

Spatial-Temporal Data Mining for Ocean Science: Data, Methodologies and Opportunities

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With the rapid amassing of *spatial-temporal* (ST) ocean data, many *spatial-temporal data mining* (STDM) studies have been conducted to address various oceanic issues, including climate forecasting and disaster warning. Compared with typical ST data (e.g., traffic data), ST ocean data presents some unique characteristics, e.g., diverse regionality and high sparsity. These characteristics make it difficult to design and train STDM models on ST ocean data. To the best of our knowledge, a comprehensive survey of existing studies remains missing in the literature, which hinders not only computer scientists from identifying the research issues in ocean data mining but also ocean scientists to apply advanced STDM techniques. In this paper, we provide a comprehensive survey of existing STDM studies for ocean science. Concretely, we first review the widely-used ST ocean datasets and highlight their unique characteristics. Then, typical ST ocean data quality enhancement techniques are discussed. Next, we classify existing STDM studies for ocean science into four types of tasks, i.e., prediction, event detection, pattern mining, and anomaly detection, and elaborate the techniques for these tasks. Finally, promising research opportunities are discussed. This survey can help scientists from both computer science and ocean science better understand the fundamental concepts, key techniques, and open challenges of STDM for ocean science.

CCS Concepts: • **Information systems** → **Spatial-temporal Data Mining**; • **Applied computing** → **Environmental sciences**.

Additional Key Words and Phrases: spatial-temporal data, ocean science, data mining, machine learning.

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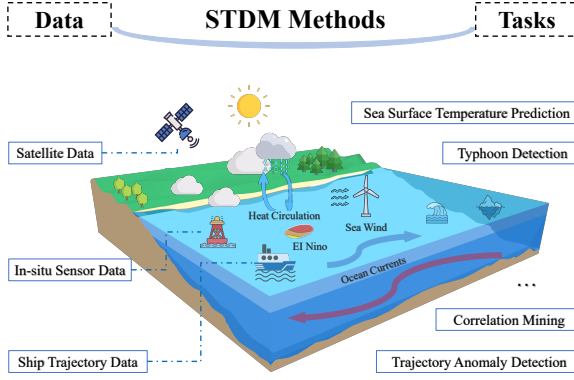


Fig. 1. The illustration of STDM for ocean science, which utilizes various STDM methods to discover unknown but potentially useful patterns from different ocean data sources for a number of data mining tasks.

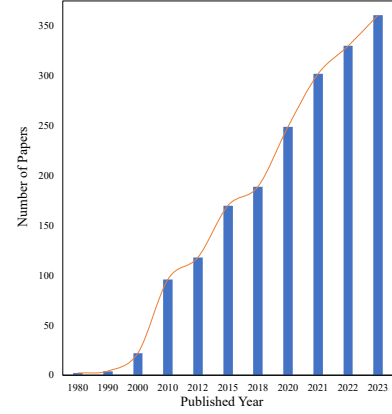


Fig. 2. 1980-2023 publications of STDM studies for ocean science (Results from Web of Science with query keywords: [Spatial-temporal & ocean] or [Spatiotemporal & ocean]).

1 INTRODUCTION

Ocean, covering more than two-thirds of the earth, plays an important role in various applications (e.g., climate forecasting and ocean transportation [149]), and is critical to human survival and sustainable development. Many real-world events and phenomena (e.g., El Niño and typhoons) occurring in ocean generally not only are associated with spatial locations but also change over time. Thus, the collected ocean data for monitoring these events and phenomena are typically spatial-temporal (ST) data in nature and require specific spatial-temporal data mining (STDM) techniques to conduct data analysis. As shown in Fig. 1, STDM for ocean science aims to uncover the ST patterns and correlations from various ST ocean data, helps us better understand the ocean system, and provides valuable support for various real-world applications. For example, accurate prediction of sea surface temperature (SST) is of great significance in weather forecasting, El Niño event detection, and disaster warning, and could also benefit aquaculture and agriculture [8].

The past decades have witnessed ever-increasing ST ocean data and lots of research on STDM for ocean science, which lays the solid foundation for addressing various oceanic issues in the data-driven paradigm. With the rapid development of data sensing technologies, numerous ocean observation sensors of different types have been deployed on various platforms, including space remote satellites, automatic buoys, and vessels all over the world, producing large amounts of ST ocean data. To be more specific, an estimate puts the size of ST ocean data in 2030 at 350 Petabytes (1 PB = 1,000 TB), and this number is predicted to grow exponentially [169]. With such huge amounts of ST ocean data, an increasing number of studies on STDM for ocean science have been conducted. According to incomplete statistics of the related publications from 1980 to 2023 on Web of Science, as shown in Fig. 2, ocean STDM receives increasing attention over time, and the increasing trend in the last three years is especially obvious. This trend indicates that STDM for ocean science has become a hot research topic in recent years.

Though STDM for ocean science is a vibrant interdisciplinary field, there are still some obstacles that hinder its development and applications.

First, there is a lack of review on available ST ocean datasets and their unique data characteristics. In the past decades, ST ocean datasets collected from different sources have been released

Table 1. A summary of the related surveys on STDm.

Year	Ref.	Contribution	Scope					
			Data	Data Quality	Tasks & Methodologies			
					ST Prediction	Event Detection	Pattern Mining	Anomaly Detection
2014	[52]	Overview the STDm methods and give some case studies of climate data.			✓	✓	✓	
2015	[197]	Provide a complexity comparison of typical STDm methods.				✓	✓	
2019	[228]	Summarize the latest deep learning methods in STDm.			✓		✓	✓
2020	[114]	Overview the GAN-based models for ST data completion.		✓				
2021	[73]	Overview the ST methods for SST prediction.	✓		✓			
2022	[244]	Summarize the current research methodologies and the challenges of STDm in ocean domain.	✓		✓	✓		✓
2022	[196]	Overview of the latest STDm methods for mutiple fields.			✓	✓	✓	
2022	[74]	Summarize some challenging issues and open problems of multiple STDm directions.			✓		✓	✓
2023	[39]	Overview the latest large foundation model in weather and climate, mainly focus on time series and text data.	✓		✓			
Ours		A survey of STDm methods for ocean science: multi-source datasets with unique characteristics, data quality enhancement methods, advanced models in various tasks, and future directions.	✓	✓	✓	✓	✓	✓

by various producers, e.g., National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and European Centre for Medium-Range Weather Forecasts (ECMWF). However, these datasets have diverse data collection protocols, sensors, and technologies, leading to diversity in data resolution, coverage, and quality. Currently, there is no systematic review of these data to facilitate researchers to choose appropriate datasets for studying different problems and tasks of ocean science. Moreover, ST ocean data has some unique characteristics, e.g., diverse regionality, high sparsity, inherent uncertainty, and deep ST dependencies, which are also not well investigated. For example, due to the large-scale coverage of the ocean on Earth, there exists diverse regionality in different areas. The collected ST ocean data in the Arctic Ocean may have opposite seasonality patterns from the data near the equator, which is difficult to model in a unified system. According to [137], the extreme weather in remote regions (e.g., the Antarctica Ocean) makes it difficult to deploy the in-situ sensors to collect data, and the heavy cloud in some periods may cause more than 80% of satellite data to be lost, which are two main reasons for the data sparsity problem. The sensors’ stability and transmission loss may both cause uncertainty in ocean data. In addition, the complex and unknown ocean circulation, as well as teleconnection between different regions in the ocean [134], may bring deep and hidden ST dependencies in the data. Ignoring these unique data characteristics could lead to low accuracy and bad interpretability of the STDm methods for ocean science. Therefore, from the data perspective, analyzing the widely-used ST ocean datasets and identifying their unique data characteristics is necessary.

Second, although there are already some surveys on STDm, a systematic and comprehensive review dedicated to the application of STDm in ocean science is currently absent from the literature. Table 1 summarizes and compares the related surveys of STDm in terms of contribution and scope. To provide a clear comparison, we put different oceanic STDm tasks into four types, i.e., ST prediction, event detection, pattern mining, and anomaly detection, which will be discussed in detail in Section 4. Concretely, Faghous et al. [52] reviewed the STDm methods and conducted several case studies in the climate domain. Ki et al. [197] provided an introduction to typical STDm methods from the perspective of computational complexity. Wang et al. [228] surveyed recent

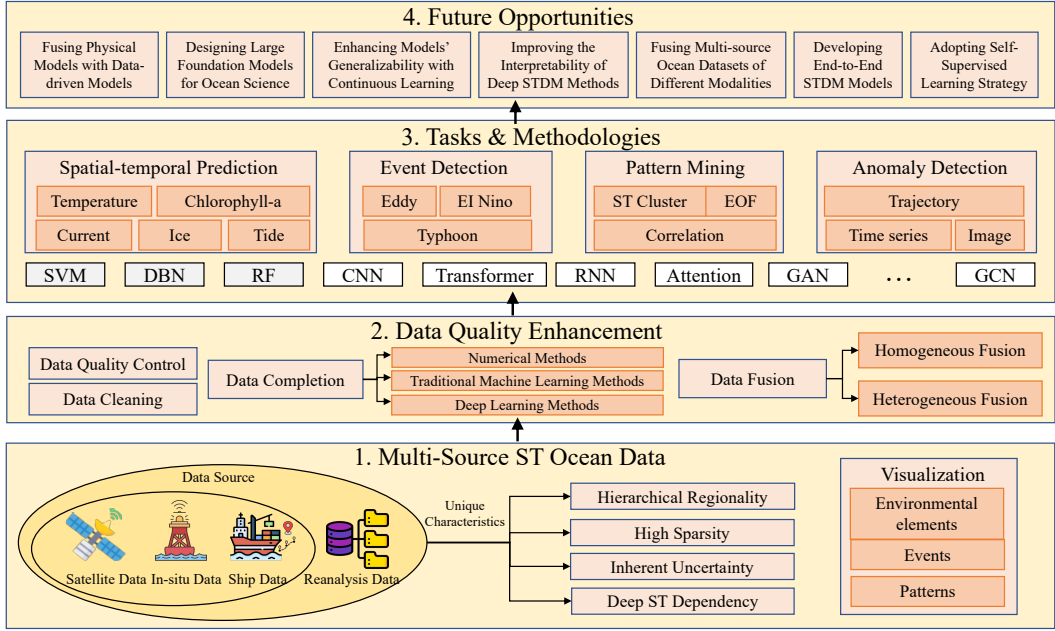


Fig. 3. The content and organization of this survey.

studies on deep learning techniques for STDM. Kim et al. [114] summarized the data completion methods for improving the quality of ST data for downstream applications. Haghbin et al. [73] reviewed the datasets and different types of methods for sea surface temperature (SST) prediction. Wu et al. [244] classified the STDM methods for the ocean into statistic methods and machine learning methods and gave case studies on some STDM tasks in the ocean. Sharma et al. [196] analyzed the typical problems of STDM, with emphasis on the tasks of prediction and clustering for ST data. Handi et al. [74] summarized some challenging issues in STDM, e.g., dynamic ST dependencies and poor data quality. Chen et al. [39] overview the latest large foundation model for weather and climate data, especially on text data and time-series data. Although these studies above give some introduction to some STDM methods related to ocean, there does not exist a survey that covers all the key components of STDM for ocean science, including available ST datasets, data processing methods to enhance data quality, STDM methods for various tasks, and future directions.

Third, STDM for ocean science is a typical multi-disciplinary research field where rapidly evolving computer science meets conventional ocean science. The development of STDM for ocean science will not only help computer scientists identify new research issues but also assist ocean science researchers in applying advanced STDM methods to solve their problems, which could benefit various oceanic applications. However, the existing and ever-arising challenges and opportunities of STDM for ocean science have not been well studied. For example, most existing methods only directly apply STDM methods to addressing ocean issues with large amounts of ST ocean data, ignoring the underlying physical laws of the ocean, which usually lack robustness and interpretability [73, 244]. Thus, to further promote the development of STDM for ocean science, it is urgent to systemically and comprehensively summarize the related STDM studies for ocean science,

and discuss their advantages and disadvantages to help researchers both in computer science and ocean science areas identify potential directions for further exploration.

Keep these in mind, in this paper, as shown in Fig. 3, we provide a comprehensive survey to systematically summarize the available ST ocean datasets, data quality enhancement methods, and STDM techniques for solving various ocean issues and highlight the arising challenges. In summary, the contributions of this survey are fourfold as follows:

- **Summarizing the wide-used and accessible ocean datasets.** We review different categories of ST ocean data, including satellite data, in-situ data, ship data, and reanalysis data, and present the popular datasets that are widely used from multiple dimensions (e.g., spatial resolution, temporal coverage, and related studies). In addition, we identify the unique data characteristics of ST ocean data and discuss typical data visualization methods.
- **Reviewing the quality enhancement methods for ST ocean data.** We analyze the fundamental but necessarily important data quality enhancement methods, including data cleaning, data completion, data fusion, and data transforming for ST ocean data, and provide the corresponding representative models.
- **Classifying the advanced STDM methods of typical ocean tasks.** This survey provides a comprehensive overview of the recent advances in STDM techniques for ocean science, and subsumes the main tasks into four types, i.e., ST prediction, event detection, pattern mining, and anomaly detection. For each type of these tasks, we provide a detailed review of the corresponding STDM techniques.
- **Pinpointing the existing challenges and future directions.** We also identify the open problems that have not been well solved and provide some promising research directions in the future, which could help researchers in both computer science and ocean science identify new research topics and promote the development of smart ocean.

The rest of this survey is organized as follows: Table 2 defines the abbreviations used in this survey to facilitate understanding. Section 2 presents different categories of ST ocean datasets, identifies their unique characteristics, and provides typical ST ocean data visualization methods. Section 3 summarizes the techniques for improving the quality of ST ocean data, including data cleaning, data completion, data fusion, and data transforming. Section 4 classifies typical STDM tasks for ocean science into four types and presents a gallery of the technologies for each task. Section 5 discusses the existing challenges and suggests future potential directions. We finally conclude this survey in Section 6.

2 DATA SOURCES, UNIQUE CHARACTERISTICS AND VISUALIZATION

In this section, as shown in Table 3, we first summarize four categories of ST ocean data, i.e., satellite data, in-situ data, ship data, and reanalysis data, according to the data sources, and present the representative datasets with their basic information, including temporal periods, spatial resolution, spatial coverage, temporal resolution, and accessible storage. After that, we identify four unique data characteristics of ST ocean data, enabling researchers to understand the critical difficulties in applying STDM techniques to solving ocean issues. Finally, the widely used visualization methods for ST ocean data are discussed.

