Jiang *et al.*
Intelligent Marine Technology and Systems (2023) 1:6
https://doi.org/10.1007/s44295-023-00006-z

Intelligent Marine Technology and Systems

RESEARCH PAPER Open Access

Global ocean observations and applications by China's ocean satellite constellation

Xingwei Jiang[1], Xiaobin Yin[2,3,4*], Lei Guan[2,3,4], Zhaohui Wang[1], Letian Lv[2] and Mutao Liu[5]

Abstract

Satellite remote sensing data form the basis of ocean observation and applications. China has established a satellite network platform comprising ocean color satellite constellations, ocean dynamic environment satellite constellations, and ocean observation and monitoring satellite constellations. This platform provides consistent and reliable ocean observation data crucial for marine scientific research, economic development, and early warning and forecasting. This paper comprehensively describes the development process and plans for China's ocean satellites from their inception. It offers detailed technical specifications of ocean satellites and outlines the current applications of ocean water color satellites (HY-1), ocean dynamics and environment satellites (HY-2), and ocean surveillance and monitoring satellites (GF-3) in ocean parameter inversion, target identification and detection, and early warning and forecasting. In the future, to enhance the level of industrialization in ocean remote sensing in China, it is imperative to leverage the diversity and timeliness of ocean remote sensing data. Additionally, emerging technologies such as cloud computing and artificial intelligence should be harnessed, and the application potential of various satellite data resources should be explored.

Keywords China, Ocean satellites, Satellite network platform, Satellite application, Ocean observation data

1 Introduction

Ocean observation technology forms the core of marine science and technology, and it is closely related to the ability to mitigate marine disasters. Currently, ocean observation platforms combining ocean remote sensing satellites, research vessels, deep submersibles, and seabed observation networks have been established. However, apart from ocean remote sensing satellites, other observation methods can either conduct intermittent and crucial node observations or experience challenges in ensuring effective data transmission capacity (Song et al. 2020). In the field of ocean observation and application, satellite remote sensing data have become a crucial data source for scientific research and management.

Remote sensing technology aims to accurately and objectively depict real phenomena through remote sensing data. The research direction is mainly focused on data processing, as reflected in the enhancement of data temporal and spatial resolution, diversification of layer types, improved efficiency of physical process inversion algorithms, and augmentation of algorithmic intelligence. Remote sensing technology originated from the field of geographic information and experienced limitations in data processing capacity and aerospace infrastructure during its early developmental stages. The initial integration of remote sensing technology primarily pertained to 'proximity' fusion, mainly within industries with a strong demand for geographic information. For example, the integration and cross-disciplinary applications

---

*Correspondence:
Xiaobin Yin
Yinxiaobin@ouc.edu.cn
[1] National Satellite Ocean Application Service, Ministry of Natural Resources, Beijing 100081, China
[2] Faculty of Information Science and Engineering, College of Marine Technology, Ocean University of China, Qingdao 266100, China
[3] Laoshan Laboratory, Qingdao 266237, China
[4] Sanya Oceanographic Institution, Ocean University of China, Sanya 572024, China
[5] China Siwei Surveying and Mapping Technology Co., Ltd., Beijing 100080, China

of remote sensing technology in fields such as oceanography, meteorology, agriculture, construction, and other disciplines and industries have given rise to new areas of study, such as ocean remote sensing and meteorological remote sensing. These developments have significantly improved comprehensive assessment capabilities in fields such as crop assessment and urban and rural planning. As new infrastructure continues to advance, communication, navigation, and other foundational capabilities have been greatly enhanced. This has enabled the gradual realization of real-time and intelligent production of remote sensing data, providing a solid foundation for expanding the scope of integration and cross-disciplinary applications. Currently, novel concepts such as remote sensing journalism and remote sensing economics have emerged, indicating that remote sensing technology is not only deeply integrated with natural science disciplines but is also rapidly integrating with humanities disciplines.

Ocean remote sensing technology has its roots in the application of United States NOAA meteorological satellites in the field of oceanography during the 1970s. Its early focus was on preliminary research in areas such as large- and meso-scale ocean dynamics, sea surface temperature (SST), estuarine and near-shore suspended sediments, oceanic fisheries, and island and reef surveys. Since the launch of Seasat-1 in the United States in 1978, numerous satellites dedicated to marine scientific research have been launched worldwide. As a result, marine satellites have evolved into a distinct category within the field of remote sensing. In 1979, China conducted its first oceanic aerial remote sensing experiment in the East China Sea (Zheng and Wu 1990). However, due to technological constraints, China's first oceanic satellite was not launched and operational until 2002 (Lu 2008). Since then, China has systematically developed its ocean satellites, resulting in three series: ocean water color, ocean power environment, and ocean surveillance and monitoring. China has also independently acquired a substantial amount of ocean remote sensing data (Lin and Jiang 2020).

China has established a series of ocean-focused satellites into three constellations: the ocean water color satellite constellation, the ocean dynamics and environment satellite constellation, and the ocean surveillance and monitoring satellite constellation. These constellations have enabled the formation of autonomous ocean satellite networks with observation capabilities. The National Satellite Ocean Application Center of the Ministry of Natural Resources has released hourly, daily, monthly, and decadal gridded remote sensing products based on China's ocean satellites to the public. These products address gaps in domestic gridded and operational data, including sea surface height anomalies and sea surface wind fields (Liu et al. 2021a, b). They serve as a stable source of ocean observation information and have become a crucial database for marine scientific research, marine economic development, marine forecasting, disaster mitigation, marine law enforcement, and other fields (Jiang et al. 2019).

This paper provides a detailed overview of the development and planning of China's marine satellites, discusses the current applications of ocean satellite constellations, and outlines future development directions. The structure of the remainder of this article is as follows: Section 2 covers the development of ocean satellites, Section 3 delves into the application status of ocean satellite constellations, and Section 4 presents the conclusions.

2 Development of ocean satellite in China

The milestone event marking the beginning of China's aerospace journey was the successful launch of Dongfanghong No. 1, China's first artificial Earth satellite, on April 24, 1970. Since then, the country has achieved significant milestones, including the development of the Long March series of carrier rockets and the Practice series of satellites. In the realm of civil spaceflight, satellite development plays a pivotal role. Presently, the Medium- and Long-term Development Plan for National Civil Space Infrastructure (2015–2025), commonly known as the 'space-based plan,' serves as a crucial guiding document for China's civil space sector. It was formulated during the 12th Five-Year Plan period and holds a central position in China's civil space strategy. In Chapter IX of the 'Outline of the Fourteenth Five-Year Plan for the National Economic and Social Development of the People's Republic of China and the Vision and Goals for 2035,' titled 'Developing and Strengthening Strategic Emerging Industries,' Section I emphasizes the importance of constructing new pillars within the industrial system. This entails a focus on strategic emerging industries such as new-generation information technology, green environmental protection, and aerospace. The plan aims to expedite the application of core technological innovations, bolster necessary resources, and nurture the growth and expansion of new sources of industrial development.

The space-based planning proposes to 'gradually build … a national civil space infrastructure consisting of three major systems, namely, satellite remote sensing, satellite communication and broadcasting, and satellite navigation and positioning, to satisfy … application needs and support … development requirements.' Accordingly, China's civil space infrastructure, following industry conventions, can be broadly categorized into 'satellite communications and broadcasting,' 'navigation,' and 'satellite remote sensing.' Regarding satellite remote sensing, the plan emphasizes the development of three major series:

land observation, ocean observation, and atmospheric observation. The goal is to establish a remote sensing satellite system comprising seven constellations and three types of thematic satellites. The land observation series encompasses constellations for high-resolution optical, medium-resolution optical, and synthetic aperture radar (SAR) observations. The ocean observation series includes constellations for ocean water color, ocean dynamics, and environment and three observation constellations for ocean surveillance and monitoring. The atmospheric observation series comprises two satellite constellations dedicated to weather observation and climate observation.

As part of the implementation of the space-based planning, the State Administration of Science, Technology, and Industry for National Defense (SASTIND) promulgated and implemented the Interim Measures for the Management of Civil Satellite Engineering in 2016. These measures regulate activities related to the management of civil satellite engineering, ranging from demonstration to satellite decommissioning. According to the Interim Measures for the Management of Civil Satellite Engineering and the practical work of relevant ministries and commissions, civil satellite engineering encompasses six major systems: satellite, launch vehicle, launch site, measurement and control, ground, and application systems. These systems fall under the purview of various state departments, including the SASTIND and the National Development and Reform Commission (NDRC). There are different departments responsible for organizing, managing, and coordinating specific aspects of civil satellite engineering, including the user department, development and construction department, and launch, measurement, and control department.

In 2018, the SASTIND, NDRC, and the Ministry of Finance jointly issued the Interim Measures for the Management of Remote Sensing Data from National Civilian Satellites. These measures outline the roles of the Land Satellite Remote Sensing Application Center, National Satellite Meteorological Center, and the National Satellite Ocean Application Service (NSOAS) as the three major satellite data centers for land, meteorology, and oceans, respectively. The document states that these centers are responsible for the acquisition, processing, archiving, and distribution of relevant satellite remote sensing data in accordance with their respective duties. This establishes their ownership status in the field of land, meteorological, and oceanic satellite engineering. In 2022, the Interim Measures for the Management of International Cooperation on Remote Sensing Data from National Civilian Satellites, issued under the auspices of the SASTIND, similarly emphasized the central role of the abovementioned three centers.

