact of mesoscale eddies on the marine ecosystem

Mesoscale eddies exert multifaceted influences on marine ecosystems by altering the physical properties of seawater, redistributing nutrients, and modifying the habitat conditions for marine organisms. For example, eddies facilitate the upwelling of deep, nutrient-rich water, supplying essential nutrients to phytoplankton in the surface ocean and thereby enhancing primary productivity (McGillicuddy et al., 1998; Mahadevan et al., 2012). Studies have shown that in the tropical Atlantic, eddy-induced upwelling transports substantial amounts of nutrients, leading to explosive phytoplankton growth, which in turn supports higher trophic levels in marine food webs (Oschlies and Garçon, 1998; Martin and Richards, 2001). Additionally, Sarma et al. (2020) demonstrated how eddies modulate nutrient availability and phytoplankton composition, while Nuncio and Kumar (2012) demonstrated that mesoscale eddies, through their modulation of stratification and vertical mixing, enhance surface chlorophyll concentrations, thereby linking eddy life cycles to ecosystem variability in the Bay of Bengal.

Figure 9 presents a schematic representation contrasting these ecological impacts in the Northern Hemisphere. Anticyclonic eddies are characterized by a downwelling mechanism that depresses the thermocline, restricts nutrient influx, and consequently leads to reduced biological productivity (Figure 9a). Conversely, cyclonic eddies induce an upward displacement of the thermocline, fostering the upwelling of nutrient-rich waters, thereby enhancing primary productivity and supporting diverse and abundant marine life (Figure 9b). This polarity-dependent impact has profound implications for marine ecosystems,

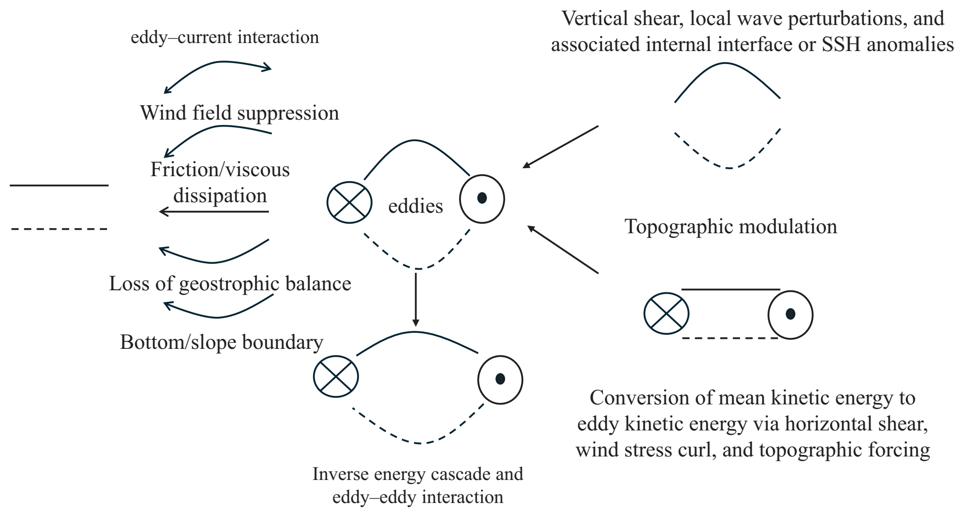


FIGURE 8
Schematic representation of multiple physical mechanisms contributing to the genesis and evolution of oceanic mesoscale eddies, which is adapted from Shang et al. (2013), licensed CC BY 4.0. The solid line represents sea surface height (SSH), while the dashed line indicates the thermocline.