2.1 Multi-source ST Ocean Data

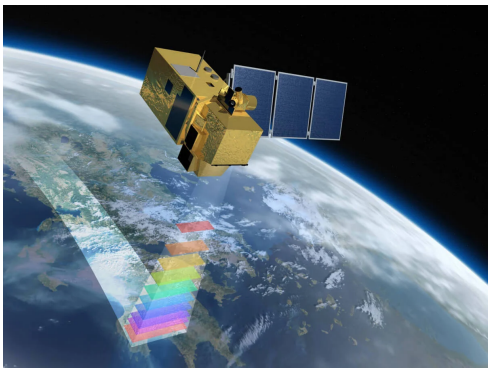
Typically, existing ST ocean data covers various ocean factors such as temperature, chlorophyll-a, ocean current, sea ice, and tide. The majority of these data are collected by various measurement devices (e.g., satellite sensors, in-situ sensors, and ship sensors) or from the outputs of reanalysis systems (e.g., ECMWF reanalysis system and NOAA reanalysis system). According to the data

Table 2. List of Abbreviations.

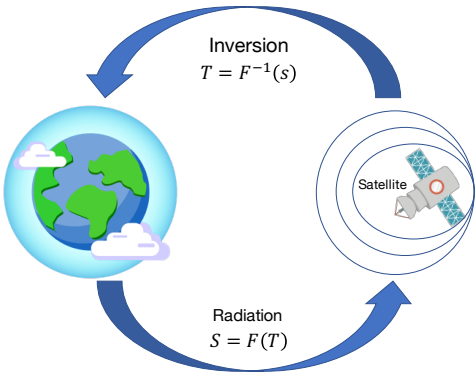
Abbreviation	Full Name
AVHRR	Advanced Very-High-Resolution Radiometer
Argo	Array for Real-time Geostrophic Oceanography
Chl-a	Chlorophyll a
OISST	Optimum Interpolation Sea Surface Temperature
El Niño	El Niño-Southern Oscillation Phenomenon
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
ECMWF	European Centre for Medium-Range Weather Forecasts
ST	Spatial-Temporal
STDM	Spatial-Temporal Data Mining
SST	Sea Surface Temperature
SSS	Sea Surface Salinity

Table 3. Comparison of different categories of ST ocean data.

Category	Spatial coverage	Temporal coverage	Spatial resolution	Temporal resolution	Quality	Timeliness
Satellite data	global	long	low	days	medium	low
In-situ data	local	short	high	hours	medium	high
Ship data	local	short	high	minutes	low	medium
Reanalysis data	global	long	low	days	high	low



(a) The collection of original satellite data.



(b) The inversion process of satellite data.

Fig. 4. Satellite data collection and inversion. (a) Satellite data collection with different bands [2]; (b) Data inversion to process the original satellite data.

sources, ST ocean data can be divided into four categories, including satellite data, in-situ sensor data, ship data, and reanalysis data. Table 3 briefly summarizes the advantages and disadvantages of the four categories of ST ocean data. The satellite data and reanalysis data usually have wide spatial coverage and a long-term observation period but have low timeliness to obtain the original data. The ship data and in-situ sensor data have better timeliness but lower data quality due to the data sparsity issue. In this section, we will introduce the typical and commonly used ST ocean datasets of the four data categories and summarize their features in Table 4.

Table 4. Public datasets and their features.

Category	Name	Period	Spatial Resolution	Coverage	Temporal Resolution	Citation	Type	Source
Satellite Data	MODIS	2000-present	0.041x0.041	Global	8 days	[95, 118, 119]	Sea surface temperature, ocean color, sea surface salinity	https://modis.gsfc.nasa.gov/
		2002-present	1 km x 1 km	Global	daily	[216]		
		2002-present	0.083x 0.083°	Global	monthly	[111]		
	AVHRR	1979-present	1.1 km x 1.1 km	Global	daily	[85, 118]	Sea surface temperature, ocean color	https://www.eumetsat.int/avhrr
	Sentinel-3	2016-present	1.2 km x 1.2 km	Global	5 days	[23, 24, 57, 84, 136, 139, 252]	Sea surface temperature, ocean color	https://sentinels.copernicus.eu/web/sentinel/
	GOCI	2010-2021	0.5 km x 0.5 km	Korean sea	hourly	[141, 171, 209, 262]	Sea surface chlorophyll-II, ocean color	https://oceancolor.gsfc.nasa.gov/data/goci/
	CZCS	1978-1986	0.825 km x 0.825 km	Global	8 days	[155]	Sea surface chlorophyll-II	https://oceancolor.gsfc.nasa.gov/data/CZCS/
In-situ data	OCN-2	2009-present	1-4 km x 1-4 km	Global	2 days	[180]	Ocean color	https://ocean.org/sensor/ocn-2/
	SeaWiFS	1997-2010	1-4 km x 1-4 km	Global	daily	[155, 237]	Ocean color	https://oceancolor.gsfc.nasa.gov/SeaWiFS/
	Argo	1996-present	Trajectories of about 14060 floats	Global	1-10 days	[15, 20, 33, 247, 253]	sea surface temperature, sea surface salinity	https://argo.uscd.edu/
	GO-BGC	2021-present	Trajectories of about 500 floats	Global	10 days	[28, 90, 199, 251]	Sea O ₂ , sea Ph	https://www.go-bgc.org/
	SOCOM	2004-present	Trajectories of about 200 floats	Antarctic Ocean	10 days	[31, 105]	Ocean carbon	https://socon.princeton.edu/
Ships Data	ANS	2016 to 2018	Trajectories of about 70000 vessels	Global	30 seconds - 1 day	[26, 31, 62, 92]	Trajectory anomalies, ship tracking	https://www.vmsdata.com/
	VMS	April, 2020	Trajectories of 750,000 vessels	Global	30 seconds - 1 day	[195, 206]	Trajectory anomalies	https://marinescadatrec.gov/
	OBST	1979-present	0.25°x0.25°	Global	daily	[99, 246, 270, 279]	Sea surface temperature	https://www.ncdc.noaa.gov
	ERA-5	1959-present	4°x4°	Global	12-hour	[124, 142, 154, 268]	Sea surface temperature	https://www.ecmwf.int
Reanalysis Data	CNEMS Level 3 SLA	2004-present	0.125°x0.125°	Global	daily	[65]	Sea level anomalies	https://marine.copernicus.eu/
	CNEMS	1993-2020	0.25°x0.25°	Global	daily	[14]	Sea surface height anomaly	https://marine.copernicus.eu/
	HuoCRUT4	1961-1990	5°x5°	Global	monthly	[193]	Air/Marine temperature anomalies	https://www.metoffice.gov.uk/
	COBE SST	1891 to present	1°x1°	Global	monthly	[42, 81, 212]	Sea surface temperature	https://psl.noaa.gov/data/
	CMAP Precipitation	1979-present.	2.5°x2.5°	Global	monthly	[47, 113, 135]	Pentad global gridded precipitation means.	https://psl.noaa.gov/data/
	WOD	1772 to 2017.	1°x1°	Global	daily	[88]	Sea temperature, salinity, oxygen	https://www.ncdc.noaa.gov/products/world-ocean-database
	Extreme-ERA5	1975-2018	0.25°x0.25°	Global	daily	[166]	sea temperature	https://www.ecmwf.int
	ClimateNet	1996-2010	1°x1°	Global	daily	[177]	tropical cyclones	https://www.ncdc.noaa.gov/products
	OSCAR	1993-present	1-4 km x 1-4 km	Global	daily,	[215, 220]	Ocean Current	https://www.esr.org/research/oscar/
	GOCD	1993-2013	1-4 km x 1-4 km	Global	daily,	[25, 27]	Ocean Current	https://www.ncdc.noaa.gov/products/global-ocean-currents-database

2.1.1 Satellite Data. Satellite data, also named remote sensing data, became available in the late 1960s and are a source of high-quality data for monitoring the ocean. The view from space allows ocean factors (e.g., SST and sea surface chlorophyll-a) to be measured globally, especially in remote regions where it is not convenient to deploy sensors. Additionally, satellites can ensure large spatial coverage and frequent observation, even in extreme weather conditions. During the past decade, much progress has been made in ocean monitoring using satellites, and the quality of satellite instruments and the accuracy of inversion algorithms have improved considerably, making satellite observations be widely used in various ocean tasks, e.g., sea ice prediction [264] and typhoon detection [188].

As shown in Fig. 4(a), satellite data collection is to detect the thermal energy emitted by the earth's surface using spaceborne microwave or infrared radiometers [103]. The surface radiation is modified in its passage through the atmosphere to the radiometer by a bunch of processes, e.g., atmospheric absorption, emission, and scattering. Thus, with appropriate data inversion, we can obtain valid estimates of various ocean factors. The general satellite data inversion process is shown in Fig. 4(b), where S denotes the radiation signal emitted by the ocean surface, and T is the target data obtained by the data inversion function F . The data inversion function F is generally non-linear; its inverse function is F^{-1} . Through the data inversion algorithms [198, 265], the radiation signal can be transferred to ST time series data of various ocean factors, e.g., SST and sea surface chlorophyll-a.

Many countries have launched satellites for various ocean applications and we introduce the wide-used satellite data as below.

- **MODIS:** The Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument onboard the Earth Observing System (EOS) Terra and Aqua platforms, and designed to monitor the atmosphere, ocean, and land surface. MODIS has a viewing swath width of 2,330 km and views the entire surface of the Earth every two days. It measures 36 spectral bands between 0.405 and 14.385 μm , and acquires data at three spatial resolutions, i.e., 0.25km, 0.5km, and 1km.
- **AVHRR:** The Advanced Very High-Resolution Radiometer (AVHRR) multi-purpose imaging instrument is used for monitoring global cloud cover, sea surface temperature, ice, snow, and vegetation cover characteristics. AVHRR provides four-to-six-band multispectral data from the NOAA polar-orbiting satellite series. AVHRR provides continuous global coverage since June 1979 and its spatial resolution is 1.1 km.
- **Sentinel-3:** Sentinel-3 is a dedicated Copernicus satellite mission delivering a variety of high-quality ocean and atmosphere measurements. The main objective of the mission is to collect parameters such as sea surface topography, sea surface temperature, and ocean surface color. It provides two-day global coverage optical data with two satellites and altimetry measurements for sea and land applications with real-time data products delivered in less than three hours. The spatial resolution of Sentinel-3 is 1.2 km.
- **GOCI:** Geostationary Ocean Color Imager (GOCI) is the first ocean color sensor launched to monitor ocean color around the Korean Peninsula. GOCI has a large temporal coverage and a revisit time of around one hour. The spatial resolution of GOCI is about 0.5 km.
- **CZCS:** The Coastal Zone Color Scanner (CZCS) is a multi-channel scanning radiometer aboard the ocean remote sensing satellite Nimbus 7. CZCS could map chlorophyll concentration, sediment distribution, salinity, ocean currents, and the temperature of coastal waters. CZCS measures reflect solar energy in six channels at a spatial resolution of 0.8 km.
- **SeaWiFS:** Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is loaded on the OrbView-2 satellite launched by NASA in 1997. SeaWiFS aims to obtain accurate ocean color data

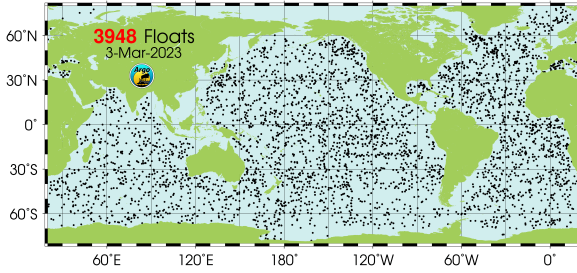


Fig. 5. The global distribution of Argo sensors in 2023 [4].

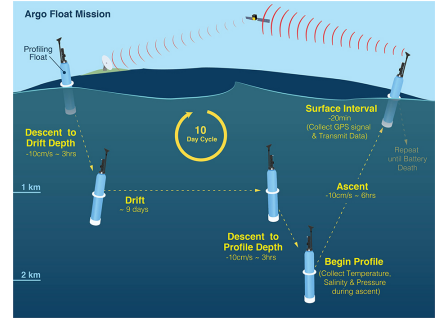


Fig. 6. The workflow of Argo sensors [5].

for the global ocean and makes this data readily available to researchers. SeaWiFS has six watercolor bands with a bandwidth of 20nm, i.e., 412nm, 443nm, 490nm, 510nm, 555nm, and 670nm. Compared with CZCS, the performance indicators of this sensor have been greatly improved, such as more reasonable band settings, higher signal-to-noise ratio, and richer band information. SeaWiFS has two spatial resolutions, i.e., 1.1 km and 4.5 km, and its temporal resolution is daily or once every two days.

2.1.2 In-situ Sensor Data. In-situ sensor data refers to the data collected where the instrument is physically located. It is a traditional but important way to collect data for ocean factors and has a long history since the 1600s [52]. In the past few decades, numerous in-situ sensors of different types, e.g., buoy sensors, underwater sensors, and station sensors, have been deployed all over the world. However, considering the wide spatial coverage of the ocean, in-situ sensor data are still sparse in space and time since they are only available when and where the sensors are physically located. In addition, due to the data privacy issue, only a small portion of in-situ sensor data is available to the public. We introduce the three available and widely used in-situ sensor datasets, i.e., Argo, Go-BGC, and SOCCOM, as below.

- **Argo:** Array for Real-time Geostrophic Oceanography (Argo) is an international program that uses profiling floats to observe temperature, salinity, currents, and other factors in the ocean. It has been in operation since the early 2000s and provides real-time data for studying climate and oceanography. Fig. 5 shows the global distribution of 3948 sensors from the Argo program [4]. As shown in Fig. 6, the Argo float mission is a 10-day cycle, and Argo sensors drift at a depth of 1000 meters (the so-called parking depth) and measure the conductivity, the temperature, etc, as it moves back up to the ocean surface. Once the float is on the surface, it will communicate with a satellite and send its location and collected data to them, then continue its mission (around 4-5 years).
- **GO-BGC:** The Global Ocean Biogeochemistry (GO-BGC) Array is a project to build a global network of chemical and biological sensors on profiling floats. The network monitors biogeochemical cycles and ocean health, including the elemental cycles of carbon, oxygen, and nitrogen through all seasons of the year.
- **SOCCOM:** The Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM) is a multi-institutional program focusing on unlocking the mysteries of the Antica Ocean, exploring the influence of carbon, nutrients, oxygen, and other factors on global climate.

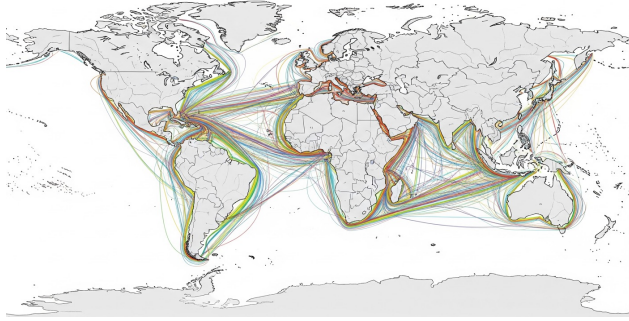


Fig. 7. The visualization of ship trajectories in the Automatic Identification System (AIS).