China has developed the following three series of ocean satellites: the ocean water color satellite constellation, the ocean dynamics satellite constellation, and the ocean surveillance and monitoring satellite. These satellites have evolved from single models to a diverse range of spectrums and have transitioned from experimental applications to operational services. Moreover, the satellites have made rapid progress toward serialization and operationalization. The three series of satellites are now operating in orbit in synchronization. During the 13th Five-Year Plan period, China achieved significant milestones in the development of its ocean observation satellite system, launching six ocean satellites in just 5 years. This pace of development represents substantial acceleration compared with the three ocean satellites launched over the previous 15 years, spanning from the 10th to the 12th Five-Year Plan periods. On June 11, 2020, the launch of the Haiyang-1D (HY-1D) satellite established a two-star network in conjunction with the Haiyang-1C (HY-1C) satellite. This development in China's ocean water color satellite constellation enabled global ocean observation coverage twice a day, significantly enhancing observation capabilities for global ocean water color and ecological environments. On May 19, 2021, the successful launch of the Haiyang-2D (HY-2D) satellite marked a significant milestone in China's ocean dynamic environment monitoring constellation. The satellite facilitates high-precision observation of global wind fields, dynamic fields, temperature fields, and more, providing real-time data crucial for ocean disaster early warning and forecasting. Two 1-m C-SAR satellites were launched at the end of 2021 and the beginning of 2022, respectively. These satellites have formed China's first C-band SAR satellite constellation, capable of observing both land and sea conditions with a remarkable 1-m resolution. This development significantly enhances China's satellite capabilities for monitoring land and sea conditions and provides crucial support for disaster prevention and control and emergency responses to climate change. Additional ocean satellites that have received approval and are under research include the new generation of ocean water color and power research satellite (HY-1E) and an ocean salinity detection satellite. Furthermore, in the follow-up period of the 14th Five-Year Plan, there are plans to develop eight more ocean satellites. These include the new-generation ocean water color operational satellite, new-generation ocean dynamics satellite, sea breeze and wave detection satellite, high-orbit ocean and coastal zone environment monitoring satellite, and high-orbit ocean surveillance microwave satellite. The demonstration of these new ocean satellites is progressing gradually as planned, and they are entering a stage of comprehensive and rapid development. Once the '14th Five-Year

Plan' satellite network is fully organized, it will effectively address the limitations associated with a single payload, i.e., a single satellite's operational lifespan and coverage. Technical indicators of the ocean satellites can be found in the Appendix Table A1–Table A5.

3 Current situation of marine satellite observation and application in China

3.1 Ocean water color satellites (HY-1)

The HY-1 series consists of ocean water color satellites primarily equipped with the Chinese ocean color and temperature scanner (COCTS), coastal zone imager (CZI), and other instruments. These satellites are used to acquire optical properties of seawater, enabling the retrieval of information such as chlorophyll concentration, SST, suspended sediment content, soluble organic matter, and pollutants. Building upon the water color satellites commonly used domestically and internationally, several studies have been conducted to enhance the capabilities of HY-1 satellites. Lee et al. (1994) developed remote sensing reflectance models for coastal waters. Tang et al. (2004) measured and analyzed the basic parameters directly related to water color remote sensing. Mao et al. (2016, 2022) developed a unified atmospheric correction to eliminate the difference in the ground reflectance between land and ocean and applied the layer removal scheme for atmospheric correction to process the HY-1C/D data. According to the HY-1 series of ocean water color satellite data, Chen et al. analyzed the performance of COCTS and CZI loads of HY-1C/D satellites in water color remote sensing inversion (Song et al. 2019; Chen et al. 2021; Cui et al. 2023) (Fig. 1). Ye et al. (2021) used an atmospheric correction algorithm and the OC4 and color index algorithms to derive global chlorophyll-*a* concentration from COCTS (Fig. 2) and evaluated the SST product of COCTS with HY-1C/D using a nonlinear SST algorithm with corresponding coefficients (Ye et al. 2022) (Fig. 3). Liu et al. (2022a, b) showed that Bayesian cloud detection and optimal estimation algorithm can improve the SST retrieval accuracy of COCTS observations. In 2023, using the observed bright temperatures of the HY-1D thermal infrared channel, cloud detection and SST inversion algorithms were implemented according to atmospheric radiative transfer simulation calculation (Liu et al. 2023).

3.2 Ocean dynamics and environment satellites (HY-2)

The HY-2 series comprises ocean dynamics and environment satellites primarily equipped with onboard microwave radiometers, radar altimeters, and scatterometers. These instruments are utilized to gather information about ocean dynamics and the environment. The satellite-borne microwave radiometer is mainly employed to acquire data on SST and sea surface wind fields. Typically, the inversion process involves utilizing a large number of synchronized measurements from satellite remote sensing and buoys, establishing a connection between remote sensing data and ocean-atmospheric parameters through regression fitting. Scholars have developed many inversion algorithms

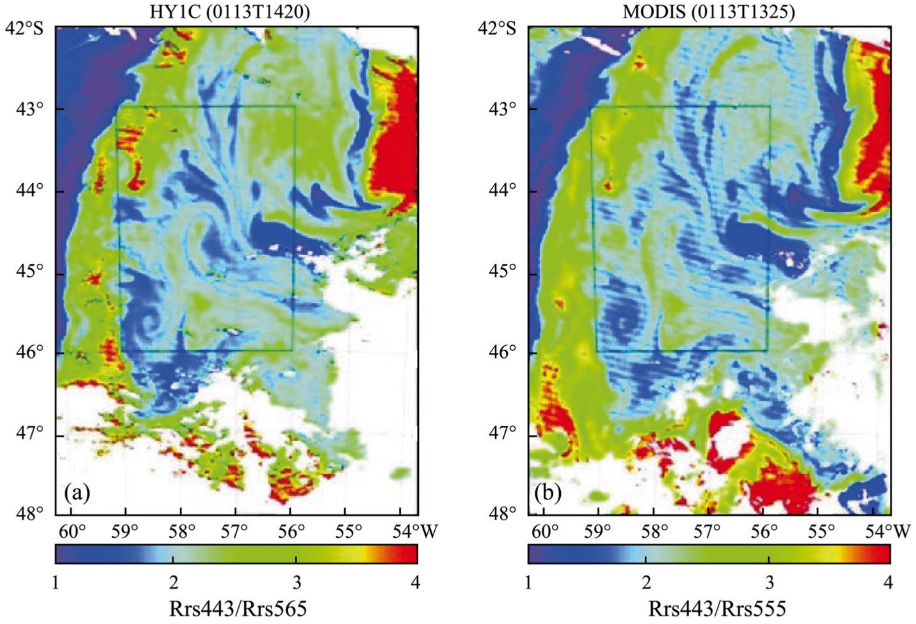

Fig. 1 Comparison of COCTS-HY1C and Terra-MODIS chlorophyll-*a* concentration distributions on January 13, 2019 (Song et al. 2019)

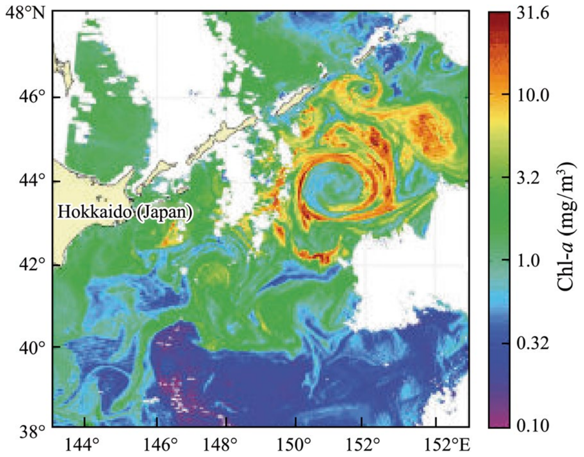

Fig. 2 COCTS/HY-1C chlorophyll-*a* concentration (May 25, 2019, 00:35 UTC) (Ye et al. 2021)

for microwave radiometer data. These include the D-matrix regression algorithm established by Goodberlet et al. (1989), the linear regression algorithm developed by Wentz and Meissner (2000), and models such as the two-scale model and the four-parameter vector model developed by Yueh (1997). Johnson and Cai (2002) and Irisov (2000) respectively conducted theoretical studies on the scattering of sea surface emissivity and sea surface bright temperature using the small slope approximation for rough sea surface. Wang and other researchers have created retrieval algorithms for Shenzhou IV, AMSR-E, and HY-2A (Li and Wang 2005; Wang and Li 2009; Wang et al. 2014) (Fig. 4). Wang et al. (2015), Yin et al. (2017), Ma et al. (2020) and Zhou et al. (2022) have improved the algorithms of microwave radiometer network observation products. Liu et al. (2020) corrected the HY-2A microwave radiometer bright temperature to improve the accuracy of SST retrieval. The satellite-borne radar altimeter is primarily used to obtain sea surface power altitude data. Le Traon et al. (1995) established the algorithmic foundation for radar altimeter data fusion products, while Dibarboure et al. (2011) developed an objective analysis algorithm for radar altimeter data, which has become the mainstream approach in current operationalized algorithms. Jia et al. (2020) developed retrieval algorithms and conducted a comparative analysis of multiple ocean satellite data (Fig. 5). The satellite-borne microwave scatterometer is mainly employed for acquiring sea surface wind field data. Lin (2000) proposed a retrieval algorithm to eliminate wind vector interference, Feng (2004) established a sea surface wind field retrieval model suitable for sea areas, and Zhang et al. (2009) provided detailed descriptions of the data preprocessing process, wind field inversion method (Zhang et al. 2012), and HY-2B in-orbit test process to prepare for HY-2 operational service (Zhang et al. 2020). Lin et al. (2016), Li et al. (2021) and Liu et al. (2022a, b) comparatively analyzed the sea surface wind field retrieval models and improved them. Liu et al. (2021a, b) compared the accuracies of HY-2A, CFOSAT, and ERA5 sea surface wind field products. Wang et al. (2020) used a MetOp scatterometer to verify the data quality of the HY-2B scatterometer and developed a geophysical model function based on the HY-2B/C/D satellite scatterometer for wind field retrieval (Wang et al. 2023). Numerous scholars have extensively explored the application potential of the HY-2 remote sensing satellite, providing crucial data and technical support for ocean scientific research, ocean disaster prevention and mitigation, and ocean environmental protection.