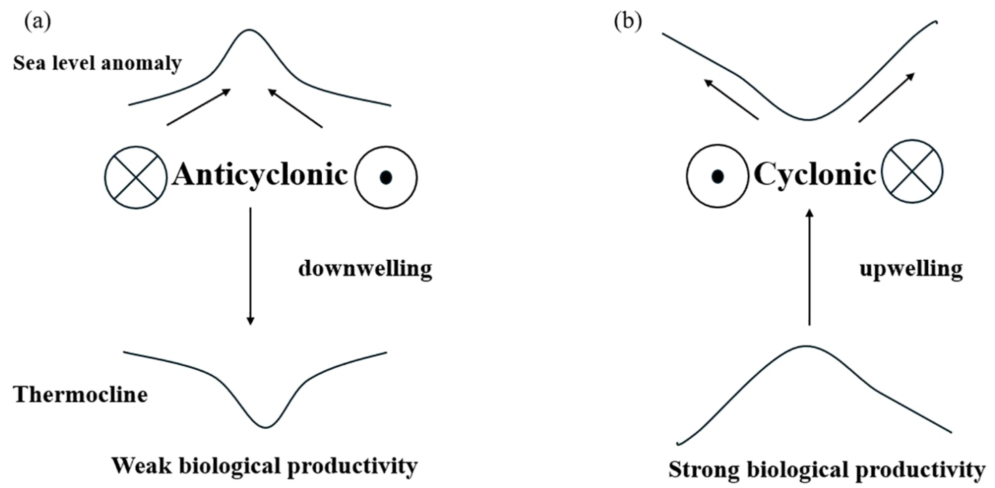


FIGURE 9
Ecological and biogeochemical impacts of **(a)** anticyclonic and **(b)** cyclonic eddies in the Northern Hemisphere.

influencing carbon cycling, fisheries dynamics, and the overall health of marine biodiversity.

Regional examples further highlight the diverse roles of eddies. Mesoscale eddies in the eastern tropical Pacific off Peru have been shown to significantly affect oxygen distribution and nutrient transport, thereby regulating productivity in the highly productive Peruvian fishing grounds (Stramma et al., 2013). In contrast, in eastern boundary upwelling systems, eddy activity can suppress biological production by isolating nutrient-rich subsurface waters from the euphotic zone (Gruber et al., 2011). Additionally, in the Kuroshio region, frontal instabilities can generate eddies that enhance local productivity by promoting vertical mixing and nutrient entrainment (Kimura et al., 1997).

These physical and biogeochemical processes underscore the integral role that mesoscale eddies play in shaping both ocean dynamics and marine ecosystems. By integrating these mechanisms into conceptual schematics, we provide a clearer understanding of how eddies originate, evolve, and influence biogeochemical cycles—offering valuable insight for interdisciplinary oceanographic studies.

Eddies also influence seawater temperature and salinity, which are critical factors for the habitat and reproductive patterns of certain species. For instance, in the Southern Ocean, mesoscale eddies significantly enhance the distribution and growth of ice algae and other phytoplankton (Thomalla et al., 2011). Furthermore, eddies modify vertical mixing within the water column, affecting the distribution and community structure of plankton. In some eddy-dominated regions, both the diversity and abundance of planktonic species are notably high, which in turn impacts the marine food chain. Eddydominated areas surrounding seamounts are often hotspots for fish and other marine organisms, meaning that eddy activity plays a crucial role in determining the distribution and abundance of fisheries resources (Morato et al., 2010; Pitcher et al., 2007). Additionally, in the context of climate change, mesoscale eddies regulate oceanic carbon cycles by influencing carbon sequestration and release, thereby indirectly affecting global climate (McGillicuddy, 2016; Siegel et al., 2014). Thus, mesoscale eddies play a vital role in marine ecosystems, with significant implications for biological communities, fisheries resources, and carbon cycling.