2.1.3 Ship Data. Ship data is collected by ships and vessels for directly observing the ocean factors, collecting biology samples, and investigating the ocean [206]. Ships can collect marine data at different locations along their trajectories. Here, we introduce two common tracking systems that record the information of ships.

- **AIS:** Automatic identification system (AIS) is an operation tracking system that provides ships' information such as the type of ship, location, and speed. Fig. 7 visualizes several AIS trajectories of ships. AIS was used by the U.S. Coast Guard in 2009 for the first time to monitor and transmit the locations of huge vessels. According to the International Maritime Organization (IMO), the goals of developing AIS are to help recognize ships, assist in target tracking, enhance the safety of marine traffic, and make the flow of vessel traffic smooth. Since 2004, installing AIS transponders for vessels over 300 tons of weight is mandatory in the International Convention for Safety of Life at Sea (SOLAS) guideline.
- **VMS:** Vessel Monitoring System (VMS) is a form of satellite tracking using transmitters on board fishing vessels. It tracks vessels in a similar way to AIS but is restricted to government regulators or other fisheries authorities. All European Union, Faroese, and Norwegian vessels that exceed 12 meters in length must be fitted with VMS units. VMS collects the locations, times, and oceanic features along the trajectories of vessels.

2.1.4 Reanalysis Data. It is important to have complete observations of the ocean system in both spatial and temporal dimensions. However, the observations discussed above are usually unevenly distributed. Even in satellite data, the observations cannot provide a complete recording of the state of the ocean system across the globe at a given point in time. Reanalysis data is the most completed data, which fills the gaps in the observational records through the simulation models or the physic models [279]. Reanalysis datasets are often globally complete and consistent in time. They are among the most-used datasets in ocean, especially in various data-driven ocean applications. We introduce the four widely-used reanalysis datasets as follows:

- **OISST:** NOAA's Optimum Interpolation Sea Surface Temperature (OISST, also known as Reynolds' SST) is a series of global reanalysis products, including the weekly OISST data and daily OISST data. OISST generates smoothed and complete ocean observation data by conducting interpolating and extrapolating operations based on a combination of ocean temperature observations from satellites and in-situ platforms (e.g., ships and buoys). The input data is first mapped to specific regular grids since they are usually irregularly distributed in space. Then, statistical methods, e.g., optimum interpolation (OI) [91], are applied to fill in the missing values.

- **ClimateNet**: is an open and expert-labeled dataset designed for high-precision analyses of extreme weather events. It focuses on capturing tropical cyclones and atmospheric rivers in high-resolution climate model outputs.
- **ERA5**: ECMWF Reanalysis Atmosphere V5 (ERA5) is published by ECMWF for monitoring the global climate, which provides hourly data with estimates of uncertainty for the parameters of atmospheric, land-surface, and ocean. ERA5 provides atmospheric parameters on 37 pressure levels, sea surface temperature, sea wave height, etc.
- **Extreme-ERA5**: is a subset from ERA5 to evaluate the prediction capability of data-driven models under extreme weather conditions. It comprises various extreme weather events defined by climate variables exceeding localized thresholds (e.g., heatwaves and cold breaks due to sea level temperature anomalies).
- **OSCAR**: Ocean Surface Current Analyses Real-time (OSCAR) is a global surface current database provided by NASA. OSCAR data are calculated based on satellite-sensed sea surface height gradients, ocean vector winds, and sea surface temperature gradients using a simplified physical model. Daily averaged surface currents are provided on a global 0.25 x 0.25-degree grid over an assumed well-mixed top 30 meters of the ocean from 1993 to the present.
- **GOCD**: The Global Ocean Current Database (GOCD) is a typical reanalysis data that integrates ocean current data from a wide variety of methods, resolutions and formats into a single universal format. Daily averaged surface currents are provided on a global 0.25 x 0.25-degree grid of the temporal coverage from 1962 to 2013.

2.2 Unique Data Characteristics

Compared with typical ST data (e.g., traffic flow data and epidemic outbreak data), ST ocean data not only contains ST dependencies between adjacent locations but also has a lot of complex and unique characteristics. Here, we summarize four unique characteristics of ST ocean data, as shown below.

Diverse Regionality. In general, the ocean can be divided into a lot of regions in different ways. For example, one general partition is based on the climate zones to divide the ocean into various regions, such as tropical zones and frigid zones. On the one hand, each region has a diverse pattern from the others. As shown in Fig. 8(a), the collected ocean data in the same region usually have similar patterns, but the data from different regions may have opposite patterns [173, 257]. On the other hand, when learning the ST correlations in ocean, it is of high importance to capture the ST correlations between regions since the ocean is a unified system. Moreover, due to the ocean current and atmospheric circulation, the correlations between regions are not static but dynamically changing over time. The dynamic nature of these correlations complicates the task to effectively learn and generalize across the varied features of all ocean regions. Therefore, adaptive learning approaches tailored to specific regional characteristics are necessary to accurately analyze ocean data and enhance the predictive performance of STDM models, ultimately leading to a more comprehensive understanding of marine ecosystems and environment changes.

High Sparsity. Sparsity is an important characteristic of ST ocean data. In-situ data and ship data are usually collected in a sparse and uneven distribution in both space and time, which leads to high sparsity in observation data for certain periods and some ocean areas. Satellite data may be highly missed due to the cloud covering the scanning cycle of satellites, and the sensors' stability and transmission loss. For example, according to [137], the missing rate of MODIS satellite data could be higher than 80% in some periods. Moreover, as illustrated in Fig. 8(b), the Chl-a data from both of the Yangtze River, China, on March 16, 2022, and the South China Sea on November 27, 2023, exhibit high sparsity, with a missing rate exceeding 50%. The high data sparsity issue hinders the ability of STDM approaches to identify and understand important oceanic patterns and trends,

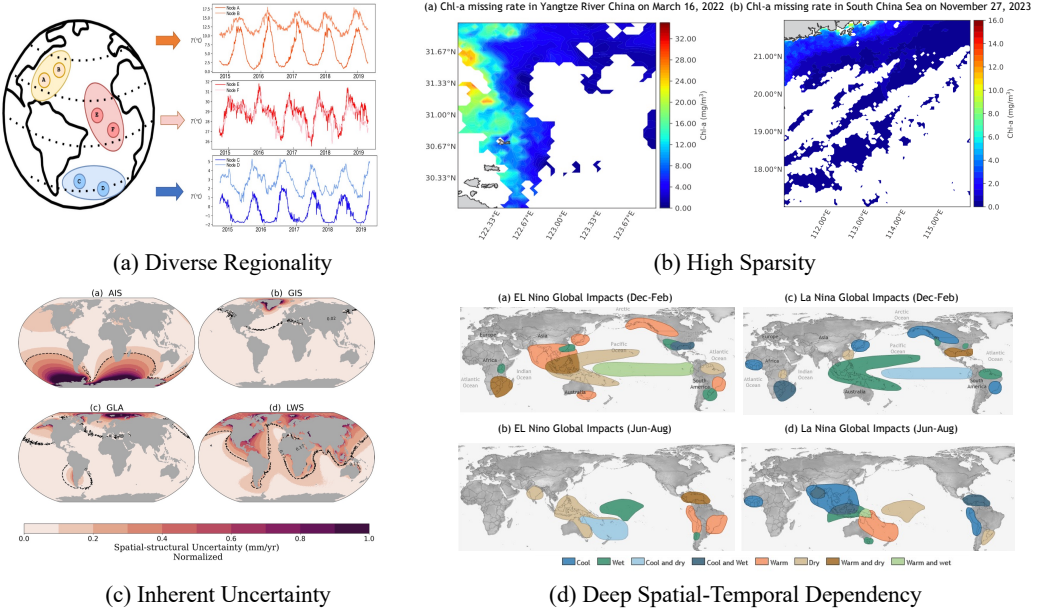


Fig. 8. The illustration of the four unique characteristics of ST ocean data. (a) shows that the SST data collected from different regions may have diverse patterns [257]. (b) shows that the Chl-a data collected in two different locations suffer from high data missing problems [230]. (c) provides the spatial uncertainty on four different datasets [29]. (d) illustrates the spatial-temporal dependency across different seasons of two well-known phenomena, i.e., El Nino and La Nina [96].

which leads to unreliable analyzing results. Thus, how to address the sparsity issue in ST ocean data is an important yet challenging task for developing STDM methods for ocean science.

Inherent Uncertainty. Another characteristic of ST ocean data is the inherent uncertainty due to the instability of the data collection process, which may cause the collected data to contain noise and deviate from real values. Concretely, the uncertainty in ST ocean data stems from the fact that many ocean datasets have biases in sampling and measurement. For instance, uncertainty might occur because a particular thermometer is miscalibrated or poorly sited. However, data producers seldom provide uncertain information about data. For example, one may have access to three different SST datasets: one reanalysis dataset at $2.5^\circ \times 2.5^\circ$ spatial resolution, another dataset at $0.75^\circ \times 0.75^\circ$ spatial resolution, and a satellite dataset at $0.25^\circ \times 0.25^\circ$ spatial resolution. As shown in Fig. 8(c), there are four different datasets to monitor the sea-level changes. For the spatial-structural uncertainty, four datasets have different biases and uncertainties [29] at different locations. Since each dataset has its own biases, effectively fusing these datasets to obtain the correct information is a challenging issue.

Deep Spatial-temporal Dependency. With the wide spatial coverage of the global ocean and long-term temporal recording, ST ocean data have more complex and deeper ST dependencies than typical ST data. Concretely, from the spatial view, the wide spatial coverage brings complicated ST dependencies between different ocean locations. For example, as illustrated in Fig. 8(d), two well-known phenomena, i.e., El Nino and La Nina, occurring in the equatorial Pacific Ocean, have been proven to cause intense storms and extreme temperatures in many regions far away from the Pacific Ocean via the tropical tropospheric and atmospheric bridge mechanism [96, 259]. From

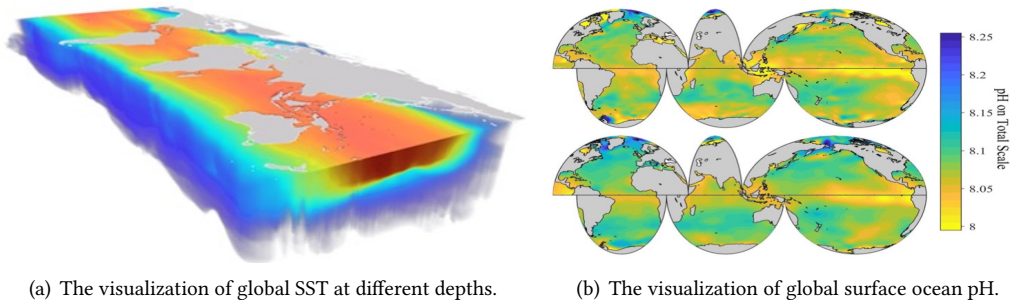


Fig. 9. The visualizations of ocean environmental elements: (a) The global SST at different depths [6], and (b) the global surface ocean pH from two different analysis projects [101].

the temporal view, the temporal dependency of these two phenomena is complicated and dynamic across different seasons, which requires STDm methods to have the capability to model such dynamics. Moreover, the spatial and temporal dependencies are often intertwined and influence the interactions between various ocean factors across different regions. Thus, modeling and capturing such intricate dependencies are crucial for understanding ocean dynamics.

2.3 Data Visualization

Visualization of ocean data is important for scientists and engineers to understand various ocean phenomena and discover their underlying complex and dynamic patterns. Since interactive visual analysis integrates the experts' knowledge into the design of models and algorithms [133], it allows us to interactively explore, analyze, and assess data at different spatial-temporal scales to gain insights into the data. We introduce three typical types of visualization methods for ST ocean data as below.

- Ocean environmental elements visualization.** Ocean environmental elements are a number of basic physical properties that affect the ocean ecosystem, including scalar data (e.g., temperature and salinity) and flow fields (e.g., trajectories and ocean currents). 2D plots (e.g., points, lines, surfaces, particles, and glyphs) and 3D volume rendering are widely used methods for the visualization of these ocean environmental elements. For example, Fig. 9 visualizes the global SST at different depths and the distribution of global surface ocean pH. Currently, with the rapid development of hardware technology, the GPU-based hybrid graphics visualization approach is popular [133]. Su et al. [208] developed an ocean data visualization system that supports line contouring, volume rendering, and dynamic simulation of the sea current field. The system employs GPU-based rendering to visualize scalar or flow fields efficiently and is used to monitor the changing processes of ocean environmental elements. Liu and Chen [144] also developed a framework for interactive visual analysis of heterogeneous marine data. Ocean environmental elements visualization could help us well understand the inherent operating processes of the ocean system.
- Ocean event visualization.** The interaction between various ocean environmental elements constitutes a variety of ocean events. For instance, ocean eddies, ocean fronts, typhoons, and El Niño are common events occurring in the ocean, which often last for several days to several months. Each event has different characters and needs special algorithms for visualization. Various methods have been proposed to visualize these events. For example, Fig. 10 visualizes the trajectory of typhoon Hato in 2017. George et al. [66] proposed a framework for the

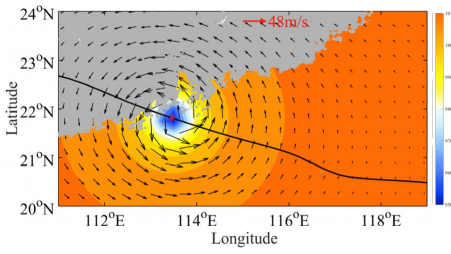


Fig. 10. The visualization of typhoon Hato at 04:00 UTC on 23 August 2017, where the black line shows the path of Hato [48].

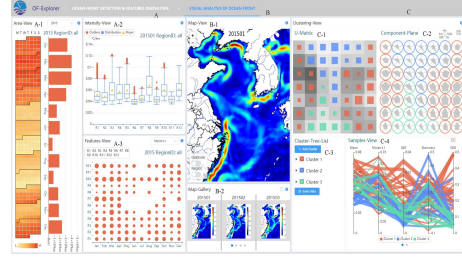


Fig. 11. The interface of OFExplorer, a visualization tool for exploring and discovering SST characteristics and patterns [248].

visual analysis of the sea level rise event and provided multiple visual analytic tools for interactive hydrodynamic flux calculation on spatial-temporal and multivariate data. Holtt et al.[84] developed an interactive visualization system for sea surface height data to support interactive exploration and analysis of the spatial distribution and the temporal evolution of ocean eddies. In general, the spatial and temporal scales of ocean events are often different, which requires event visualization methods to be adaptable to changeable scales [123].