3.3 Ocean surveillance and monitoring satellites (GF-3)

Haiyang-3 is a series of ocean surveillance and monitoring satellites. Among them, the Gaofen-3 (GF-3)

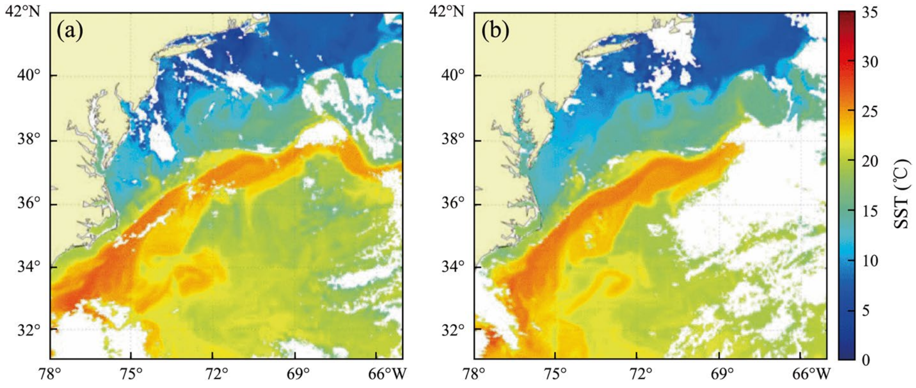

Fig. 3 SSTs obtained on April 27, 2021, at **a** 17:35 UTC and **b** 06:20 UTC from COCTS covering Gulf Stream waters on the HY-1D satellite: **a** daytime SST; **b** nighttime SST (Ye et al. 2022)

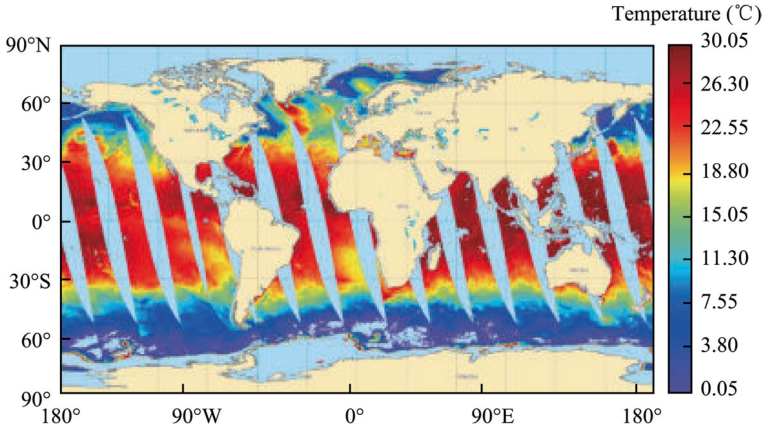

Fig. 4 Retrieval results of sea surface temperature for HY-2A up-orbiting (Wang et al. 2014)

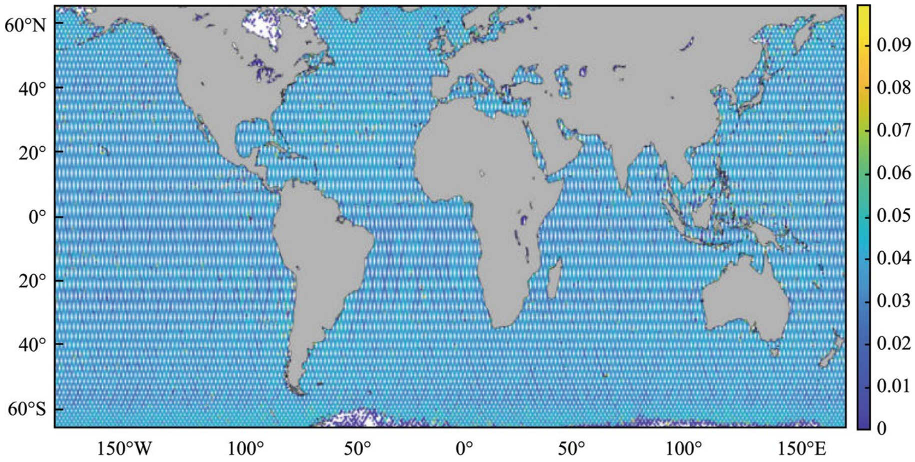

Fig. 5 Sea surface altitude as reflected by HY-2B radar altimeter (Jia et al. 2020)

satellite is China's first ocean surveillance and monitoring satellite. It primarily carries a C-band multipolarized SAR (C-SAR) with 12 imaging modes, including strip, scanning, and wave modes. The spatial resolution of the fine mode can reach 1 m (Yuan et al. 2018), making it the satellite with the most extensive range of imaging modes globally. It comprehensively captures multipolarized information from both the ocean and land, enabling all-weather and continuous surface observation (Lin et al. 2019; Zhang and Liu 2017). GF-3 is primarily used for high-precision monitoring of various oceanic phenomena, such as ships (Liu et al. 2017; Ma et al. 2018) (Fig. 6), islands and coastal zones (Huang et al. 2021) (Fig. 7), marine oil spills (Fu and Qin 2019), and sea surface wind fields (Shao et al. 2018, 2020; Wan et al. 2021; Fang et al. 2022; Yao et al. 2022) (Fig. 8). Yuan et al. (2018), Shao et al. and others developed C-SAR-based retrieval algorithms related to ocean parameters and conducted various ocean applications (Shao et al. 2018, 2020; Yao et al. 2022). In terms of marine parameter retrieval, Wang et al. (2022) proposed an effective wave height retrieval algorithm based on residual networks for GF-3 quad-polarized SAR data by utilizing cross-spectral information and radar backscattering data from GF-3 fully polarized data. Lin et al. (2017) confirmed the capability of GF-3 data to observe the fine structure of typhoons, and domestic scholars have developed numerous retrieval methods for sea surface wind fields based on GF-3 data. Regarding target identification and detection, Liu et al. (2017) implemented a target detection method for maritime vessels based on pixel classification within a Bayesian framework, enhancing the effectiveness of sea surface ship identification.

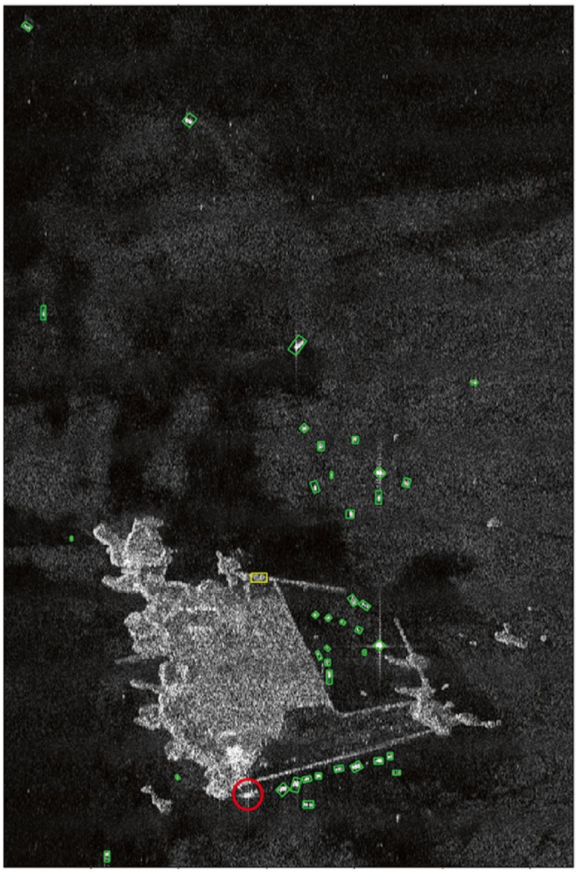

Fig. 6 GF-3 vessel detection results for narrow ScanSAR mode images (Liu et al. 2017)

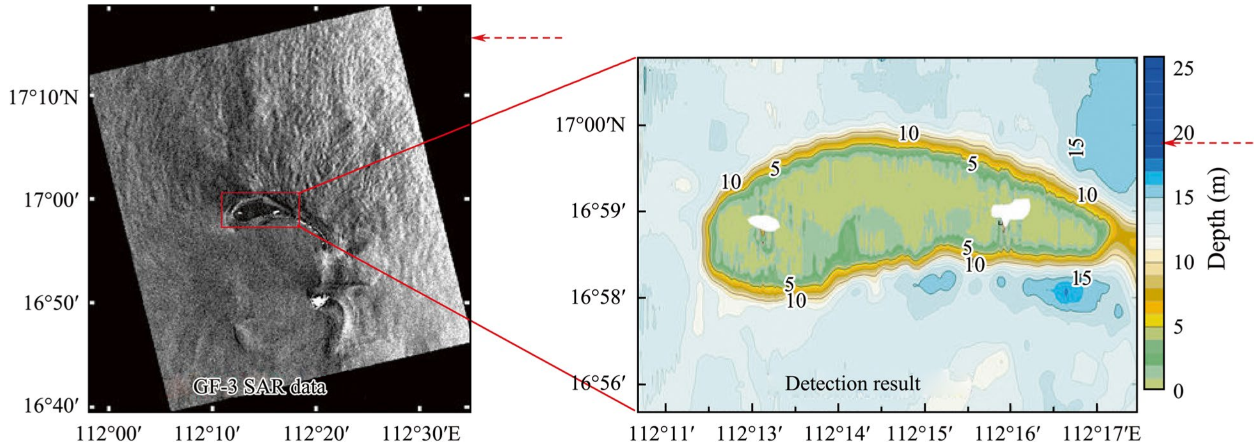

Fig. 7 Identification of underwater topography of Qilianyu Island in the South China Sea based on GF-3 SAR images (Huang et al. 2021)

3.4 Development of artificial intelligence in ocean remote sensing

Recently, there has been significant progress in the application of artificial intelligence (AI) technology in the field of marine satellites. Combining ocean satellite data with AI algorithms can help achieve efficient and accurate ocean observation and resource management. Deep learning techniques have enabled automated tasks such as target detection, internal wave recognition (Fig. 9), and marine pollution monitoring. AI has also found applications in marine weather forecasting and ocean disaster monitoring, playing a vital role in marine environmental protection and resource management (Qian and Chen 2018; Li et al. 2020a, 2020b; Chen et al. 2022).

Recently, Zhao et al. (2019) proposed a method for training and testing on embedded devices using a custom AI streaming architecture based on GF-3 satellite SAR images. Guo et al. (2022) utilized GF-3 SAR imagery and a convolutional neural network architecture based on transfer learning for the identification and retrieval of sea surface wind streaks. Men et al. (2022) introduced a new neural network (NN) AC algorithm for atmospheric correction of CZI data in coastal waters, effectively eliminating atmospheric effects on image quality. Yang et al. (2023) developed a ResNet-based method using HY-1C satellite COCTS imagery to retrieve global sea surface chlorophyll-*a* concentration, achieving higher accuracy in chlorophyll-*a* concentration estimation.

Thus, the integration of ocean satellites and AI will become increasingly seamless in the future. Ocean satellites will provide higher-resolution data, which, when combined with AI technology, will enable more precise marine monitoring and prediction. This integration will afford more opportunities for marine science, resource management, environmental protection, and other fields, offering further support for humanity's improved understanding and utilization of the oceans.