### 3.4.3 Variability characteristics of oceanic mesoscale eddies

Eddy-eddy interaction refers to the interaction between mesoscale eddies and large-scale circulation. Due to its role in energy cascade, it has long been a hot topic for many researchers (Kubryakov et al., 2021; Dong et al., 2012). The primary areas of interest for eddy-eddy interaction research include the Kuroshio Extension (Kubryakov et al., 2021; Sun et al., 2021; Arbic et al., 2013), the Southern Ocean (Jeong et al., 2019; Waseda et al., 2003; Lenn et al., 2011), and the Gulf Stream Extension (McWilliams et al., 1978; Wilkin and Morrow, 1994). Among these, Waseda et al. (2003) used modeling to simulate the four stages of eddy-Kuroshio interaction: westward propagation of the eddy, advection of the eddy by the Kuroshio, formation of a meander, and separation and reappearance of the eddy from the Kuroshio. Waterman and Jayne (2011) emphasized the important role that eddies play in stabilizing the western boundary currents. Additionally, Chen et al. (2014) found that, apart from the Southern Ocean, Kuroshio, and Gulf Stream Extension regions, eddy interactions in other areas are mostly local. Although the Arctic Ocean is not a recent research hotspot, it is still worth attention due to its strong connection with climate change. In the Arctic Ocean, there are two high-frequency eddy interaction zones: the Beaufort Gyre in the northwest (Manucharyan and Spall, 2016; Regan et al., 2020) and the Lofoten Basin east of Greenland (Raj et al., 2020). Manucharyan and Spall (2016) proposed that mesoscale eddies limit the accumulation and release of freshwater in the Beaufort Gyre. Raj et al. (2020) found that energy transfer related to mesoscale eddies affects the circulation in the Lofoten Basin. Compared to mid- and low-latitude regions, these two areas present many unresolved issues for future research on eddy-eddy interaction. Mesoscale eddies play an important role in ocean dynamics of the Southern Ocean, but the Southern Ocean has not been a major focus of recent research. From maps of eddy kinetic energy (EKE), it is clear that the highest energy is concentrated in the Antarctic Polar Front, and the increase in EKE primarily occurs in the western and central parts of the Southern Ocean Pacific sector. It indicates that the positive Southern Annular Mode (SAM) index is related to anomalous westerly wind forcing, which enhances eddy characteristics and increases mesoscale eddy activity in the Southern Ocean (Frenger et al., 2013). The eddy interactions in this region respond well to climate patterns. The Bay of Bengal (BoB) and Arabian Sea (AS) are two dynamically complex, monsoon-influenced regions that have become central to mesoscale eddy research. Their distinct oceanographic settings—shaped by strong wind forcing, boundary currents, and topographic features—make them ideal for integrated observational studies. In the BoB, numerous studies have demonstrated the importance of combining satellite and *in-situ* platforms to capture eddy formation and evolution. For instance, Cheng et al. (2018) used satellite data and wind stress analyses to reveal how local atmospheric forcing contributes to eddy generation. Chen et al. (2012) explored interannual variability using altimeter data and reanalysis data, highlighting how large-scale climate drivers modulate eddy activity. Dandapat and Chakraborty (2016), combining satellite altimetry with Argo float observations, identified seasonal and spatial patterns of eddies in the western Bay of Bengal, while Cui et al. (2016) focused primarily on sea level anomaly (SLA)-based analyses to characterize eddy structures and variability. To improve resolution in nearshore regions where altimetry becomes less reliable, Mandal et al. (2019, 2020) incorporated high-frequency (HF) radar observations to track coastal eddy structures and their interactions with tides and shelf dynamics. In the Arabian Sea, mesoscale eddy dynamics have been similarly investigated through multiplatform approaches. Varna et al. (2023) analyzed mesoscale eddy characteristics in the eastern Arabian Sea using 26 years of altimeter data and numerical simulations, identifying seasonal patterns and remote forcing mechanisms associated with eddy generation and westward propagation. Al Saafani et al. (2007) tracked the westward propagation of eddies into the Gulf of Aden, illustrating cross-basin transport and interaction with large-scale circulation based on the SLA from altimetry. Ship-based observations, such as those by Bower et al. (2002), provided valuable *in-situ* measurements linking Gulf of Aden eddies to Red Sea Water pathways.