- **Ocean pattern visualization.** Ocean patterns are related to complex ocean processes, which are hidden in the spatial and temporal variability of ocean data. ST pattern visualization is used for understanding the evolution characteristics of the ocean environmental elements (e.g., temperature and salinity) or phenomena (e.g., eddies and fronts) over time to detect trends, periodicity, and other important factors. For example, Xie et al. [248] developed the visualization tool OFExplorer, as shown in Fig. 11, to discover the changing patterns of SST. Another ocean pattern visualization approach integrates the changes of ocean environmental elements in both time and space into a 3D volume rendering [184] by reducing the feature dimension through slicing, averaging, and aggregation operations or using PCA-like methods [189, 202].

3 DATA QUALITY ENHANCEMENT

High data quality is of great significance to ensure that the results of STDM are reliable, accurate, and complete [114]. However, in practice, it is difficult to get high-quality ST ocean data for various reasons, such as limited spatial and temporal coverage, failures of data collection devices, and data loss during transmission. Meanwhile, the diversity of the data sources also affects the quality of ST ocean data. To address the data quality issue, a number of studies have been conducted on data quality enhancement, which makes ST ocean data more suitable for specific applications. In this section, we first overview the typical data quality control methods and then summarize the three foundational data processing operations, i.e., data cleaning, data completion, and data fusion, and the corresponding techniques to improve the quality of ST ocean data. In addition, we introduce the data transforming process, which transforms the data representation to meet the specific requirements of STDM tasks.

3.1 Data Quality Control

Conducting spatio-temporal data mining over erroneous data could lead to invalid conclusions. Conversely, rejecting extreme but valid data may result in missing important events [45]. Therefore, the goal of data quality control is to minimize or eliminate incorrect data, enabling better decision-making. Five commonly-used metrics for data quality are listed as follows:

- **Data Range Checks:** Verify that the data values fall within expected ranges [98]. For example, sea surface temperature should be within the range of -2°C to 35°C .
- **Physic Consistency Checks:** Ensure that related data points are consistent with each other by Physics law [125]. For instance, with both sea surface salinity and temperature data, we can check their consistency with known physical and oceanographic laws.
- **Temporal Consistency:** Check for temporal consistency in time-series data and ensure that there are no sudden, unexplained jumps or drops in the data by utilizing the sliding windows.
- **Spatial Consistency:** For spatial data, ensure that the values are consistent across neighboring regions. Sudden changes in values across small spatial distances may indicate errors.
- **Cross-Validation:** Cross-validate the data with other reliable sources or datasets to ensure its accuracy.

3.2 Data Cleaning

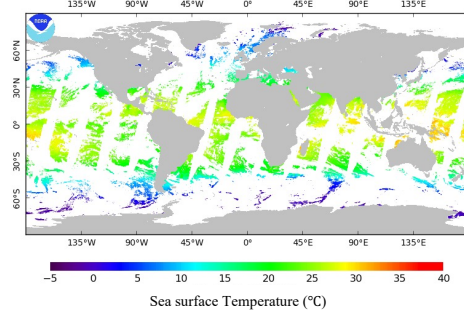
Data cleaning aims to remove incorrectly formatted data, which may result in inaccurate analysis and unreliable results. Data cleaning requires a good understanding of the real distributions and statistical implications of the original data. Existing methods, e.g., **statistical analysis methods**, **proximity measurement methods** and **density-based clustering methods**, for data cleaning usually use constraints, rules, and patterns to detect and remove the outliers in data [278]. Statistical analysis methods usually detect outliers that do not follow the given data distributions or regression equations. Proximity measurement methods first define a proximity measure between data points and then identify those abnormal data points that are far away from the other data points. Density-based clustering methods often detect data outliers by comparing their local density with the neighboring data points and are suitable for non-uniformly distributed data. For ST ocean data, we could utilize the above methods to remove the incorrectly formatted data points to improve data quality for downstream STDM tasks.

3.3 Data Completion

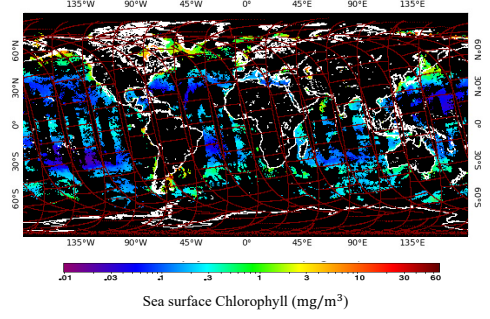
The issue of data missing or sparsity is very common in ST ocean data due to the influence of various inevitable factors such as cloud occlusion, bad weather, and sensor failure. If missing values are not well treated, the data analysis results may be unreliable and inaccurate, leading to bias in further applications. As shown in Fig. 12(a) and Fig. 12(b), due to the cloud occlusion, both AVHRR data and MODIS data have many missing values. According to Fig. 12(c), the monthly missing rate of MODIS data in the Northern South China Sea is often between 20% and 50%, and the missing rate of SST even reaches 60% in 2012, let alone the daily data missing rates. Apparently, compared with typical ST data such as traffic data and crowd volume data, the missing rate in ocean data is extremely high, making it difficult to conduct data analysis and restricting the development of real-world applications (e.g., weather forecasting and typhoon detection). Therefore, data completion is regarded as a necessary step in ST ocean data quality enhancement and a variety of data completion methods have been proposed. In this section, we briefly introduce the problem definition of data completion and the related techniques.

As shown in Fig. 13, we use matrix $X = (X_1, \dots, X_j, \dots, X_T) \in \mathbb{R}^{N \times T}$ to represent the time-series of recorded ocean data for N nodes (e.g., grid ocean regions and sensor locations) at T timestamps, where X_j represents the observation values for all nodes at timestamp τ_j , and $x_{i,j}$ is the observation value of node v_i at timestamp τ_j . In addition, a masked matrix $M = (M_1, \dots, M_j, \dots, M_T) \in \mathbb{R}^{N \times T}$ is introduced for X , where each entry $m_{i,j} = 0$ if the entry $x_{i,j} \in X$ is missing, otherwise $m_{i,j} = 1$.

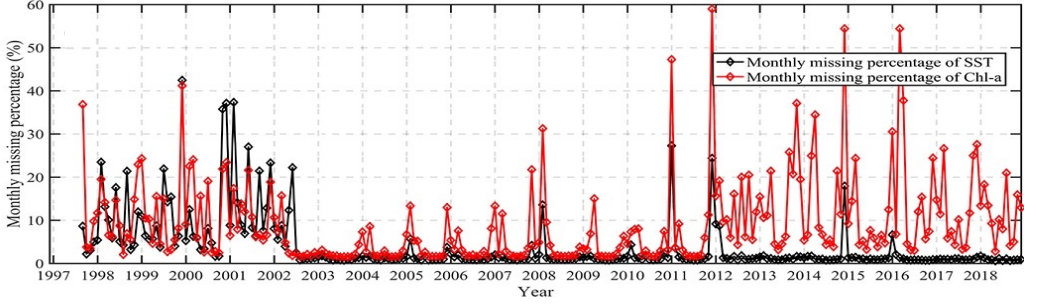
Given the incomplete data matrix X and its masked matrix M , the data completion problem aims to fill the missing values in X and ensure that the filled values are close to the real values, i.e.,



(a) The spatial distribution of SST records from AVHRR satellite data on 3 October 2021, where the white areas have no data, and the gray areas are lands [1].



(b) The spatial distribution of Chl-a records from MODIS satellite data on 3 October 2021, where the black areas have no data [3].



(c) The monthly missing percentages of SST and Chl-a in the area of Northern South China Sea from 1997 to 2018 [150].

Fig. 12. Distributions and missing rates of global SST and Chl-a data. (a) / (b) The spatial distribution of SST / Chl-a records from AVHRR / MODIS satellite data on 3 October 2021, and (c) the monthly average missing rates of SST and Chl-a in the Northern South China Sea from 1997 to 2018.

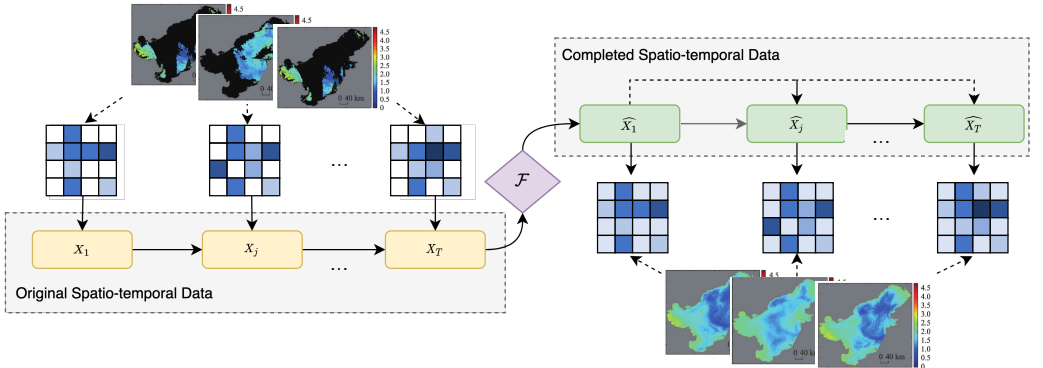


Fig. 13. The general framework of ST data completion, where the input is incomplete ST data, the output is completed data, and \mathcal{F} could be various data completion algorithms.

Table 5. Major existing methods of ocean data completion.

Category	Strengths	Weaknesses	Model	Year	Approach
Numerical methods	Need a small amount of data, simple, fast, flexible, and adaptable.	Cannot model non-linear data, depend on a correct domain knowledge.	OI [91]	1987	min-variance
			Kriging [168]	1990	linear combination of nearby data
			DINEOF [11]	2005	Empirical Orthogonal Function (EOF)
			STGF [277]	2024	averaging neighbors' data
Traditional machine learning based methods	Can model dynamic, non-linear, and noisy data, easy to set up, self-adaptable, self-organizing, and error tolerant.	Have a high computational cost and tend to overfit when applied to long-term data.	ANN [176]	2008	artificial neural network
			RF [38]	2019	a multitude of decision trees
			KNN [89]	2021	averaging k-nearest neighbors
			SVR [160]	2021	calculating the best model to fit points
Deep learning methods	Extract deep features from the data, can work with noisy data, captures temporal dependencies over variable periods of time, high accuracy.	High complexity, high computational cost, need to be tuned carefully lack of interpretability	MF [140]	2022	matrix decomposition
			CNN [218]	2021	convolutional neural network
			GAN [170]	2021	generative adversarial network
			STA-GAN [231]	2022	generative adversarial network
			GCN [137]	2023	graph completion network
			U-Net [261]	2023	attention network
			Transformer [71]	2024	transformer network

$$\hat{X} = \mathcal{F}_{\theta}\{X, M\}, \quad (1)$$

$$\tilde{X} = X + \hat{X} \odot (O - M), \quad (2)$$

where \hat{X} is the generated data matrix by data completion model function \mathcal{F} , θ denotes all the learnable parameters in the model, O is a matrix whose entries are all ones, and \odot denotes Hadamard product. Finally, we can get the completed data \tilde{X} .

Existing ST data completion methods can be roughly divided into three categories, i.e., numerical methods, traditional machine learning-based methods, and deep learning methods. And the summarization and comparison of these methods are in Table 5.

3.3.1 Numerical methods. Numerical methods learn the linear correlations from past observations and the domain knowledge (e.g., physical laws of the ocean) to achieve data completion. History average (HA) only uses the average of past data to fill in the missing values, which is too simple to learn the non-linear relationships. To simulate the true data distribution, the Optimal Interpolation (OI) method [91] uses the min-variance to obtain the ideal unbiased approximation of missing data and is widely used to build cloud-free SST products by fusing data from multiple platforms, such as satellite data, in-situ data, and ship data. For example, the OI method is employed in the NOAA OISST products [91] and the blended foundation SST products [85]. In addition, the OI method is popular for analyzing daily SST by fusing the AVHRR satellite data and the Tropical Rainfall Measuring Mission Microwave Imager products. Distance-based data completion methods fill the missing data with the average of the data within a certain physical distance and are also popular in the early ages. For example, Kriging and IDW [21]) have been proposed to achieve SST data completion based on the spatial relevance of original data. DINEOF is widely used to complete Chl-a data, SST data, ocean wind data, and multivariate ocean factors [70, 256].

In practice, numerical methods are simple, flexible, and widely used for filling in missing values in various ocean data products. However, they cannot well learn the complex nonlinear relationships in ocean data, and some methods are highly dependent on expert knowledge to set the values of parameters, which is not sufficient to achieve accurate ST data completion.

3.3.2 Traditional machine learning-based methods. Traditional machine learning-based methods aim to utilize historical ocean data to train machine learning models to simulate data distributions for data completion. For example, Chen et al. [38] used RF to improve the completion of Chl-a data with two external factors, i.e., the Ocean Color Index and the Rayleigh-corrected Reflectivity. Distance-based method K-Nearest Neighbors (KNN) and kernel-based SVR method have also been adopted to fill missing values of ocean data based on distance measurement [89, 160]. Artificial

Neural Network (ANN) is applied for the completion of SST data in the Mediterranean [176]. Jouini et al. [106] proposed the Self-Organizing Map (SOM) network to complete Chl-a data under heavy cloud coverage by integrating SST and sea surface height (SSH).

In sum, traditional machine learning-based methods are easy to set up and have the ability to model the dynamic, non-linear, and noisy features of ST ocean data. However, they have a high computational cost, tend to overfit when applied to long-term data, and cannot well capture the complex ST dependencies in ocean data.