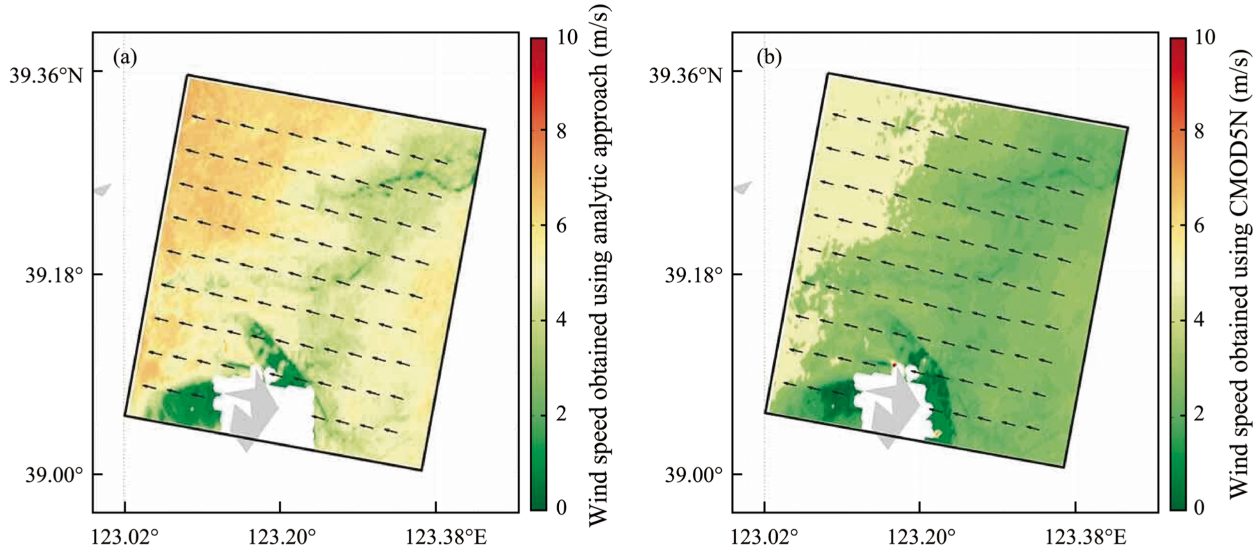

Fig. 8 Sea surface wind field based on GF-3 SAR retrieval (Yao et al. 2022)

3.5 Great achievements inspired by marine construction

During the 13th Five-Year Plan period, significant progress was made in capacity-building across various areas, including marine early warning and forecasting, ecological restoration, sea area and island surveys, polar oceans, and fisheries. In terms of marine early warning and forecasting, research and development efforts were dedicated to fusion products related to sea surface wind fields, waves, current fields, SSTs, and other environmental elements derived from autonomous ocean satellites. Operational monitoring of ecological and marine disasters, such as red tide, green tide, and typhoons, was conducted through multi-source remote sensing. Regarding ocean ecological restoration, demonstrations were conducted for monitoring coral reefs, mangroves, and other typical ecological operations. Remote sensing was employed for monitoring the red line of ocean ecological protection. In terms of sea and island surveys, several remote sensing surveys of China's islands and coastal zones were completed, resulting in the accumulation of a wealth of high-resolution remote sensing satellite and on-site survey data. These data were used for monitoring and assessing the implementation of ocean territorial spatial planning. An operational remote sensing monitoring system for questionable areas was also established. In the field of polar and oceanic research, technology was developed to provide remote sensing products related to global marine environmental elements. These products served global oceanic and polar surveys and monitoring. In the area of fisheries and fishing, efforts were made to expand the application areas for oceanic fishery navigation and environmental protection. Fishery forecasting was enhanced to guide fishing vessels in targeted fishing operations, thereby strengthening China's capacity to support the development and utilization of high-seas fishery resources.

3.6 Data distribution services

To promote the application and services of ocean satellites, NSOAS has intensified its efforts to facilitate the utilization of ocean satellites in coastal provinces and municipalities. Operating within the framework of provincial satellite application development by the Ministry of Natural Resources, a platform dedicated to remote sensing applications of marine satellites has been established. This platform is guided by the operational requirements of provincial application centers and tailored to the technical characteristics of marine satellite applications. The platform can deliver multi-source satellite data, primarily sourced from autonomous ocean satellites, in a real-time operational manner. It provides essential support and services to provincial satellite centers along the coast in various domains, including ocean environment monitoring, ocean ecological protection and restoration, ocean economic management, ocean disaster prevention and

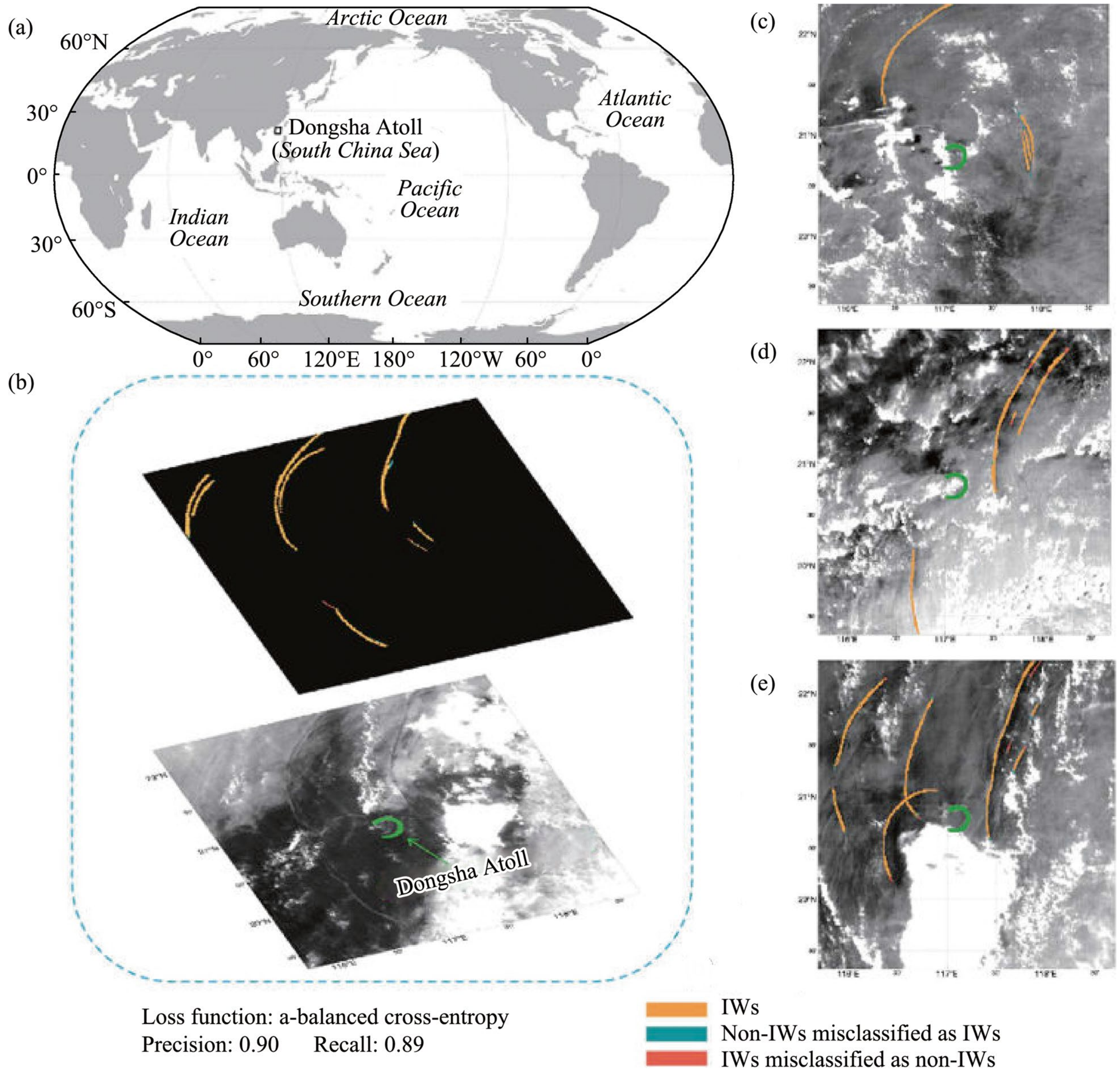

Fig. 9 Internal wave identification by artificial intelligence: **a** the study area; **b**–**e** input Himawari-8 images overlaid with their corresponding trained model extraction results (Li et al. 2020b)

mitigation, and ocean security. By establishing a collaborative mechanism, the synergy between provincial centers and ministry-level centers is optimized, resulting in enhanced application efficiency. NSOAS adopts a personalized strategy to customize its services based on the specific demands for ocean satellite data in different regions. For example, it supports Hebei, Jiangsu, and Zhejiang Provinces in conducting operational monitoring of offshore sea ice, red tides, and typhoons. It ensures marine forecasts and aids strait transport navigation in Fujian Province, provides ocean fishing forecasts in Shandong Province, and assists Guangdong Province in conducting surveys of marine wind energy resources.

To better serve users of ocean satellite data, NSOAC has established an ocean satellite data distribution system and a data-sharing service platform available in English and Chinese. The login address for the ocean satellite data distribution system is https://osdds.nsoas.org.cn. Additionally, a dedicated network line

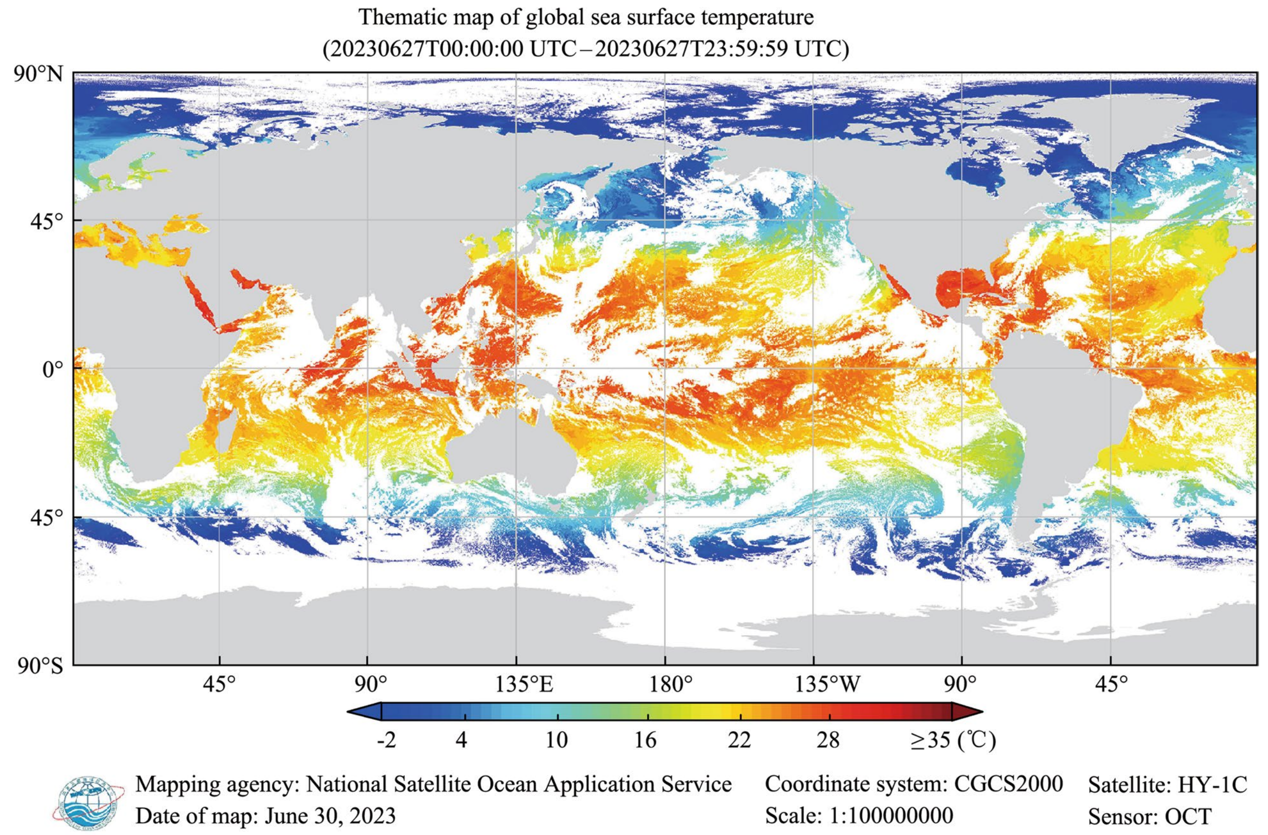

Fig. 10 HY-1C COCTS global sea surface temperature thematic map (July 2, 2023) (National Satellite Ocean Applications Service: http://www.nsoas.org.cn/)