### 3.4.4 Investigating energy evolution induced by mesoscale eddies using remote sensing and numerical models

Utilizing altimetry data and numerical models to study the energy cascade induced by mesoscale eddies provides valuable insights into eddy dynamics and energy transfer processes. Satellite altimetry data, by capturing variations in sea surface height, enables the accurate identification of mesoscale eddy location, intensity, and evolution (Kubryakov et al., 2021), thereby providing a fundamental basis for analyzing energy distribution. Meanwhile, numerical models simulate ocean circulation, eddy dynamics, and temperature-salinity structures, revealing the energy transfer processes across different scales within eddies (Klein et al., 2008; Qiu and Chen, 2012). During the formation of mesoscale eddies, energy is typically transferred from large-scale wind stress or ocean currents to mesoscale structures through nonlinear interactions, and ultimately dissipated at smaller scales via turbulence. By integrating altimetry data with numerical models, researchers can quantify the energy transfer from large to small scales and analyze the energy variations induced by eddies (Qiu and Chen, 2005; Scott and Wang, 2005; Chelton et al., 2011). For instance, studies have shown that in the tropical Atlantic, eddy formation involves energy input from large-scale circulation, which is subsequently converted into kinetic energy through eddy interactions before eventually dissipating into turbulence (Chelton et al., 2011a). Such research not only enhances the understanding of mesoscale eddy formation and evolution but also reveals their potential impacts on oceanic energy distribution, circulation patterns, and climate variability.

### 3.4.5 Heat and material transport by mesoscale eddies

The presence of mesoscale eddies plays a crucial role in global oceanic material transport. The primary contribution of eddy transport lies in the redistribution of heat, salinity, and biochemical components. In particular, studies in the Southern Ocean have highlighted these effects: Zhang Z. et al. (2014) analyzed water mass properties, while Dong et al. (2014) tracked heat and salt materials entrained and transported by eddies. Zhang Y. et al. (2014) investigated the movement of deep-sea sediments to determine the penetration depth of eddy influence. Similarly, Xu et al. (2014) explored the role of eddies as energy carriers or sources, elucidating the mechanisms of oceanic energy redistribution. Theoretical and observational analyses indicate that, due to Earth's rotation, cyclonic and anticyclonic eddies exhibit westward propagation while also moving poleward and equatorward, respectively (Beron-Vera et al., 2008). The temperature and salinity anomalies within eddies are often carried along through advection, enabling eddies to transport heat and salt effectively. Mesoscale eddies serve as an intermediate link in the energy cascade from large to small scales, with their eddy kinetic energy (EKE) accounting for 80%–90% of the total kinetic energy of the surface current field (Xu et al., 2014). As a result, mesoscale eddies play a critical role in the global oceanic energy budget, influencing ocean circulation, oceanic heat transport, global climate change, biogeochemical processes, and environmental shifts. Due to the relatively low resolution of current ocean models, studies on eddy-driven heat and salt transport in high-resolution global ocean circulation models remain limited. However, previous satellite altimetry data, ocean circulation models, and current meter temperature records reveal significant poleward eddy fluxes in the Antarctic Circumpolar Current (ACC) of the Southern Ocean. Using sea surface height anomaly (SSHA) data from satellite altimetry, Dong et al. (2014) tracked individual eddies and found that eddy transport is primarily driven by their movement. Jayne and Marotzke (2002) identified that eddy heat transport consists of both rotational and divergent components, with the divergent component being strongest in the ACC, locally influencing heat budgets and heat transport.

# 4 Discussion

This study systematically analyzes the current research progress in the field of oceanic mesoscale eddies using remote sensing methods through bibliometric approaches. It examines the publication output in this field, the international activity of researchers, the national collaboration network, and keyword co-occurrence and burst analysis. Based on the current state of research, the following discusses potential future development directions.