3.3.3 Deep learning-based methods. To capture the complex ST dependencies, deep learning-based data completion methods have been introduced to improve the quality of sparse ST ocean data. For example, Jean-Marie [218] achieved the completion of SST data using a neural network (NN) and proved that the NN is superior to the OI and EOF methods. Zhao et al. [274] proposed an LSTM-based method to fill the missing values of wave height data. Chen et al. [40] proposed the FTC-LSTM method that combines Fourier Transform Convolution (FTC) and LSTM to simultaneously capture global spatial features and global temporal features of Chl-a for data imputation. Ye et al. [261] proposed an attention U-Net model for reconstructing MODIS data and introduced attention gates to learn the most important features of missing data. Barth et al. [17] proposed the Data-Interpolating Convolutional Auto-Encoder (DINCAE 1.0) for the completion of Chl-a data. Han et al. [79] extended DINCAE 1.0 by introducing SST data. Furthermore, Yan et al. [254] proposed the DNCAE-BME method for reconstructing Chl-a data and utilized Bayesian Maximum Entropy (BME) to integrate multiple types of information. Then, DINCAE 2.0 was proposed to handle multivariate data, including SST, Chl-a, and wind speed, for reconstructing MODIS-Terra SST and altimetry observations [18]. Wang et al. [231] proposed the STA-GAN model, which demonstrates strong performance in satellite data completion. This model utilizes the ST attention mechanism of Graph Attention Networks (GAT) to learn short-term temporal dependencies and dynamic spatial dependencies and incorporates Generative Adversarial Networks (GAN) to capture the original distribution of satellite data. Considering the limited observational information from highly sparse remote sensing data, Wang et al. [229] further proposed the S2-STI method, which incorporates external data such as SST and Photosynthetically Active Radiation (PAR) to enhance the accuracy of Chl-a data imputation. Specifically, this method generates ST embedding representations for the external data to enrich the information about Chl-a data and develops a GAN-based Data Imputation (GDI) module to reconstruct the distribution of Chl-a data.

Deep learning-based data completion algorithms achieve high accuracy in ST ocean data completion and can capture dynamic dependencies over time. However, they still have some weaknesses. First, they are of high complexity, and the training and tuning processes are time-consuming. Besides, they are treated as "black boxes" and have low interpretability. Therefore, it is still worth exploring to reduce the time complexity of deep ST ocean data completion methods and enhance interpretability.

3.4 Data Fusion

For many STDM tasks, e.g., climate forecasting and typhoon tracking, multi-source ocean data collected by various producers, e.g., NOAA, NASA, and ECMWF, are required to obtain comprehensive knowledge. These different datasets usually have diverse data collecting standards, equipment, and technologies, leading to different ST resolutions, different ST coverage, and different data quality. For example, in-situ observations can provide precise information about the ocean at specific locations, but they have issues of sparsity, uneven distribution, and low resolution. Meanwhile, satellite data can provide continuous observation of the ocean over a wide area and for long periods but is unable to obtain fine-grained information at the location level. Therefore, combining the benefits of

multi-source observation data to build high-quality ST ocean datasets is an essential yet challenging problem. Specifically, for STDM in ocean, data fusion is integrating multiple data sources to obtain more comprehensive and consistent information about the ocean. Existing methods for fusing multi-source ST ocean data can be roughly classified into two categories, i.e., homogeneous data fusion methods and heterogeneous data fusion methods.

3.4.1 Homogeneous data fusion methods. Homogeneous data fusion aims to combine the datasets from the same source into a comprehensive dataset to improve the data quality. At early ages, the most common way to fuse homogeneous data is to utilize their statistical characteristics (e.g., local mean matching, regression analysis, and statistical region merging). However, it is difficult to fuse the observation records of two datasets from the same source with different spatial and temporal scales. To solve this problem, Nguyen et al. [164] presented the spatial data fusion methodology based on the spatial-random-effects model, where the spatial distribution is learned based on the data of different temporal scales within the same region. Kang et al. [151] proposed the Dynamic Fused Gaussian Process (DFGP) to combine a low-rank representation with a general covariance matrix with a dynamic-statistical approach to fuse the satellite data from different sensors. Jung et al. [107] utilized RF to fuse two satellite datasets to provide high-quality SST data. Raizer et al. [178] introduced a digital wavelet transform method to combine information in both spatial and temporal domains across two satellite datasets. More recently, Hou et al. [87] proposed a spatial-temporal ocean data fusion model based on ConvLSTM to fuse multi-source data to predict SST.

3.4.2 Heterogeneous data fusion methods. Heterogeneous data fusion aims to combine data from different data sources, thus providing more comprehensive information than the dataset from a single source. Due to the variety in form and content across spatial and temporal scales, it is much more difficult to fuse heterogeneous data than homogeneous data. Chen et al. [7] developed a Bayesian inference model to fuse in-situ and satellite data for accurate chlorophyll-a estimation. Han et al. [78] introduced a CNN-based fusion algorithm to combine satellite image data with time-series data. Wang et al. [226] proposed an ODF-net to fuse in-situ observations, satellite observations, and reanalysis data using a self-training attention mechanism for short-term SST prediction.

In conclusion, fusing multi-source data can enhance data consistency and quality and improve the accuracy of STDM tasks for ocean science. However, existing methods for fusing ST ocean data usually rely heavily on prior statistical knowledge of linear principles, normal distributions, and error covariances. In addition, these methods are often tailored for specific datasets and tasks, and there are no unified data fusion frameworks that can fuse various ST ocean data sources. These limitations are still open issues that need further exploration.

3.5 Data Transforming

In practice, different ocean application scenarios correspond to different categories of STDM tasks and problem formulations, and different STDM tasks usually have different requirements for the formats of input data. Therefore, the original data from multiple sources cannot be directly used for various STDM tasks. An important process before putting data into STDM models is to transform the data to meet the specific requirements of the data mining task. As shown in Fig. 14, we provide a clear mapping from different data sources to different data instances (i.e., ST points, Trajectories, Time series, and ST raster) and four types of tasks (cf. Section 4 for the details). For example, an ST point refers to a tuple containing spatial and temporal information as well as ocean features (e.g., temperature and chlorophyll-a), which can be obtained by in-situ sensors and ship sensors. Then, a series of ST points collected at different locations can be utilized for detecting various events (e.g., El Niño and typhoon). A trajectory, usually collected by a sailing ship or moving sensor, consists of

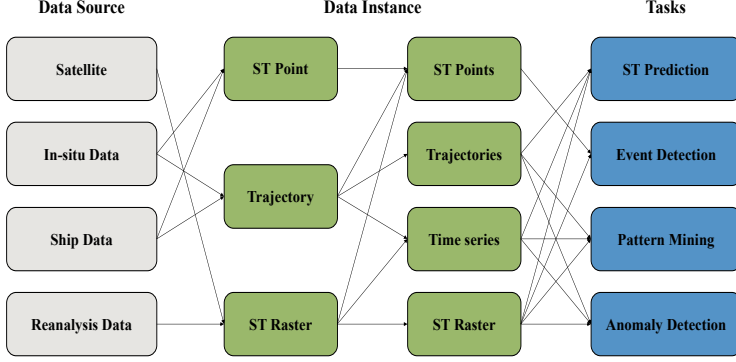


Fig. 14. A mapping from the data sources to the data instances and the four types of ocean STDM tasks.

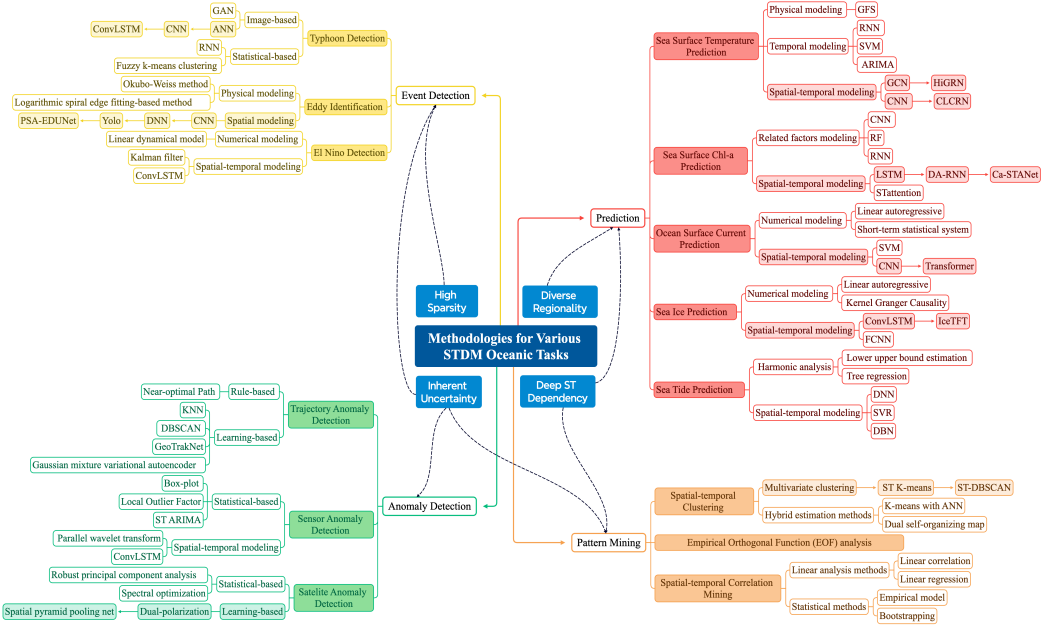


Fig. 15. The taxonomy of methodologies of different ocean STDM tasks.

the continuous measurements of an ST feature over a set of moving reference points in space and time and can be utilized in ship anomaly detection, as well as pattern mining tasks. ST raster data refers to the measurement of a continuous or discrete ST field recorded at fixed locations in space and at fixed points in time, which is usually collected by the satellite sensors and obtained from the outputs of reanalysis models. ST raster data is an important data format for STDM tasks and also can be transformed into other data instances (e.g., ST points and time series) for different tasks.

4 TASKS & METHODOLOGIES

To provide a clear overview of the STDM techniques for ocean science, we classify the STDM tasks into four typical categories, i.e., prediction, event detection, pattern mining, and anomaly

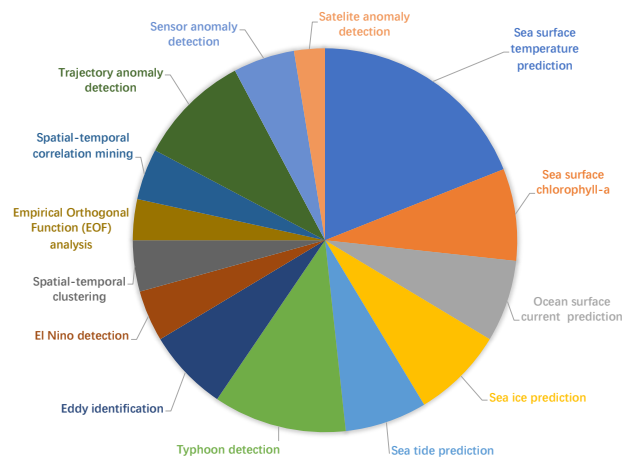


Fig. 16. The distribution of publications of various ocean STDM tasks (data from the Web of Science).

Table 6. Representative studies for the ocean STDM tasks.

Task Categories	Tasks	Related studies
Spatial-temporal Prediction	Sea surface temperature prediction	[183],[207],[8], [238], [269] [243], [267], [260],[246],[86],[270],[210], [73], [7], [118],[63] [256], [174]
	Sea surface chlorophyll-a prediction	[146],[181], [266],[82],[263],[126],[235],[95].
	Ocean surface current prediction	[61],[16],[191],[72],[182],[192],[97],[214], [272].
	Sea ice prediction	[264],[224],[223],[175],[43], [143],[143], [276] .
	Sea tide prediction	[190],[109, 110],[68],[167],[258],[185],[194].
Spatial-temporal Event Detection	Typhoon detection	[113],[255],[148], [116],[10], [37], [118],[188],[67].
	Eddy identification	[239],[32],[200],[158],[127],[147],[50].
	El Niño detection & prediction	[64],[30],[213],[233],[117].
Spatial-temporal Pattern Mining	Spatial-temporal clustering	[83],[240],[69],[93],[7]
	Empirical Orthogonal Function (EOF) analysis	[44],[162].
Spatial-temporal Anomaly Detection	Spatial-temporal correlation mining	[41]
	Trajectory anomaly detection	[204],[242],[76],[58],[13],[186],[187],[60],[128], [204],[163], [128].
	Sensor anomaly detection	[152],[12],[112].
	Satellite anomaly detection	[153],[77],[53].

detection, based on the problem formulation. We then introduce the typical downstream applications and representative methods for each category of tasks. Fig. 15 illustrates the overall taxonomy of representative methodologies of different ocean STDM tasks and highlights the most crucial characteristics (c.f. Section 2.2) that need to be addressed for each category of tasks. For instance, capturing diverse regional variations and deep ST dependencies is highly important for ST prediction tasks in the ocean. In addition, Fig. 16 presents the distribution of published research papers on these tasks (data from the Web of Science), among which SST prediction and typhoon detection are the most popular. Table 6 further overviews the representative studies for each category of STDM tasks, and Table 7 summarizes the representative methods by comparing their complexity, spatial-temporal modeling techniques, and enhancing modules.

Table 7. The comparison of representative STDM methods in ocean science.

Task Categories	Methods	Complexity	Spatial modeling	Temporal modeling	Enhancing modules
Spatial-temporal Prediction	ConvLSTM [246, 263]	Low	CNN	LSTM	
	DA-RNN [235]	Low	Attention	LSTM	
	TransLSTM [97]	Low	Transformer	LSTM	
	CLCRN [138]	Medium	Conditional local convolution	LSTM	
	HiGRN [257]	High	GRU	RNN+Attention	Regional clustering
	ECM-HMSTM [63]	High	hybrid multiscale U-Net	Yolo	Error correction
Spatial-temporal Event Detection	ConvLSTM [37, 116]	Low	CNN	LSTM	
	FCRNN [10]	Low	MLP	RNN	
	ConvLSTM+EMD [233]	Medium	CNN	RNN	Empirical Mode Decomposition
	GAN [188]	High	DNN	Generator	Physical models
	Data-Attention-Yolo [234]	High	Attention	Pyramid Split Attention	
	PSA-EDUNet [275]	Medium	U-Net		
Spatial-temporal Pattern Mining	HEK [69]	Low	K-means clustering	ANN	
	DSOM [157]	Low	Attention	Self-Organizing Map	
	LR [41]	Low	55	Linear Regression	
	Cluster [53]	Low	KNN	SVM	
Spatial-temporal Anomaly Detection	GMVAE [250]	Medium	55	Variational Autoencoder	Dynamic Time Warping
	GeoTraKNet [163]	Low	55	Variational RNN	Gaussian approximation
	RPCA [203]	Low	55	Low-rank Decomposition	
	SPFN [227]	Medium	Spatial Pyramid Pooling	Multivariate Gaussian Distribution	

4.1 Spatial-temporal Prediction

Spatial-temporal prediction is an important STDM task for ocean science that predicts the future changes of various ocean factors, e.g., temperature, chlorophyll-a, and ice concentration. ST prediction aims to understand the regularity of historical observations to predict future observations. The key challenge in ST prediction is that ocean factors have complex spatial and temporal dependencies. For example, events occurring in a region may affect other regions far away (spatially and temporally). For ST prediction in the ocean, we overview the experiments setting for ST prediction and five representative tasks, i.e., sea surface temperature prediction, sea surface chlorophyll-a prediction, ocean surface current prediction, sea surface chlorophyll-a prediction, and sea tide prediction.