has been established with 19 users, including institutions directly under the Ministry of Natural Resources, local provincial and municipal departments, and bureaus. A public WeChat service number and a 24-h service telephone number have also been made available. As of October 2021, the cumulative distribution of ocean satellite data reached approximately 270 TB. Differentiated services are offered based on user types, including three distribution methods: order downloads, File Transfer Protocol (FTP) downloads, and data pushes. These methods cater to users of the intranet dedicated line, large customers via FTP on the extranet, and ordinary users via the extranet website. Currently, the ocean satellite data distribution system has over 2000 registered users, including businesses, scientific research institutes, colleges, universities, and other relevant organizations.

Figures 10, 11, 12, 13 and 14 show thematic map products of SST, chlorophyll concentration, sea surface height, and sea surface wind field produced by NCSOA. These products are generated based on data from HY-1/COCTS, HY-2 microwave radiometer, satellite altimeter, and microwave scatterometer, respectively.

4 Summary

China has incorporated ‘actively expanding the space for marine economic development’ as a dedicated chapter in its ocean-related initiatives. This chapter is further divided into three sections: ‘building a modern marine industrial system’, ‘creating a sustainable marine ecological environment’, and ‘deeply participating in global ocean governance’. Presently, ocean observation technology remains a core component of marine science and technology, playing a pivotal role in shaping a modern ocean industry system. Its capabilities are directly linked with the development of the marine ecological environment and global ocean governance. Ocean remote sensing products, as integral components of the ocean observation technology system, have successfully transitioned

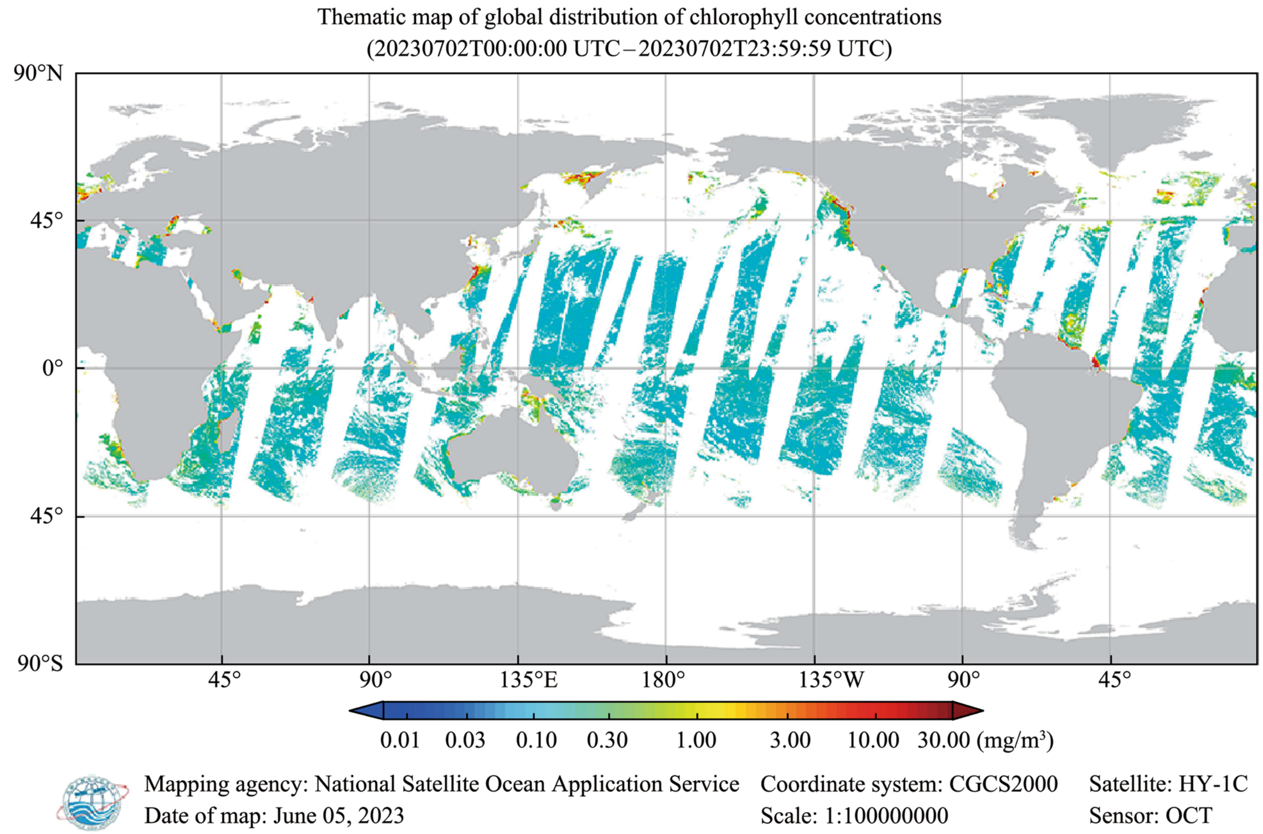

Fig. 11 HY-1C thematic map of global distribution of COCTS chlorophyll concentration (July 4, 2023) (National Satellite Ocean Applications Service: http://www.nsoas.org.cn/)

from scientific and technological innovation to commercial operation.

China has established a series of marine satellites as part of its civil space infrastructure plan, and commercial marine satellites are steadily expanding. The field of ocean remote sensing and spaceflight is evolving globally, with parallel developments in China, the United States, and Europe. China's public welfare services in ocean remote sensing are becoming increasingly effective, as evidenced by the completion of the national–provincial ocean remote sensing application system and the consistent release of operational ocean remote sensing products. In terms of value-added services in ocean remote sensing, both theoretical research and practical applications have begun to take shape. Market trends are increasingly influencing industry development, garnering considerable attention. However, the construction of China's marine remote sensing application system still lags behind of developed nations and lacks sufficient investment. The existing application system is operating at full capacity, and its support capacity is nearing its limit. This situation not only hampers the ability to efficiently process and store large-scale data from in-orbit satellites but also falls short of meeting the pressing needs of the national natural resource survey and monitoring in terms of functionality.

Compared with foreign countries, a considerable gap still exists between the industrialization of ocean remote sensing in China and that in developed nations. Therefore, there is an urgent need to align the development of ocean remote sensing with the globalized service landscape. It is crucial to seize the opportunity presented by the rapid advancement in aerospace engineering technology and marine scientific research capabilities and accelerate the exploration of industrial development models. Recently, with the growing demand for satellite remote sensing and spatial information services, along with the continuous implementation of favorable policies, the number of domestic

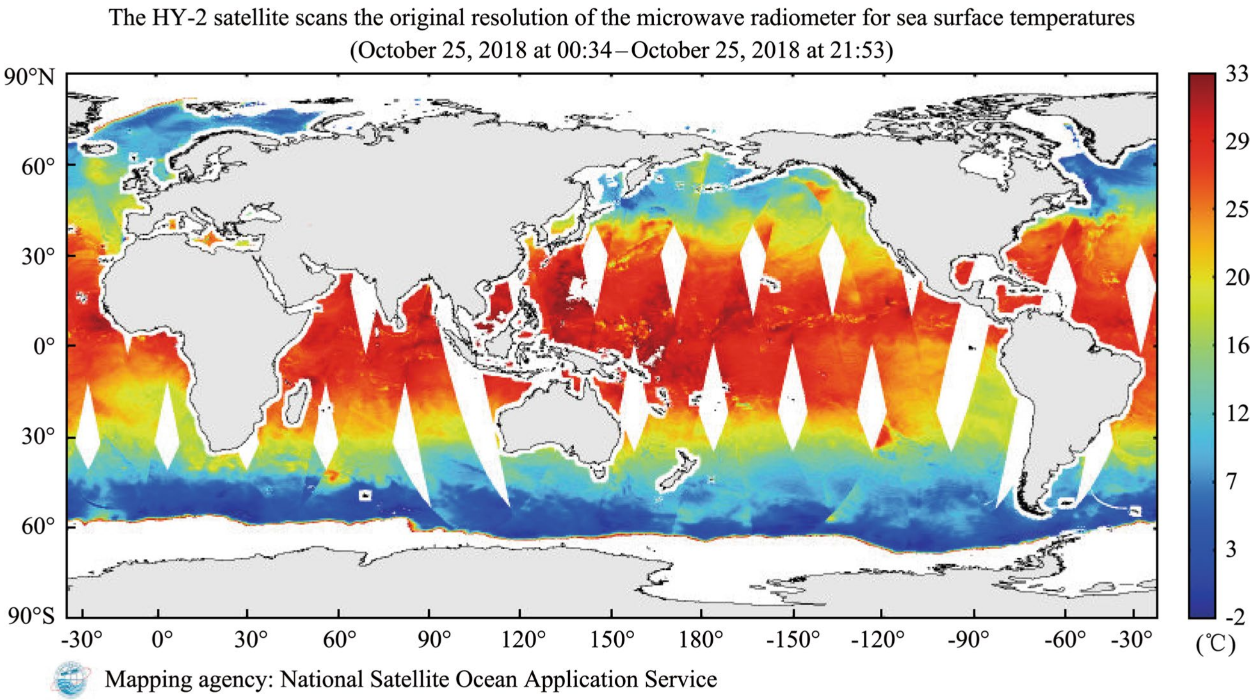

Fig. 12 HY-2 scanning radiometer sea surface temperature products (October 25, 2018) (National Satellite Ocean Applications Service: http://www.nsoas.org.cn/)