## 4.1 The next-generation satellite observation missions

In recent years, the rapid advancement of satellite remote sensing technology has significantly promoted research on ocean mesoscale eddies, with the upcoming full deployment of the SWOT (Surface Water and Ocean Topography) satellite receiving considerable attention. Developed jointly by NASA (National Aeronautics and Space Administration) and CNES, the core innovation lies in its use of interferometric radar altimetry (KaRIn), which enables unprecedented high-resolution measurements of sea surface height (Srinivasan and Tsontos, 2023). Compared to traditional satellite altimetry data, SWOT improves spatial resolution from tens of kilometers to approximately 1–2 km, greatly enhancing the ability to detect mesoscale and sub-mesoscale oceanic processes (Du and Jing, 2024; Zhang Z. et al., 2024). This breakthrough allows scientists to characterize the structure, evolution, and impact of ocean eddies more precisely on ocean circulation and climate systems, advancing global ocean dynamics research to a new level. Additionally, its wide measurement swath (~120 km) and high-resolution data offer new possibilities for improving global ocean models and weather forecasting.

However, despite the significant breakthroughs that SWOT has brought to mesoscale eddy research, certain limitations remain. First, although its spatial resolution has significantly improved compared to traditional altimetry satellites, fully resolving turbulent processes and small eddies smaller than 1 km in open ocean regions remains challenging (Wang Y. et al., 2024). In addition, SWOT observational data primarily cover surface features, making the investigation of deep ocean dynamic processes reliant on the combined analysis of buoy measurements, profiling instruments, and numerical simulations (Fu et al., 2012; Morrow et al., 2019). Furthermore, the observational orbit of SWOT determines that its temporal coverage is not continuous, with a revisit cycle of approximately 10–21 days, which may lead to an incomplete capture of rapidly evolving ocean eddy processes (Lee et al., 2010; Yang et al., 2019). To fully utilize the potential of SWOT data, future research should integrate additional satellite observations, *in situ* measurements, and high-resolution numerical models. This integration will help overcome limitations in spatial and temporal coverage, providing a more comprehensive understanding of the dynamical characteristics of mesoscale eddies and their impact on the global climate.

## 4.2 Integration with numerical models

In recent years, numerical models have played a crucial role in the study of ocean mesoscale eddies. Ocean numerical simulations not only provide high spatial and temporal resolution data but also help scientists investigate the impact of different dynamic processes on mesoscale eddies. Traditional geostrophic vortex theory and quasi-geostrophic approximations have provided significant guidance for mesoscale eddy simulations. However, with an improved understanding of ocean turbulence characteristics and submesoscale processes, numerical models are evolving toward higher accuracy and more complex physical mechanisms. For example, high-resolution ocean circulation models, such as HYCOM (HYbrid Coordinate Ocean Model) and MITgcm (Massachusetts Institute of Technology General Circulation Model), allow for more detailed analyses of the generation, evolution, threedimensional structure, and influence of mesoscale eddies on material and energy transport (Zhang Y. et al., 2024; L'Hégaret et al., 2015; Fu et al., 2021; Trott et al., 2023). Furthermore, with the advancement of ensemble assimilation techniques, data assimilation methods such as four-dimensional variational assimilation (4D-Var) and ensemble Kalman filter (EnKF) have demonstrated significant potential in improving the initial conditions and dynamic process representation in eddy simulations (Gao et al., 2008; Weiss and Grooms, 2017; Li et al., 2024).

Despite significant progress in the study of ocean mesoscale eddies using numerical models, several challenges remain. For instance, the energy cascade, interactions, and coupling of mesoscale eddies with submesoscale processes are still difficult to simulate accurately. These challenges are primarily constrained by model spatial resolution, turbulence parameterization schemes, and computational resources (Stanev et al., 2020; Cao et al., 2021). Additionally, due to the large temporal and spatial variability of mesoscale eddies, the accuracy of model results depends on high-quality observational data for validation and correction (Wang X. et al., 2024). Therefore, future research should further integrate satellite remote sensing data, *in situ* observations (such as Argo floats and profiling instruments), and advanced numerical simulation methods to enhance the understanding of mesoscale eddy dynamics. The fusion of multi-source data and multi-scale approaches will provide more reliable scientific support for global climate change research, improvements in ocean forecasting systems, and marine resource management.