4.1.1 Experiments settings. Given the time series $\mathcal{X} = \{X_0, X_1, \dots, X_t\}$, we have $X_t = \{x_{1,t}, x_{2,t}, \dots, x_{N,t}\} \in \mathbb{R}^{N \times d}$ that records d -dimension data at N locations at time t , where d represents the dimension of observed factors. Then, ST prediction aims to seek a function \mathcal{F} to predict the features in upcoming τ time steps based on the data of the last T time steps, i.e.,

$$\{\hat{X}_{t+1}, \hat{X}_{t+2}, \dots, \hat{X}_{t+\tau}\} = \mathcal{F}_{\theta}\{X_{t-T+1}, X_{t-T}, \dots, X_t\} \quad (3)$$

where θ denotes the learnable parameters in function \mathcal{F} . Commonly used metrics for evaluating ST prediction include Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE), both measuring the average errors of the prediction values and ground-truth values. Mean Absolute Percentage Error (MAPE) is also frequently used to provide a normalized measure of prediction accuracy. Additionally, the correlation coefficient (R) is used to assess the strength and direction of the linear relationship between observed and predicted values. These metrics collectively provide a comprehensive assessment of ST prediction models' performance in capturing the spatial and temporal dynamics in ocean data.

4.1.2 Sea surface temperature prediction. Sea surface temperature (SST) is one critical parameter for monitoring global climate change, and accurate SST prediction is important to weather forecasting, disaster warning, and ocean environment protection. The major challenge in predicting SST is that SST has dynamic patterns changing over time, long-term temporal dependencies, and complex spatial dependencies. SST prediction has been studied for decades, and existing methods for SST prediction can be roughly grouped into three categories, i.e., physical models [183, 207], temporal methods [8, 267], and spatial-temporal methods [86, 138, 260, 270].

Physical models combine the laws of physics, e.g., Newton's laws of motion, the law of conservation of energy, and the seawater equation of state, to predict SST. For instance, the Global Forecast System (GFS) [183] conducts SST prediction by combining the Navier-Stokes equation, solar radiation function, and ocean latent heat circulation equation to simulate the changes of SST. Although physical models have been widely used in the past decades, they require a good understanding of the underlying changing mechanism of SST to choose the determining factors of physical functions. However, the changing mechanism of SST is complicated, making it difficult to use only the factors of explicit equations to capture SST patterns.

Temporal methods, as a widely used type of SST prediction methods, formulate SST prediction as a time series prediction problem that can be solved by various temporal models, e.g., vector autoregressive models, hidden Markov models (HMM), support vector machines (SVM) model, and some temporal deep learning methods [8, 138, 260, 267]. For example, Aguilar et al. [243] introduced warm water volume as an additional feature to enhance SST prediction with an SVM model. Generally speaking, these are linear models that use a window of past information to predict the SST records in the future. Although these methods can predict the trend of SST to a certain extent, they ignore the long-term dependencies, leading to low overall prediction accuracy. Zhang et al. [267] employed a fully connected LSTM to predict future SST in Bohai, where the LSTM structure models SST sequences and the fully connected structure produces the prediction results. These temporal methods mainly focus on extracting the temporal features of SST and cannot well capture the spatial correlations among the SST time series.

Spatial-temporal prediction methods combine typical deep learning methods such as CNN, RNN, and GCN to capture the ST dependencies in ocean data. Xiao et al. [246] employed the ConvLSTM model for SST prediction by using CNN to extract the spatial information of gridded SST and LSTM to capture the temporal dependencies of SST. Hou et al. [86] proposed a dilated convolutional model to obtain long-term dependencies of SST series, and the model achieves better prediction performance than ConvLSTM. To learn the complicated non-adjacent connections among SST series, researchers also model the spatial correlations of SST time series with GCN. As shown in Fig. 17, CLCRN [138] utilizes a GCN-based method to establish local spaces for modeling the dependencies of the spatial neighbors and predicting future SST. Zhang et al. [270] developed the memory GCN to build a distance-based adjacency matrix to represent the spatial correlations of SST series at different locations. To capture regional correlations, Yang et al. [257] proposed the HiGRN to capture the hierarchical relationship between regions for global SST prediction. Gao et al. [63] proposed a hybrid multi-scale spatial-temporal model combined with the error correction map to predict SST.

Spatial-temporal prediction methods have been widely used to capture the ST dependencies in SST and achieve good performance. However, most of them focus on capturing the static dependencies in SST, ignoring the dynamic ST dependencies and the combination with the physic models, which is still worth exploring in the future.

4.1.3 Sea surface chlorophyll-a prediction. Predicting the sea surface chlorophyll-a (Chl-a) concentration could facilitate the monitoring and early warning of harmful algal bloom events that have serious impacts on marine fisheries. For Chl-a prediction, the major difficulty is to model the seasonality and the related factors affecting Chl-a. To discover the related factors, Liu et al. [146] used the absolute principal components score (APCS) method to simulate the effects of multiple chemical variables on Chl-a in Lake Qilu. However, these statistical methods are of low prediction accuracy. In recent years, various machine learning methods (e.g., SVM, decision trees (DT), RF, feed-forward neural network (FFNN), and regression models) are widely used for Chl-a prediction [266]. For example, an FFNN model [181] was used to forecast the Chl-a concentration seven days in advance

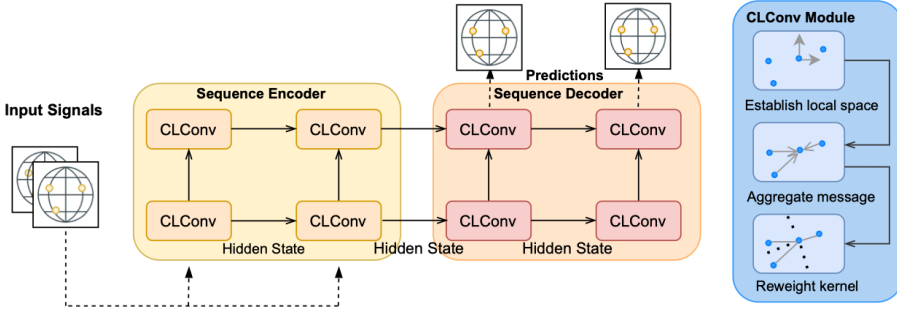


Fig. 17. The framework of the CLCRN model, which is implemented based on the Sequence to Sequence architecture with the encoder fed with previously observed data and the decoder generating the predictions [138].

in Lake Kasumigaura of Japan. Hill et al. [82] used a CNN to predict Chl-a concentrations in the Gulf of Mexico region. Moreover, Yossof et al. [263] adapted an LSTM model and a CNN model to predict the harmful algal blooms on the western coast of Sabah.

4.1.4 Ocean surface current prediction. Ocean surface current refers to the large-scale, regular, and stable flows of water on the surface of ocean in a certain direction. Accurate prediction of ocean currents can not only assist shipping, fishery, and tourism to produce economic benefits, but also play an important role in many marine tasks such as vessel path planning and Autonomous Underwater Vehicles (AUS) controlling. The major challenge in ocean surface current prediction is to model the dynamics of slow and large-scale currents. Earlier studies on ocean current prediction mostly used numerical modeling methods and linear statistical models. For instance, physical methods could derive currents from sea surface height using established physical equations [201]. Frolov et al. [61] developed a statistical model that utilizes linear autoregressive techniques to predict ocean surface currents. Barrick et al. [16] introduced a short-term statistical system to forecast ocean surface currents in Northern Norway using only a few hours of prior data. Despite their effectiveness, both physical and statistical methods require significant processing costs and parameters manually determined by domain experts.

With the advancement of machine learning, non-parametric prediction methods are increasingly being adopted for ocean current forecasting. Various machine learning algorithms, such as Gaussian Processes, SVM, Genetic Algorithms, and ANN, have been employed to enhance the accuracy of current prediction [72, 182, 191, 272]. For instance, Sarkar et al. [192] developed an ANN model incorporating fully connected layers alongside recurrent LSTM layers to predict tidal currents in specific regions. To capture the dynamic ST dependencies of ocean currents, Alexandre et al. [97] introduced a Transformer model integrated with LSTM to leverage real-time in-situ data for current prediction. Similarly, Nathachai et al. [214] proposed an ST model that capitalizes on distinct domain characteristics by employing a CNN to capture spatial properties and a Gated Recurrent Unit (GRU) to capture temporal dynamics.

Although existing studies can capture the ST features in ocean surface current data and achieve good prediction performance, the large-scale spatial dependencies and the correlations with other related factors (e.g., wind flow and the ocean tides) are still not well considered, which affects the prediction accuracy of ocean surface currents.

4.1.5 Sea ice prediction. Sea ice prediction is a crucial task in monitoring and preventing global warming and also plays an important role in coastal port traffic and vessel path planning. For the study of sea ice, the data from satellites are often the main or even the only data source because it is difficult to obtain in-situ sea ice observation data due to extreme weather. According to [161], the ever-increasing melting speed has made it more difficult to make accurate sea ice prediction. Consequently, utilizing the limited data to predict future sea ice data is a challenging issue.

Traditional machine learning methods, e.g., BP network, ANN, and linear regression, are widely used for sea ice prediction. For example, Li et al. [130] developed a sea ice-intensive degree-day prediction method that combines kernel Granger Causality analysis (KGC) and SVM to predict sea ice. However, these machine learning methods cannot well capture the ST dependencies in sea ice data, which leads to low prediction accuracy. To directly capture the spatial dependencies, Wang et al. [224] introduced a CNN-based approach that utilizes satellite image data to estimate sea ice during melting seasons. Wang et al. [223] proposed a fully connected CNN (FCNN) model to predict sea ice along Canada's east coast. To capture temporal dependencies, Petrou et al. [175] employed ConvLSTM for short-term sea ice prediction. To identify the impactful factors on sea ice, Mu et al. [161] proposed an interpretable long-term prediction model (IceTFT) that fuses multiple atmospheric and oceanic variables, and utilizes the temporal fusion transformer and multi-head attention mechanism to automatically adjust the weights of predictors and filter spuriously correlated variables.

Most existing studies on sea ice prediction are purely data-driven methods [143, 276]. However, it has been proven that combining physical knowledge with machine learning is an effective way to achieve accurate sea ice prediction. How to combine the physical mechanisms of sea ice with data-driven methods is a challenging issue for achieving accurate sea ice prediction.

4.1.6 Sea tide prediction. Tides are periodic fluctuations of the ocean surface and are caused by the gravitational pull of the sun and moon. Tidal energy generated by the fluctuation of tidal water level is a vital renewable energy source. For a long time, tide prediction has provided safety guarantees for port operations, shipping traffic, and coastal protection, and also provides essential support for offshore aquaculture and the prevention of natural disasters [280].

In the early ages, the most commonly used technique to predict sea tides was harmonic analysis, which forecasts the tidal variations with historical observations. However, harmonic analysis suffers from the fact that the parameters are numerous, some of which have a very long return period, thus costing a lot of time. Currently, the widely used methods for tidal prediction are also based on machine learning. For example, Sarkar et al. [190] used the BP algorithm, cascade correlation algorithm, and conjugate gradient algorithm to predict the tides continuously. Kavousi-Fard et al. [109] proposed a probabilistic method that uses Lower Upper bound Estimation (LUBE) to model the uncertainties of tidal current prediction in the Bay of Fundy, NS, Canada. Granata et al. [68, 167] used tree regression, RF, and multilayer perceptron to predict the tide level of Venice based on satellite data.

The high sparsity and large spatial resolution of satellite data present significant challenges in developing a high-quality unified sea tide prediction model. To address this issue, Yang et al. [258] combined satellite data and tide gauge data to estimate tidal sea levels using a Deep Belief Network (DBN). Riazi et al. [185] developed a DNN that incorporates tidal generating forces along with geological and biological factors for tidal level prediction. Despite these advancements, the deep correlations inherent in sea tide data remain unexplored by current methods.

4.2 Spatial-temporal Event Detection

In ocean science, an ST event usually means that there are significant and persistent changes happening at a particular time and location, such as typhoons, eddies, and other extreme ocean phenomena. Monitoring and detecting these events can provide early warning to prevent severe damage to personal safety and social safety. In recent years, extreme ocean events become more and more frequent under the circumstance of global warming. Therefore, accurate detection of ST events in ocean is important. Specifically, in this section, we give a brief overview of the detection of typical ST ocean events, including typhoon, eddy, and El Niño event.

4.2.1 Experiments settings. Event detection often uses both real-world and simulation data to ensure a comprehensive evaluation of detection methods' effectiveness and robustness. Thus, cross-validation techniques are employed to provide a robust and unbiased assessment of the model's performance. In addition to cross-validation, real-world scenario testing is crucial for evaluating the system's performance under diverse conditions. This includes testing the system in various seasonal and geographic conditions to ensure its reliability and effectiveness across different environments. Commonly used metrics for event detection include Accuracy, Precision, Recall, and F1 score, which can assess the model's ability to correctly identify events. MAE and RMSE are used to measure the accuracy of continuous variables such as wind speed and tidal heights. Confusion Matrix is also commonly used to provide detailed statistics of true positives, false positives, true negatives, and false negatives. Additionally, sensitivity analysis could test the model under various hypothetical scenarios to evaluate its response to different types of events.

4.2.2 Typhoon detection. A typhoon refers to a large storm system that has a circular or spiral system of violent winds and typically has hundreds of kilometers in diameter. Typhoons often occur in the tropical ocean and are usually accompanied by strong winds, heavy rain, and storm surges. Typhoon detection is of high importance to provide early warnings for disaster management in coastal areas. Typhoons usually move rapidly and are affected by multiple environmental parameters, e.g., SST, cloud cover, atmospheric pressure, and wind speed. To detect a typhoon, it is crucial to capture the extreme changes of these factors at a particular time and location. Typhoon detection has been studied for decades, and existing methods can be roughly grouped into two categories, statistical-based methods and image-based methods, according to the type of data.

For the statistical-based methods, typhoon-related atmospheric and oceanic factors (e.g., SST and wind speed) and tide-gauge data are collected for the detection of typhoons. For example, Sophie et al. [67] combined the NOAA unifying tropical cyclone data with the ERA reanalysis wind field data to construct a fusion neural network for typhoon path prediction. To predict the typhoon formation process and intensity, Chen et al. [37] combined CNN and LSTM to learn the spatio-temporal relationship among typhoon-related atmospheric and oceanic variables. To combine more factors, Alemany et al. [10] established a fully connected RNN with a lot of oceanic factors, i.e., typhoon center location, wind speed, and central pressure at 6-hour intervals from NOAA. Moreover, many researchers formulate typhoon detection as an ST clustering problem, which can not only discover the typhoon but also localize central typhoon cyclones. Kim et al. [113] evaluated the performance of three clustering methods, i.e., K-means clusterin, Fuzzy C-means clustering (FCM), and hierarchical clustering, for typhoon detection. The results indicated that FCM outperformed the others in terms of clustering efficiency and fitting degree, highlighting its effectiveness in handling the inherent uncertainty in typhoon data. Yang et al. [255] employed a mixed regression clustering algorithm alongside the mass moment method for analyzing typhoon cyclone trajectories and accurately identified the typhoon tracks in the South China Sea.