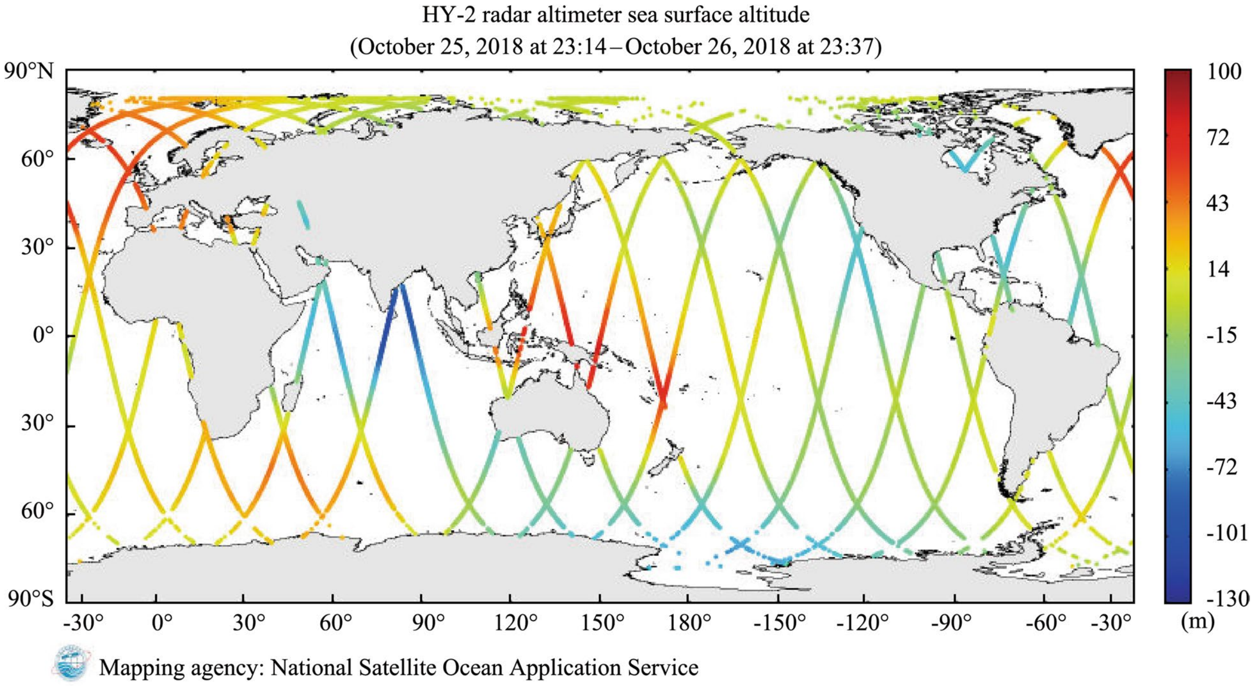

Fig. 13 HY-2 altimeter sea surface height product (October 25, 2018) (National Satellite Ocean Applications Service: http://www.nsoas.org.cn/)

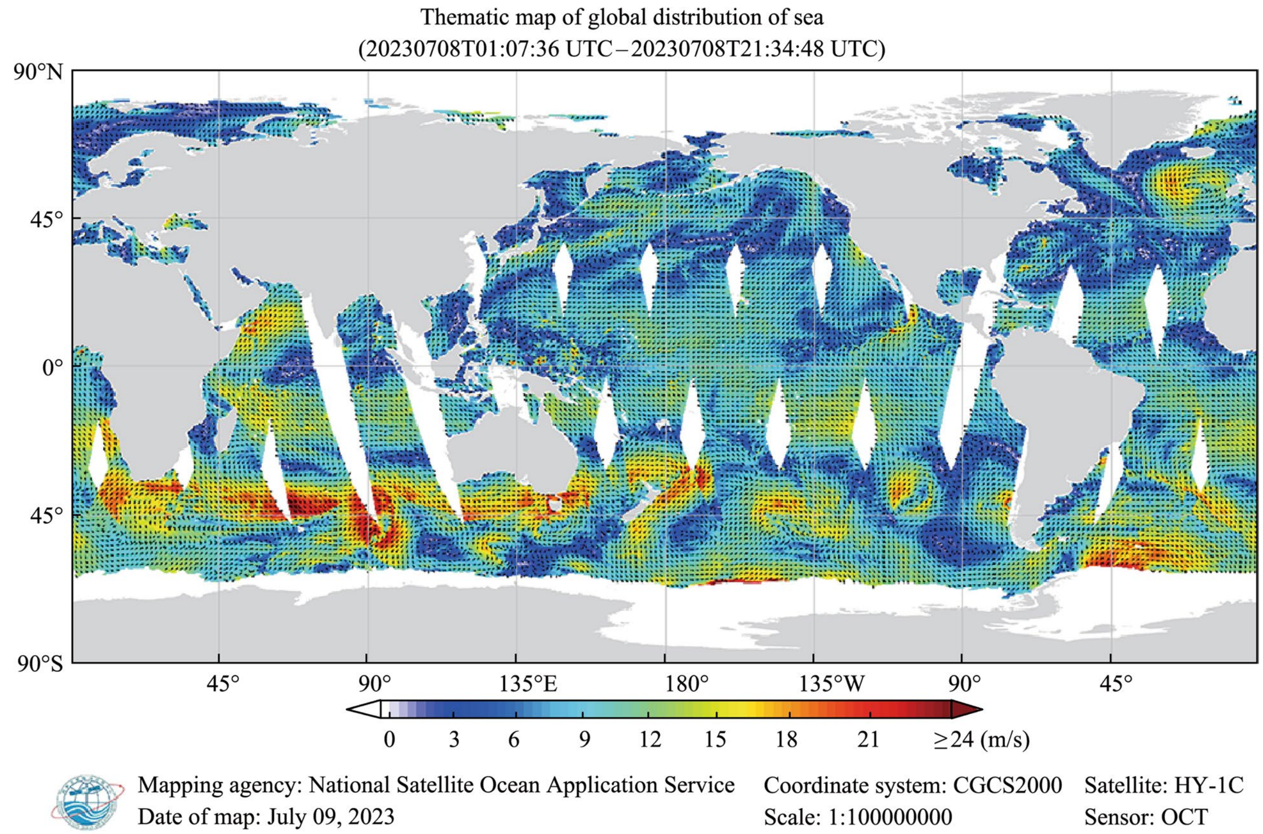

Fig. 14 Thematic map of the global distribution of the HY-2B scatterometer sea surface wind field (July 8, 2023) (National Satellite Ocean Applications Service: http://www.nsoas.org.cn/)

remote sensing satellite launches has increased annually. China's remote sensing market is experiencing rapid growth, presenting new opportunities for the development of ocean remote sensing. In the era of the digital economy, harnessing the full potential of marine remote sensing data, which are extensive, diverse, and time-sensitive, and developing new application scenarios based on them have become a fresh challenge for the advancement of ocean remote sensing.

During the 14th Five-Year Plan period, the development of the digital economy reached new heights. With the deepening of concepts such as 'intelligent ocean' and 'value-added marine information service' and the growing integration of technologies such as cloud computing, AI, and big data in the ocean domain, innovation in ocean science and technology has gained fresh momentum. Ocean application scenarios are expanding into new domains, creating an increased demand for a national-level operational application system for ocean remote sensing satellites. This system should be well-coordinated, strategically planned, and feature-rich, promoting information sharing and providing efficient services. There is an urgent need to strengthen and expedite the development of ground infrastructure and application systems for remote sensing satellites focused on natural resources. Additionally, it is critical to adapt to the requirements of significant reform tasks in the new period, such as the management of national natural resources, by fully exploiting the application potential of various types of satellite data resources. This will contribute to enhancing the engineering, operationalization, and industrialization of applications based on natural resource monitoring using remote sensing satellites.

Appendix

Technical indicators of the ocean satellite

Table A1 Overall technical specifications of the HY-1 series of satellites

		HY-1A (decommission)	**HY-1B**	**HY-1C**	**HY-1D**
Information	Launch date	2002-5-15	2007-4-11	2018-9-7	2020-6-10
	Orbital height (km)	798	798	780	780
	Rail inclination (°)	98.8	98.8	98.6	98.6
	Local time at the descending node	8:53 – 10:10	10:30 ± 30 min	10:30 ± 30 min	13:30 ± 30 min
	Cyclicality (min)	100.8	100.8	—	—
	Repeat observation period	COCTS: 3 days; CCD: 7 days	COCTS: 1 day; CCD: 7 days	COCTS: 1 day; CCD: 3 days; UV imager: 1 day	COCTS: 1 day; CCD: 7 days; UV imager: 1 day
COCTS	Substellar point ground resolution (m)	1100	1100	1100	1100
	Number of bands	10	10	10	10
	Bandwidth (μm)	0.402 – 12.50	0.402 – 12.50	0.402 – 12.50	0.402 – 12.50
	Width (km)	—	—	≥ 2900	≥ 2900
CCD	Substellar point ground resolution (m)	250	250	250	250
	Number of bands	4	4	4	4
	Bandwidth (μm)	0.42 – 0.89	0.433 – 0.695	0.42 – 0.89	0.42 – 0.89
	Width (km)	—	—	≥ 950	≥ 950
Other	UV imager	—	—	Bandwidth (μm) 0.345 – 0.365 0.375 – 0.395	Bandwidth (μm) 0.345 – 0.365 0.375 – 0.395
	Ship identification system	—	—	Operating frequency: 1.975 MHz; 162.025 MHz; 156.775 MHz; 156.825 MHz; Monitorable width: ≥ 1000 km	Operating frequency: 1.975 MHz; 162.025 MHz; 156.775 MHz; 156.825 MHz; Monitorable width: ≥ 1000 km