## 4.3 Big Data and Artificial Intelligence

Traditional research methods have primarily relied on numerical simulations and statistical analysis. However, when handling such large datasets and highly complex physical processes, the efficiency and accuracy of traditional approaches are limited. Therefore, the introduction of big data technologies and artificial intelligence (AI) provides new solutions for the automatic identification, classification, tracking, and dynamical analysis of mesoscale eddies. In recent years, deep learning-based eddy detection algorithms, such as convolutional neural networks (CNN) and recurrent neural networks (RNN), have been widely applied to satellite observations and model simulation data. These methods enable efficient extraction of eddy structures within ocean flow fields, overcoming the bottlenecks of traditional methods in terms of data processing efficiency and identification accuracy (Santana et al., 2020, 2022; Safari et al., 2024).

Furthermore, artificial intelligence not only enhances the accuracy of mesoscale eddy detection but also demonstrates significant potential in eddy dynamics research. For example, machine learning can be applied to optimize eddy parameterization schemes, improving numerical models' ability to simulate mesoscale eddy energy cascades and cross-scale exchanges (Zhang et al., 2023; Wang G. et al., 2024). Additionally, intelligent methods based on data assimilation are emerging, integrating AI with numerical models. By training data-driven model correction schemes through deep learning, these approaches enhance the predictive capability for mesoscale eddies (Wang et al., 2020; El Kadiri et al., 2024). Moreover, big data analysis techniques, such as clustering analysis, pattern recognition, and selforganizing maps, can extract statistical characteristics of ocean mesoscale eddies. When combined with high-resolution satellite data, such as AVISO sea surface height data and Argo profiling data, these techniques enable long-term eddy tracking and climate impact assessments (Chelton et al., 2011). In the future, with the continued advancement of AI algorithms and big data technologies, integrating multisource data fusion and high-performance computing is expected to overcome the limitations of traditional models in mesoscale eddy research, driving ocean dynamics studies toward higher precision and greater efficiency.

# 5 Conclusion and perspective

This paper utilizes bibliometric methods to analyze the research progress on global mesoscale eddy from a macro-statistical perspective. It concludes that research literature on mesoscale eddy has undergone three distinct development phases over the past half-century, each closely linked to advancements in satellite remote sensing technology. The United States and China are leading countries in this field, with a significant number of publications, most of which appear in *Journal of Geophysical Research-Oceans*, a leading journal in mesoscale eddy research. Both countries have also formed four close international cooperation groups with other nations, with scholars such as Chelton D.B., Qiu B, McGillicuddy D.J., Chaigneau A, and Gaube P and Changming Dong being prominent experts. Furthermore, keyword burst indicates that research on mesoscale eddy focuses on altimetry observations and shows a trend towards interdisciplinary studies combining oceanography and biology.

Recent research directions include methods for detecting eddies with remote sensing technology, the three-dimensional structure of mesoscale eddy, eddy interactions, and eddy-induced heat and salt transport. The advancement of new-generation satellite missions such as SWOT is expected to significantly enhance the study of ocean mesoscale eddy and represents a frontier for future research. In recent years, substantial research on mesoscale eddy has made it a focal point of study. According to recent statistics, China ranks second in the volume of research publications on ocean mesoscale eddy, following the United States. To maintain its leading position, China should strengthen international cooperation, work with multiple countries on global ocean mesoscale eddy research and increase research investments. Moreover, amid global warming and rapid polar ice melt, China should focus on the study of polar mesoscale eddy, particularly those under polar ice coverage, the interaction between mesoscale eddy and sea ice, and the three-dimensional structure of polar mesoscale eddy. Additional research should also address the relationship between mesoscale eddy and climate change, including their impact on ocean heatwaves, polar sea ice, carbon balance, and marine ecosystems.

# Data availability statement

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

# Author contributions

FX: Conceptualization, Formal Analysis, Methodology, Writing – original draft, Writing – review & editing. ZW: Conceptualization, Data curation, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. HW: Data curation, Investigation, Writing – review & editing. TL: Formal Analysis, Supervision, Writing – review & editing. XS: Project administration, Supervision, Writing – review & editing. HP: Methodology, Funding acquisition, Supervision, Writing – review & editing.

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# Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

# Generative AI statement

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## Publisher's note



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