With the development of computer vision and the increasing amount of satellite image data, CNN-based methods are widely used to discover typhoons. Kovordanyi et al. [118] established a multi-layer ANN to predict the movement of cyclones based on the AVHRR images from NOAA. Ruttgers et al. [188] proposed a GAN-based detection method and discovered that integrating reanalysis data from physical models with satellite image data significantly improved the detection performance. Kim et al. [116] introduced a ConvLSTM-based model to capture both spatial and temporal dynamics for detecting typhoon tracks and predicting future trajectories. Considering that typhoons are relatively rare weather phenomena and the proportion of positive and negative samples is seriously unbalanced, Zhao et al. [273] proposed a CNN-based detection method with data enhancement technology, such as shearing, rotation, and gray-level transformation, to generate new samples for better typhoon events detection.

The state-of-the-art typhoon detection methods can already achieve quite good detection performance. However, achieving real-time typhoon detection is still a challenging problem due to the high complexity of detection methods and the complex dynamics in the development of typhoons.

4.2.3 Ocean eddy identification. An eddy is a circular current of water. Ocean eddies play an important role in ocean energy transfer and nutrient distribution. Accurately identifying the variation of ocean eddies is the key to understanding the oceanic flow and ocean circulation system [239]. It is challenging to autonomously detect eddies since they are not static objects but a distortion evolving through a continuous field. Images obtained from satellite sensors have a large spatial resolution and a wide swath of observation, which makes them effective sources for gaining comprehensive and detailed information to detect ocean eddies. Existing methods for ocean eddy identification can be roughly grouped into two categories, i.e., physical-based methods and data-driven methods.

The physical-based methods describe and detect the eddies with their physical information. The Okubo-Weiss method [239] is the most popular statical and physical procedure to discover the patterns of eddies, and it also has good interpretability. Chelton et al. [32] tracked and analyzed global eddy variability using sixteen years of unified sea surface height data, which allows for a comprehensive understanding of eddy dynamics on a global scale. Yang et al. [158] proposed a logarithmic spiral edge fitting-based method to extract eddy information, such as the center position, diameter, and edge size, from satellite images. These methods are dependent on the physical parameters, geometrics, and handcrafted features related to eddies. However, eddies are highly dynamic, and the underlying physical processes are too complex to be described using physical models with predetermined parameters.

Instead of extracting factors based on expert knowledge, data-driven models can learn high-level eddy features automatically from data. For example, Du et al. [50] utilized a spatial pyramid model and an SVM classifier method to recognize the eddies in satellite image data. As shown in Fig. 18, Wang et al. [234] proposed the object detection method using the Data-Attention-Yolo to process the satellite data on eddy identification. To better capture the spatial pyramid correlations, Zhao et al. [275] developed the pyramid split attention (PSA) eddy detection U-Net model (PSA-EDUNet) that targets oceanic eddy identification from ocean remote sensing imagery. These data-driven methods utilizing satellite data are proven to be effective for eddy detection. However, due to the limited resolution of satellite data, existing methods can only discover eddies with a large diameter but lack the ability to detect eddies with a diameter smaller than 50 km.

4.2.4 El Niño detection. El Niño is an irregularly periodic variation in winds and SST over the tropical Eastern Pacific Ocean, and it can cause extreme weather events, e.g., floods and droughts, around the world. An El Niño event can be identified if the absolute value of the 3-month mean of SST in the Niño 3.4 region (5°S-5°N, 170°E - 120°W) reaches or exceeds 0.5°C and lasts for at least

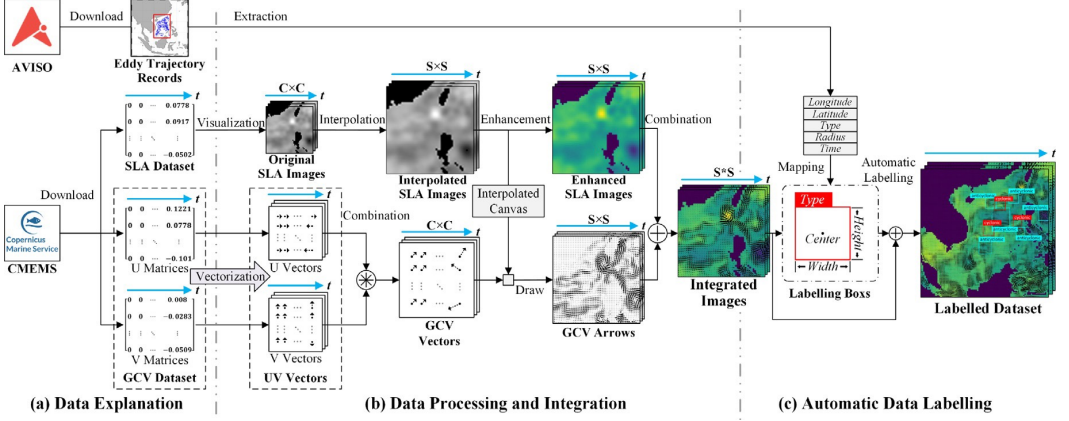


Fig. 18. The framework of data-attention-YOLO for eddy identification method, where (a) the two input datasets, (b) the data processing and integration process, and (c) automatic data labeling that is designed to transform the original eddy data to the labeled integrated data [234].

5 months. In general, El Niño event has mutual influence with many other regions across the world. Therefore, the biggest challenge for El Niño detection is to capture the complex ST dependencies of the SST in different regions within a large spatial coverage.

Most early El Niño detection models use physical laws and mathematical equations to deduce the results from the complicated interaction between the atmosphere and ocean [117]. However, these methods need domain knowledge and require a lot of factor setting of functions. To address this issue, many researchers use data mining methods for El Niño detection, which do not involve physical equations and achieve better performance than the physical methods [30, 213]. For example, Cane et al. [30] proposed a linear dynamical model to identify the El Niño event one year ahead.

Recently, deep learning methods have been introduced to achieve long-term (e.g., more than one year) prediction and detection of El Niño events. For instance, Wang et al. [233] combined the ConvLSTM Encoder-Decoder model with the Empirical Mode Decomposition (EMD) technique to achieve El Niño prediction three years in advance. This hybrid approach integrates spatial-temporal modeling with signal decomposition to enhance prediction accuracy. Besides, Gao et al. [64] proposed a new inflation scheme based on a local ensemble transform Kalman filter to improve the long-term prediction of El Niño events. Though these methods provide valuable suggestions on whether El Niño events will occur, it is still difficult to accurately detect the onset of an El Niño event because a series of reactions together lead to the El Niño events.

4.3 Spatial-temporal Pattern Mining

ST patterns mining is a fundamental STDM task to discover the hidden, potentially useful, and unknown associations and correlations in ocean data, which is of great importance for various applications, such as finding circulation regimes, identifying extreme-causing weather patterns and evaluating the effects of climate changes. In this section, we review some notable ST pattern mining approaches, including clustering, EOF analysis, and correlation mining, in the ocean.

4.3.1 Experiments settings. Many statistical analyses and data-driven methods have been proposed to uncover the associations and correlations among ST ocean data. Common evaluation metrics include classification metrics (e.g., accuracy, precision, recall, and F1 score) and regression metrics (e.g., MSE, RMSE, and MAE). For clustering tasks, evaluation metrics such as the silhouette score,

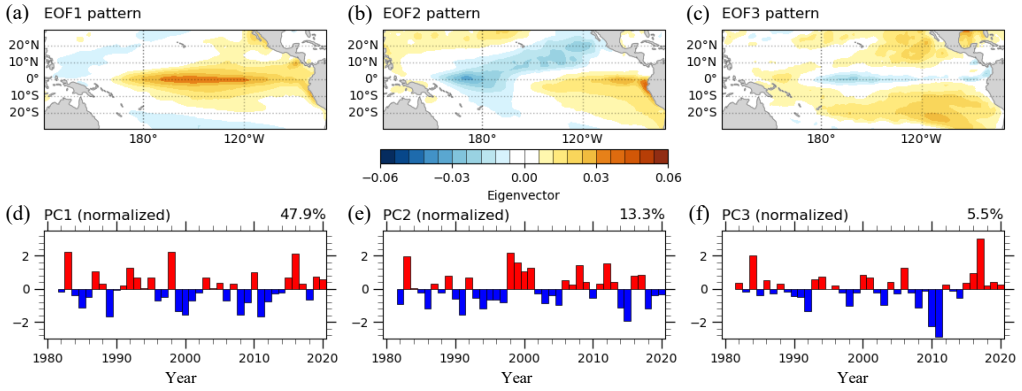


Fig. 19. Spatial distributions (a,b,c) and time series (d,e,f) of the SST anomalies of the first three modes by EOF decomposition in the North Pacific Ocean from 1982 to 2020.

purity, and entropy are often employed. Beyond these quantitative metrics, collaboration with domain experts is also essential to validate the findings based on existing oceanic knowledge and environmental implications to ensure credibility.

4.3.2 Spatial-temporal clustering. Clustering is one key data analysis task in data mining that aims to group data samples with high similarity into the same class. In general, each data sample to be classified is defined as an input vector, and the clustering result is determined by calculating the similarity between the input vector and the clustered vectors. If the similarity reaches a certain value, the input vector is divided into the corresponding classes. Compared with linear regression analysis, clustering methods (e.g., hierarchical clustering, k-means clustering, and self-organizing maps clustering) are able to reveal unknown and hidden patterns without prior knowledge from domain experts.

In the early stages, hierarchical clustering methods were utilized to discover the spatial patterns of ocean circulation in the northern hemisphere [159]. Hoffman et al. [83] developed a quantitative statistical clustering technique termed Multivariate Spatio-Temporal Clustering (MSTC), which can discover regions with similar environmental characteristics, e.g., the dry high-altitude weather of North American and Asian winters, and the warming weather in Antarctica and western Greenland. White et al. [240] employed the k-means method to generate climate and vegetation clusters, which are then used to infer phenological responses to climate changes. Gu et al. [69] introduced a hybrid estimation method that combines the k-means clustering algorithm with an ANN model to reveal the seasonal variation patterns of sea surface temperature (SST) and salinity in the Indian Ocean. Moreover, Rafael et al. [157] applied the dual Self-Organizing Map (SOM) method to analyze ocean salinity and current data from 1993 to 2012 and uncovered the ocean circulation and its variability patterns, revealing recurrent circulation patterns during different seasons.

Although there are already some studies on ST clustering, the physical meaning and significance of the generated clusters are often debatable. Moreover, there are no guarantees to find meaningful ST patterns because of the high spatial and temporal variability in ocean data. Therefore, developing an effective ST clustering method to produce clustering patterns with physical meanings is still a big challenge for ocean science.

4.3.3 Empirical Orthogonal Function analysis. One of the most fundamental tools in ST pattern finding is Empirical Orthogonal Function (EOF) analysis. EOF is synonymous with the eigenvectors in the traditional eigenvalue decomposition of a covariance matrix [80]. According to Cressie and Wikle [44], EOF analysis is simply principle component analysis (PCA) in the discrete case. In the continuous case, EOF is a Karhunen-Loeve (KL) expansion.

EOF analysis has been traditionally used to identify a low-dimensional subspace that best explains the ST variance of ocean data. In order to better understand the spatial distribution characteristics of the SST in the North Pacific, the EOF method [102] is used to analyze the variability of SST during 1980-2020, and three spatial distributions with large variance contribution were obtained, as shown in Fig. 19. By identifying the dominant spatial structures and their evolution over time, we can discover clear ST patterns. For instance, Harika and Virendra [162] utilized the EOF method to identify three broad divisions of the ocean region—western, central, and eastern—based on seasonal ice mass gain or loss from satellite data. In sum, EOF is a powerful analysis method that has been widely used in ocean science. However, the existing versions of EOF are slightly out of date, and there is a need to develop new EOF-based methods to take full advantage of the large amount of ST ocean data and the advanced STDM techniques.

4.3.4 Spatial-temporal correlation mining. Correlation mining in ocean aims to analyze the relationship between ocean variables, e.g., understanding ocean-atmosphere interaction, studying the effects of climate change, and finding the hidden correlations of teleconnection patterns. Various methods, including linear analysis methods and statistical decomposition methods, have been proposed for ST correlation mining in ocean. For example, Chen et al. [41] used linear regression to explore the correlations between different oceanic regions and the fire activities in the Amazon, which demonstrates the interconnectedness of oceanic and terrestrial systems. Furthermore, Liu et al. [145] used linear analysis to reveal a significant correlation between forest resources and SST in the western-north Pacific Ocean area, indicating the influence of oceanic conditions on terrestrial ecosystems. In practice, finding the underlying correlation in the ocean is of high interest to us, but it is still a difficult task that requires prior oceanic knowledge and tons of experiments.

4.4 Spatial-temporal Anomaly Detection

Anomalies refer to the sets of observations that deviate from expected behaviors as compared with other observations. ST anomaly detection in ocean domain is an important task used in a wide variety of ocean applications. For example, trajectory anomaly detection can be used to detect whether a ship is currently undertaking a voyage that may cause an accident or whether it has changed its route to avoid bad weather conditions. In this section, we summarize three typical ST anomaly detection tasks, i.e., trajectory anomaly detection, sensor time-series anomaly detection, and satellite image anomaly detection, for STDM in ocean.

4.4.1 Experiments settings. For ST anomaly detection in ocean, the data are collected from various sources such as satellites, sensors, and buoys. Experimental settings thus differ according to the data types. In general, for ST anomaly detection, we usually use clustering methods and probabilistic methods for trajectory data, RNN-based models for time-series data, and CNNs for image data. Commonly used metrics include precision, recall, F1-score, and ROC curves. Detected anomalies are typically analyzed and visualized using heatmaps and time-series plots to provide detailed insights. Specifically, a unique challenge with trajectory data is the lack of labeled data, resulting in most studies relying on case studies to validate model performance.

4.4.2 Trajectory anomaly detection. During the voyage of the ship, various abnormal situations may be encountered, such as equipment failure, rocking and collision, and illegal activities. It is

of high significance to implement effective trajectory anomaly detection, which enables timely detection and notification of abnormal events, and helps quickly take measures to protect property safety and people safety. With over 1,490,776 ships tracking worldwide [242], it is difficult and time-consuming to manually find anomalies. Therefore, automatically analyzing the trajectory data to quickly and accurately detect anomalies is of high necessity. To this end, many trajectory anomaly detection methods have been proposed, and these methods can be roughly divided into two categories, i.e., rule-based methods and learning-based methods. These methods primarily focus on identifying abnormal behaviors in the trajectories of ships by analyzing spatiotemporal characteristics such as position, speed, and direction.