Table A2 Overall technical specifications of the HY-2 series of satellites

		HY-2A (decommission)	**HY-2B**	**HY-2C**	**HY-2D**
Information	Launch date	2011-8-16	2018-10-25	2020-9-21	2021-5-19
	Orbital height (km)	969	968	957	959
	Rail inclination (°)	99	99	66	66
	Cyclicality (day)	14	14	10	10
	Adjacent track spacing (km)	—	207.64	292.52	292.52
	Intersection period (min)	104.46	104.46	104.10	104.10
Scanning microwave radiometer	Operating frequency and polarization mode (GHz)	6.6 VH, 10.7 VH, 18.7 VH, 23.8 VH, 37 VH	6.6 VH, 10.7 VH, 18.7 VH, 23.8 VH, 37 VH	—	—
	Width (km)	> 1600	> 1600	—	—
	Calibration accuracy (K)	1.0 (180 – 350)	1.0 (95 – 320)	—	—
Calibration of microwave radiometers	Operating frequency (GHz)	18.7, 23.8, 37	18.7, 23.8, 37	18.7, 23.8, 37	18.7, 23.8, 37
	Calibration accuracy (K)	1.0 (180 – 320)	1.0 (120 – 320)	1.0 (120 – 320)	1.0 (120 – 320)
Microwave scatterometer	Operating frequency (GHz)	13.256	13.256	13.256	13.256
	Width (km)	H-pol: > 1350 V-pol: > 1700	H-pol: > 1350 V-pol: > 1700	H-pol: > 1350 V-pol: > 1700	H-pol: > 1350 V-pol: > 1700
	Wind speed measurement accuracy (m/s)	2	2	2	2
	Wind speed measurement range (m/s)	2 – 24	2 – 24	2 – 24	2 – 24
	Wind direction measurement accuracy (°)	20	20	20	20
Radar altimeter	Operating frequency (GHz)	13.58, 5.25	13.58, 5.25	13.58, 5.25	13.58, 5.25
	Measuring high precision (cm)	≤ 8 (nadir-viewing)	≤ 2 (nadir-viewing)	≤ 2 (nadir-viewing)	≤ 2 (nadir-viewing)
	Effective wave height measurement range (m)	0.5 – 20	0.5 – 20	0.5 – 20	0.5 – 20
Other	Ship identification system	—	Operating frequency: 161.975 MHz; 162.025 MHz; 156.775 MHz; 156.825 MHz; Monitorable width: ≥ 1000 km	Operating frequency: 161.975 MHz; 162.025 MHz; 156.775 MHz; 156.825 MHz; Monitorable width: ≥ 1000 km	Operating frequency: 161.975 MHz; 162.025 MHz; 156.775 MHz; 156.825 MHz; Monitorable width: ≥ 1000 km
	Data collection system	—	Operating frequency: 401.65 MHz ± 55 kHz; Modulation method: BPSK	Operating frequency: 401.65 MHz ± 55 kHz; Modulation method: BPSK	Operating frequency: 401.65 MHz ± 55 kHz; Modulation method: BPSK

Table A3 Overall technical indicators of the Haiyang-3 (Gaofen-3) series of satellites

		GF-3		**1m C-SAR 01/ GF-3 02**		**1m C-SAR 02/ GF-3 03**	
Information	**Launch date**	**2016-8-10**		**2021-11-23**		**20224-7**	
	Orbital height (km)	**755**		**755**		**755**	
	Rail inclination (°)	**98.4**		**98.4**		**98.4**	
		Resolution (m)	**Width (km)**	**Resolution (m)**	**Width (km)**	**Resolution (m)**	**Width (km)**
Image mode	Ultra-fine stripmap (UFS)	1	10	Same as GF-3		Same as GF-3	
	Fine stripmap (FSI)	3	30				
	Wide fine stripmap (FSII)	5	50				
	Standard stripmap (SS)	10	100				
	Quad-pol stripmap (QPSI)	25	130				
	Wide quad-pol stripmap (QPSII)	8	30				
	Narrow ScanSAR (NSC)	25	40				
	Wide ScanSAR (WSC)	50	300				
	Global observation (GLO)	100	500				
	Wave (WAV)	500	650				
	Extended incidence angle (EXT)—low	10	5				
	Extended incidence angle (EXT)—high	25	130				

Table A4 General technical specifications of China-France Oceanography SATellite (CFOSAT)

	SWIM (for monitoring sea surface waves)	**SCAT (for sea surface wind measurements)**
Operating frequency	13.575 GHz	13.256 GHz
Width	180 km	> 1000 km
Resolution	70 km × 90 km	25 km × 25 km / 12.5 km × 12.5 km
Wind speed accuracy and range	—	± 2 m/s or 10% (take the greater value) (4 – 24 m/s)
Wind direction accuracy	—	± 20°
Detectable wavelength range	70 – 500 m	—
Wavelength accuracy	10% – 20%	—

Table A5 China ocean satellite data products

Product type	Payload	Sources	Resolution	Index	Remark
Wind field	Scatterometer	HY-2A/B	25 km / 0.25°	Wind speed ≥ 2 m/s Wind direction ≥ 20°	L2B, L3, L4
		CFOSAT	25 km / 12.5 km		L2B
		Metop-A/B	25 km / 12.5 km		L2
Wind speed	Altimeter	HY-2A/B	7 km	≥ 2 m/s	OGDR, IGDR
	Radiometer	HY-2B	56 km × 93 km, 74 km × 122 km, 31 km × 51 km		L2B
Effective wave height	Altimeter	HY-2A/B Jason-3	7 km	≥ 50 cm	OGDR, IGDR
		SARAL Cryosat-2 Jason-CS			L3NRT
Sea surface temperature	Rediometer	HY-2B	74 km × 122 km, 56 km × 93 km, 31 km × 51 km, 25 km / 0.25°	1 K	L2B L2C L2D
	COCTS	HY-1C/D	1.1 km, 9 km		L2B, L3A
Sea surface height	Altimeter	HY-2A/B	7 km	≥ 5 cm	OGDR, IGDR, GDR
Sea surface height anomaly	Altimeter	HY-2B	0.25°		L3
Sea surface dynamic anomaly	Altimeter	HY-2B	0.25°		L3
Geostrophic current	Altimeter	HY-2B	0.25°		L3
Atmospheric water vapor content	Radiometer	HY-2B	27 km × 44 km, 74 km × 122 km, 56 km × 93 km, 31 km × 51 km		L2B, L2C, L4A
Cloud liquid water content	Radiometer	HY-2B	27 km × 44 km, 74 km × 122 km, 56 km × 93 km, 31 km × 51 km		L2B, L2C, L4A
Chlorophyll concentration	COCTS	HY-1C	1.1 km, 9 km	40%	L2B, L3A
Suspended sediment content	COCTS	HY-1C	1.1 km	40%	L2B
	CZI	HY-1C	50 m		L2B
Vegetation index	CZI	HY-1C	50 m		L2B
Bohai sea ice products	COCTS	HY-1C	1.1 km		
	CZI	HY-1C	50 m		
Oil spill monitoring products	SAR	GF-3	8 m		L2A
Green tide monitoring report	COCTS	HY-1C	250 m		Multi-data fusion
Wave spectrum	SWI	CFOSAT			L2B
Ship position information	Ship identification system	HY-1C, HY-2B			L1B
Land optical products	CZI	HY-1C	50 m		

Acknowledgements
This research was funded by the Hainan Key Research and Development Program (Grant No. ZDYF2023SHFZ089), the Aerospace Science and Technology Innovation Project of Hainan Province (Grant No. ATIC202301001), and the Hainan Provincial Natural Science Foundation of China (Grant No. 122CXTD519).

Code availability
Not applicable.

Authors' contributions
Conceptualization, Xingwei Jiang and Xiaobin Yin; methodology, Xingwei Jiang and Xiaobin Yin; investigation, Lei Guan and Zhaohui Wang; writing–original draft preparation, Xingwei Jiang, Xiaobin Yin and Letian Lv; writing—review and editing, Xiaobin Yin and Lei Guan; supervision, Zhaohui Wang and Mutao Liu.

Availability of data and materials
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors have read and agreed to the published version of the manuscript.

Competing interests
The authors declare that there is no conflict of interest or Competing interests between them. Xingwei Jiang and Lei Guan are one of the Editorial Board Members, but they was not involved in the journal's review of, or decision related to, this manuscript.

Received: 14 August 2023 Revised: 5 September 2023 Accepted: 11 September 2023

References

Chen G, Yang J, Wu LX (2022) Artificial intelligence-aided remote sensing of the intermediate ocean. Sci Technol Foresight 1(2):103–120

Chen S, Du K, Lee ZP, Liu JQ, Song QJ, Xue C et al (2020) Performance of COCTS in global ocean color remote sensing. IEEE Trans Geosci and Remote Sens 59(2):1634–1644

Cui HL, Chen SG, Hu LB, Wang JW, Cai HB, Ma CF et al (2023) HY1C/D-CZI noctiluca scintillans bloom recognition network based on hybrid convolution and self-attention. Remote Sens 15(7):1757

Dibarboure G, Pujol MI, Briol F, Le Traon PY, Larnicol G, Picot N et al (2011) Jason-2 in DUACS: updated system description, first tandem results and impact on processing and products. Mar Geod 34(3–4):214–241

Fang H, Perrie W, Fan G, Cai JZ, He Y, Yang JS et al (2022) High-resolution sea surface wind speeds of super Typhoon Lekima (2019) retrieved by Gaofen-3 SAR. Front Earth Sci 16(1):90–98

Feng Q (2004) Study of sea surface wind remote sensing by satellite multisensor data. PhD thesis, Ocean University of China

Fu H, Qin P (2019) Comparison of different polarization modes of SAR images based on GF-3 for oil film recognition on sea surface–a case study of 'Sangji' vessel accident. Mar Dev Manage 3:54–56

Goodberlet MA, Swift CT, Wilkerson JC (1989) Remote sensing of ocean surface winds with the special sensor microwave/imager. J Geophys Res Oceans 94(C10):14547–14555

Guo CG, Ai WH, Hu SS, Du XY, Chen N (2022) Sea surface wind direction retrieval based on convolution neural network and wavelet analysis. IEEE J Sel Top Appl Earth Observ Remote Sens 15:3868–3876

Huang LY, Yang JG, Meng JM, Zhang J (2021) Underwater topography detection and analysis of the Qilianyu Islands in the South China Sea based on GF-3 SAR images. Remote Sens 13(1):76

Irisov VG (2000) Azimuthal variations of the microwave radiation from a slightly non-Gaussian sea surface. Radio Sci 35(1):65–82

Jia YJ, Yang JG, Lin MS, Zhang YG, Ma CF, Fan CQ (2020) Global assessments of the HY-2B measurements and cross-calibrations with Jason-3. Remote Sens 12(15):2470

Jiang XW, He XQ, Lin MS, Gong F, Ye XM, Pan DL (2019) Progresses on ocean satellite remote sensing application in China. Acta Oceanol Sin 41(10):113–124

Johnson JT, Cai YY (2002) A theoretical study of sea surface up/down wind brightness temperature differences. IEEE Trans Geosci Remote Sens 40(1):66–78

Le Traon PY, Gaspar P, Bouyssel F, Makhmara H (1995) Using TOPEX/POSEIDON data to enhance ERS-1 data. J Atmos Oceanic Technol 12:161–170

Lee Z, Carder KL, Hawes SK, Steward RG, Peacock TG, Davis CO (1994) Model for the interpretation of hyperspectral remote-sensing reflectance. Appl Optics 33(24):5721–5732

Li Y, Wang Z (2005) Retrievals of sea surface temperatures, wind speeds, volume water vapor contents from SZ-4 RAD brightness temperatures. Remote Sens Technol Appl 20(1):133–136

Li X, Huang B, Jia T, Qin T (2020a) Ocean remote sensing by spaceborne synthetic aperture radar (SAR) and big data. J Nanjing Univ Inf Sci Technol 12(2):191–203

Li XF, Liu B, Zheng G, Ren YB, Zhang SS, Liu YJ et al (2020b) Deep-learning-based information mining from ocean remote-sensing imagery. Nati Sci Rev 7(10):1584–1605

Li XZ, Lin WM, Liu BC, Wang ZX, Zhang BA, He YJ (2021) Sea surface wind retrieval using the combined scatterometer and altimeter backscatter measurements of the HY-2B satellite. IEEE Trans Geosci Remote Sens 60:5101312

Lin M (2000) A modified model based on estimation of sea surface wind field from spaceborne scatterometer. J Remote Sens 4(1):61–65

Lin M, He X, Jia Y, Bai Y, Ye X, Gong F (2019) Advances in marine satellite remote sensing technology in China. Acta Oceanol Sin 41(10):99–112

Lin M, Jiang X (2020) Ocean observation from Haiyang satellites. Chin J Space Sci 40(5):898–907

Lin M, Ye X, Yuan X (2017) The first quantitative joint observation of typhoon by Chinese GF-3 SAR and HY-2A microwave scatterometer. Acta Oceanol Sin 36(11):1–3

Lin WM, Portabella M, Stoffelen A, Verhoef A, Lang SY, Zhang YG et al (2016) On the improvement of the HY-2A scatterometer wind quality control. 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Beijing, China, 10-15 July 2016, pp 407–410

Liu JQ, Jiang XW, Wang LL, Ye XM, Ding J, Zeng T et al (2021a) Observation and application of Haiyang-1 C, D satellite network. Satell Appl 2021(9):19–26

Liu MK, Guan L, Chen G, Zhao W (2020) Retrieval of sea surface temperature from HY-2A scanning microwave radiometer. IEEE Trans Geosci Remote Sens 58(10):7216–7231

Liu MK, Guan L, Liu FL, Liu JQ (2023) Retrieval and validation of sea surface temperature from HY-1D COCTS. J Remote Sens 27(4):953–964

Liu MK, Merchant CJ, Embury O, Liu JQ, Song QJ, Guan L (2022a) Retrieval of sea surface temperature from HY-1B COCTS. IEEE Trans Geosci Remote Sens 60:5002913

Liu SQ, Lin WM, Portabella M, Wang ZX (2022b) Characterization of tropical cyclone intensity using the HY-2B scatterometer wind data. Remote Sens 14(4):1035

Liu YX, Lin MS, Jiang XW, Sun XJ, Song XZ (2021b) A comparison of multiplatform wind products in the South China Sea during summer and autumn in 2019. J Oceanol Limnol 39(6):2181–2194

Liu ZY, Liu B, Guo WW, Zhang ZH, Zhang B, Zhou YH et al (2017) Ship detection in GF-3 NSC mode SAR images. J Radars 6(5):473–482

Lu XQ (2008) Monitoring ocean using satellite remote sensing technique in China. Mar Forecasts 25(4):85–89

Ma MY, Chen J, Liu W, Yang W (2018) Ship classification and detection based on CNN using GF-3 SAR images. Remote Sens 10(12):2043

Ma XF, Lin MS, Zhou W, Zhang YG (2020) Principle and development of new microwave radiometer to obvserve ocean. Mar Environ Sci 39(4):622–629

Mao ZH, Pan DL, He XQ, Chen JY, Tao BY, Chen P et al (2016) A unified algorithm for the atmospheric correction of satellite remote sensing data over land and ocean. Remote Sens 8(7):536

Mao ZH, Zhang YW, Tao BY, Chen JY, Hao ZZ, Zhu QK et al (2022) The atmospheric correction of COCTS on the HY-1C and HY-1D satellites. Remote Sens 14(24):6372

Men JL, Liu JQ, Xia GP, Yue T, Tong RQ, Tian LQ et al (2022) Atmospheric correction for HY-1C CZI images using neural network in western Pacific region. Geo-Spat Inf Sci 25(3):476–488

Qian C, Chen G (2018) Big data science for ocean: present and future. Bull Chin Acad Sci 33(8):884–891

Shao WZ, Jiang XW, Nunziata F, Marino A, Yang ZH, Zhang YG et al (2020) Analysis of waves observed by synthetic aperture radar across ocean fronts. Ocean Dyn 70(11):1397–1407

Shao WZ, Yuan XZ, Sheng YX, Sun J, Zhou W, Zhang QJ (2018) Development of wind speed retrieval from cross-polarization Chinese Gaofen-3 synthetic aperture radar in typhoons. Sensors 18(2):412

Song QJ, Chen SG, Xue C, Lin MS, Du KP, Li SC et al (2019) Vicarious calibration of COCTS-HY1C at visible and near-infrared bands for ocean color application. Opt Express 27(20):A1615–A1626

Song XC, Du JF, Wang SQ, Li HJ (2020) Research progress of marine scientific equipment and development recommendations in China. Strateg Study Chin Acad Eng 22(6):76–83

Tang JW, Tian GL, Wang XY, Wang XM, Song QJ (2004) The methods of water spectra measurement and analysis I: above-water method. J Remote Sens 8(1):37–44

Wan Y, Guo S, Li LG, Qu XJ, Dai YS (2021) Data quality evaluation of sentinel-1 and GF-3 SAR for wind field inversion. Remote Sens 13(18):3723

Wang H, Yang JS, Lin MS, Li WW, Zhu JH, Ren L et al (2022) Quad-polarimetric SAR sea state retrieval algorithm from Chinese Gaofen-3 wave mode imagists via deep learning. Remote Sens Environ 273:112969

Wang Z, Li Y (2009) Retrieval of AMSR-E data with the on-board microwave radiometer AMSR-E marine geophysical parameters. J Remote Sens 3:16

Wang ZH, Song QT, Jiang XW, Zhang Y (2015) Non-linear retrieval algorithm for passive satellite microwave radiometers. Chin High Technol Lett 25(4):376–383

Wang ZX, Stoffelen A, Zou JH, Lin WM, Verhoef A, Zhang Y et al (2020) Validation of new sea surface wind products from scatterometers onboard the HY-2B and MetOp-C satellites. IEEE Trans Geosci Remote Sens 58(6):4387–4394

Wang ZX, Zou JH, Lin MS, Lin WM, Zhang YG, Li XZ et al (2023) Development of a geophysical model function for HY-2 satellite microwave scatterometer wind retrievals. J Remote Sens 27(4):871–880

Wang ZZ, Bao JH, Li Y, Shen H (2014) Study on retrieval algorithm of ocean parameters for the HY-2 scanning microwave radiometer. Strateg Study Chin Acad Eng 16(6):70–82

Wentz FJ, Meissner T (2000) Algorithm theoretical basis document. In Version 2. Remote Sensing Systems, Santa Rosa, CA, USA, 95401(707):545–2904

Yang GY, Ye XM, Xu Q, Yin XB, Xu SY (2023) Sea surface chlorophyll-*a* concentration retrieval from HY-1C satellite data based on residual network. Remote Sens 15(14):3696

Yao R, Shao WZ, Jiang XW, Yu T (2022) Wind speed retrieval from Chinese Gaofen-3 synthetic aperture radar using an analytical approach in the nearshore waters of China's seas. Int J Remote Sens 43(8):3028–3048

Ye XM, Liu JQ, Lin MS, Ding J, Zou B, Song QJ (2021) Global ocean chlorophyll-*a* concentrations derived from COCTS onboard the HY-1C satellite and their preliminary evaluation. IEEE Trans Geosci Remote Sens 59(12):9914–9926

Ye XM, Liu JQ, Lin MS, Dong J, Zou B, Song QJ et al (2022) Evaluation of sea surface temperatures derived from the HY-1D satellite. IEEE J Sel Top Appl Earth Observ Remote Sens 15:654–665

Yin XB, Wang ZZ, Song QT, Huang YZ, Zhang RY (2017) Estimate of ocean wind vectors inside tropical cyclones from polarimetric radiometer. IEEE J Sel Top Appl Earth Observ Remote Sens 10(5):1701–1714

Yuan XZ, Lin MS, Liu JQ, Xie CH, Zhao LB, Ye XM et al (2018) Application of GF-3 satellite in the field of ocean. Satell Appl 6:17–21

Yueh SH (1997) Modeling of wind direction signals in polarimetric sea surface brightness temperatures. IEEE Trans Geosci Remote Sens 35(6):1400–1418

Zhang QJ, Liu YD (2017) Overview of Chinese first C band multi-polarization SAR satellite GF-3. Aerosp China 18(3):22–31

Zhang Y, Mu B, Lin MS, Song QT (2020) An evaluation of the Chinese HY-2B satellite's microwave scatterometer instrument. IEEE Trans Geosci Remote Sens 59(6):4513–4521

Zhang Y, Lin MS, Jiang XW (2009) The preprocess and Sigma-0 product of SZ-4 scatterometer mode. Remote Sens Technol Appl 24(6):5

Zhang Y, Jiang XW, Song QT, Lin MS (2012) The comparative analysis of C-band geophysical model function. Remote Sens Inf 27(1):6

Zhao C, Wang P, Wang J, Men ZR (2019) A maritime target detector based on CNN and embedded device for GF-3 images. 2019 6th Asia-Pacific Conference on Synthetic Aperture Radar (APSAR), Xiamen, China, 26-29 November 2019, pp 1–4

Zheng Q, Wu KQ (1990) Ten-year review of the development of remote sensing of the oceans in China (1979–1989). Mar Sci Bull 9(3):90–96

Zhou W, Wang SS, Lin MS (2022) The accuracy evaluation and analysis of HY-2B microwave radiometer in typical ocean areas. Mar Sci Bull 41(5):510–518

Publisher's Note