Concretely, rule-based methods use a set of rules for anomaly detection, which requires a good understanding of the anomalies [204]. For example, Soleimani et al. [204] proposed a near-optimal path method to detect ship trajectory anomalies and provided reasonable explanations for the detected anomalies. Kontopoulos et al. [122] introduced a real-time system for detecting AIS switch-offs as a typical anomaly, in which vessels turn off their transponders to conceal their locations. However, in practice, it is difficult to design a complete set of rules to cover various trajectory anomalies. Moreover, rule-based methods are often time-consuming and labor-intensive, limiting their applications.

For learning-based methods, many researchers utilize stochastic methods and machine learning methods, e.g., the classification model [53], gaussian process [186], gaussian mixture model [13], density estimation model [187], and Bayesian network [60], to achieve trajectory anomaly detection. For example, Fahn et al. [53] proposed a typical classification method based on SVM and KNN to classify ship trajectories for detecting the abnormal ones. However, classification-based detection methods require manually labeling the trajectories and are prone to the risk of overfitting [75]. To solve this problem, Han et al. [76] introduced the density-based clustering method DBSCAN to learn the distribution of trajectories without labeling. Xie et al. [250] developed the Gaussian Mixture Variational Autoencoder (GMVAE) using an unsupervised classification method and achieved a high detection rate (91.26%). Martha et al. [58] combined autoregressive and cluster analysis to detect anomalies in maritime navigation trajectories. To further capture the hidden and deep correlations, Duong et al. [163] proposed GeoTrakNet to utilize neural networks to learn the probability representation of AIS trajectories for detecting trajectory anomalies. Fig. 20 visualizes the results of three typical trajectory anomaly detection methods on the same dataset, where the GeoTrakNet achieves the best performance. Kexin et al. [129] proposed an adaptive vessel trajectory anomaly detection model based on transfer learning and transformer architecture, which introduces multiple attention modules to mine the dynamic dependencies between data points in the trajectory sequence. David et al. [172] proposed a context information extraction process over Automatic Identification System (AIS) real-world ship data, building a system with the capability to extract representative points of a trajectory cluster. Furthermore, Venskus et al. [217] proposed a maritime automated identification system using a self-organizing map to detect ship anomalies.

Although there exist many methods for ship trajectory anomaly detection in ocean, an objective and fair comparison between these methods is hardly possible due to closed evaluation datasets and missing ground truth for anomalies. Therefore, it is worthwhile to further explore unsupervised or semi-supervised trajectory anomaly detection methods based on the large volume of unlabeled trajectory data and limited labeled data.

4.4.3 Sensor time-series anomaly detection. Sensor time-series anomaly detection focuses on analyzing the time-series data, e.g., temperature, salinity, and current speed, collected by ocean sensors to identify abnormal variations in environmental conditions. Many in-situ sensors are usually located in harsh environmental conditions and transmit the collected data across networks. Hence,

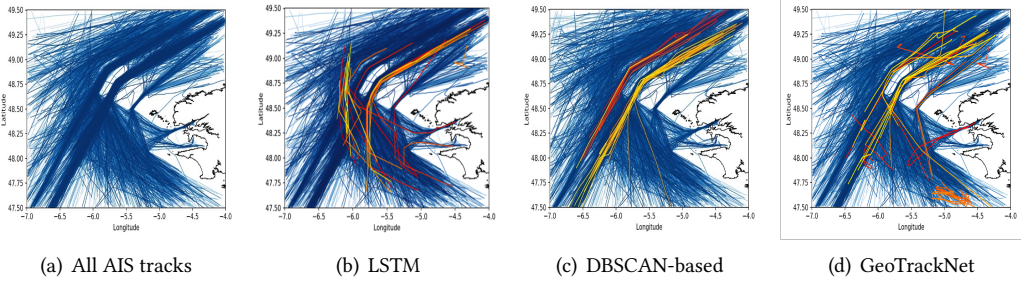


Fig. 20. The visualization of AIS trajectories and the corresponding detection results of three trajectory anomaly detection methods [163] from January 1 to March 31, 2017, where blue color indicates normal trajectories and the other colors indicate the detected abnormal trajectories.

the collected data usually contain a series of outliers and anomalies. Detecting these outliers and anomalies is important for improving the quality and reliability of the ST ocean datasets. To this end, the major difficulty is to differentiate the true anomaly rather than the regular fluctuation, which requires a good understanding of the corresponding environmental circumstances. Researchers have developed many automated statistical and machine-learning methods to jointly use spatial and temporal information for detecting sensor time-series anomalies. For example, Anbaro [12] used an ST ARIMA model to define the coherent ST neighborhoods and then detected the outliers, which have their values significantly different from the mean of nearby ST neighborhoods. To analyze the anomaly from the typical statistics, Kumars [152] utilized three typical outlier detection algorithms, i.e., Box-plot, Local Distance-based Outlier Factor, and Local Outlier Factor, to detect the outliers in wave height time-series records. Recently, Chen et al. [36] proposed an outlier detection method based on the neighborhood rough residual network to detect outliers in IoT-Enabled Maritime Transportation Systems.

4.4.4 Satellite image anomaly detection. Satellite image anomalies refer to defective remote sensing images that may contain abnormal color, color cast, and unknown objects. Satellite image anomaly detection has a broad application, e.g., ship invading detection and extreme cloud detection. Detecting image anomalies is more difficult than detecting the anomalies in trajectory data and time series data because visual features are more difficult to capture than numerical features. Marino et al. [153] proposed an incoherent dual-polarization detector to identify the anomaly of small icebergs in satellite images. Han et al. [77] proposed a spectral anomaly detection method based on dictionary optimization with sparse and low-rank constraints, where the error matrix that cannot be fully expressed by the optimized spectral dictionary is defined as an anomaly. Christopher et al. [203] developed a Robust Principal Component Analysis (RPCA) approach to distinguish clouds and other transient anomalies in satellite images.

Recently, various CNN-based methods have been applied for satellite image anomaly detection due to their high capability in analyzing image data and achieved promising detection results [222, 227]. For example, Wang et al. [227] proposed a spatial pyramid pooling network with the multivariate Gaussian distribution to detect ships by regarding a ship as an abnormal ocean area. However, most existing satellite image anomaly detection methods still rely on labeled images with manual expert annotations and cannot take full advantage of the large amount of unlabeled satellite image data.

5 FUTURE OPPORTUNITIES

The progress in STDM for ocean science has imposed significant impacts on various ocean applications, as discussed above. However, there are still some open issues that require continuous efforts from both computer science and ocean science. In this section, we highlight multiple promising research directions for further advancing the STDM techniques in ocean science.

5.1 Designing large foundation models for ocean science

Recently, the large foundation models (e.g., BERT [46], GPT [59], and ViT [179]) have received tremendous popularity in computer science and surpassed many state-of-the-art machine learning models by pre-training on big datasets and fine-tuning for different downstream tasks [55]. In ocean science, large ST ocean datasets of wide spatial coverage have been collected for various oceanic tasks, which lays the solid foundation for designing unified large models. Many latest methods (e.g., ClimaX [165], Fuxi [35], Pangu-Weather [22], and Fengwu [34]) are trained with a large amount of ocean data, and can accurately predict the future results [232]. For example, the Pangu-Weather forecasting model is trained on 39-year global weather datasets and achieves great performance on different downstream forecasting tasks such as medium-range weather forecasting and extreme weather forecasting. Ideally, large foundation models should be trained on multi-source ST ocean datasets to capture the underlying patterns and regularity among different data sources and produce more accurate analysis results for various tasks. Unfortunately, these are still under-explored in existing studies. Therefore, designing large foundation models in the domain of ocean science presents excellent opportunities to incorporate various tasks and diverse data sources, ultimately improving the results of various STDM tasks.

5.2 Fusing physical models with data-driven models

Over the past centuries, numerous physical models (e.g., ocean calculation models, numerical ocean models, and physical oceanography models [205]) have been developed and play a crucial role in addressing various oceanic applications. They employ a series of functions and theories to simulate physical processes within the ocean, such as ocean circulation and heat transfer. These methods perform well on many oceanic tasks but rely on the factors determined by expert knowledge. With the advancements in data science, data-driven models, which do not require extensive expert inputs, have gained attention for their ability to capture hidden information by utilizing historical data for training [228]. Some recent studies find that it is reasonable and feasible to combine physical models with data-driven methods [219]. To this end, physics-aware AI, physics-informed machine learning, and physics-guided machine learning [9, 108] have been introduced. These methods combine the advantages of physics models and data-driven models and can provide more robust and accurate results in many fields, such as robotics, civil engineering, and finance. Specifically for ocean science, the physical-guided models can achieve high physical consistency and reduce the uncertainty of results. Taking the SST prediction as an example, Arka et al. [100] integrate traditional physical laws (e.g., temperature density and energy conservation) and recurrent graph networks to predict SST. However, the studies on Physical-guided STDM in the ocean are limited, and most of them are focused on the prediction of ocean factors (e.g., temperature, ice, and salinity [156, 245]). Multiple obstacles still exist in fusing physical models with data-driven models, e.g., the difference in data formats, problem definitions, and model structures. Therefore, designing a general paradigm to fuse physical models with data-driven models is an interesting and promising research direction.

5.3 Enhancing the models' generalizability with continuous learning

Lots of STDM models operate on the assumption of independent and identically distributed (IID) training and test data [221]. Despite showing promising results, STDM should be substantially improved through continuous learning to perform good generalization ability on various unseen scenarios. Continual learning [225], also referred to lifelong or incremental learning, is the process of updating a model over time as new data emerges. Given the ever-evolving nature of ocean patterns, continuous learning is particularly beneficial. It enables models to adapt to new changes and enhances their predictive accuracy and robustness. However, the implementation of continuous learning in models poses some challenges. First, models undergoing learning can experience a phenomenon known as "catastrophic forgetting" where a model may forget previously learned patterns after being updated with new data. Balancing the maintenance of model stability while still allowing it to learn from new data poses a significant challenge. Second, the computational power and storage capacity of a device inherently limit on-device machine learning. Deploying and updating large climate models on devices with limited resources could be difficult. Techniques for model compression, efficient computation, and selective model updating are essential to make on-device adaptation of models feasible. Despite these obstacles, continuous learning presents a promising avenue for enhancing the performance and generalizability of STDM models.

5.4 Improving the interpretability of deep STDM methods

Many STDM approaches are based on deep-learning models, e.g., CNN, RNN, and Transformer, and achieve good performance on various tasks. However, these approaches are typically regarded as black boxes with poor interpretability [54, 121]. The interpretability of STDM methods means the ability to present and explain the model behaviors in understandable forms to humans, which enables users to easily make reasonable and convincing decisions [49, 104]. For ocean science, it is of high importance to build a connection between the STDM results and the underlying physics to provide valuable advice for various ocean applications, e.g., the warning of extreme weather conditions. Although attention mechanisms have been used in some previous STDM studies for ocean science to increase the model interpretability (e.g., periodicity and local spatial dependency), developing more interpretable STDM methods to reveal the natural laws of the ocean remains an open problem [120, 271].

5.5 Fusing multi-source ocean datasets of different modalities

As discussed in Section 2, the ocean data used in STDM tasks usually has multiple sources, including satellite data, in-situ data, ship data, and reanalysis data, and these datasets are often in different modalities. Fusing multi-source datasets can obtain comprehensive information to help STDM models perform better than single datasets. Although there are already some studies on data fusion (cf. Section 3.4), there are still many challenges in fusing multi-source datasets. First, most existing ocean STDM methods focus on fusing different data sources for the same ocean factor (e.g., SST) in single tasks (e.g., SST prediction) and cannot combine the observations of multiple factors (e.g., SST, ocean current, and Chl-a) for multiple tasks (e.g., SST prediction, current prediction, and Chl-a prediction) at the same time. Second, it is difficult to handle the heterogeneity in spatial and temporal resolutions for different datasets, e.g., image satellite data, gridded reanalysis data, and ST points data. Recently, some researchers have used transfer learning and meta-learning to fuse different ocean data sources and introduce the pre-trained models in computer vision and urban computing [241] to capture the features of multi-modal ocean datasets. However, the challenges mentioned above are still not well addressed and require deeper investigation in the future.

5.6 Developing end-to-end STDM models

Currently, many STDM methods for ocean science require the input ST ocean data to be complete and of high quality. To meet such requirements, data cleaning, data completion, and data fusion are conducted over the original ST ocean data. However, these processes are time-consuming and may lead to the loss of some crucial data information. For example, in the SST prediction task, the missing rate of SST records retrieved from the satellite data may be higher than 80% for some periods and locations due to the cloud coverage [137]. Existing methods for SST prediction usually utilize data completion methods (e.g., history average, optimal interpolation, and GAN-based networks) to fill in the missing values before conducting the prediction. However, these methods ignore the sparse distribution of original data and the reasons behind the sparsity (e.g., typhoons and heavy rainfall), which may seriously influence the prediction accuracy. Therefore, developing end-to-end STDM models to learn knowledge and patterns directly from the original sparse ST ocean data is also a promising research direction.

5.7 Adopting self-supervised learning strategy

Self-supervised learning [56, 131, 236] is an effective direction of machine learning where models learn knowledge from the data itself, eliminating the need for manual labeling. This approach emerged from the need to utilize the vast amounts of unlabeled data available in various fields. Nowadays, self-supervised methods [19, 132, 211] are increasingly being utilized in ocean science to enhance data analysis and prediction capabilities. They leverage vast amounts of unlabeled ocean data, such as satellite data, in-situ data, and ship data, to learn patterns and features without the need for extensive manual labeling. For example, automated anomaly detection of ships using self-supervised learning models can facilitate early warning systems by identifying unusual patterns in ocean conditions and detecting anomalies in ship trajectories. However, self-supervised learning in ocean science still encounters several challenges. First, data quality and availability can be inconsistent, thus impacting model accuracy. Second, the complexity of ocean systems makes it difficult to learn the intricate correlations and dynamic patterns in ST ocean data without labels. It is thus necessary to develop more robust and general self-supervised methods based on the large volume of ST ocean data.

6 CONCLUSION

The increasing numbers of satellites, buoys, and other ocean observation facilities have generated a flood of ST ocean data, which makes it possible to develop STDM methods for various ocean applications, e.g., weather forecasting and typhoon detection. The past decades have witnessed the rapid development of STDM techniques for ocean science, which enable us to uncover the underlying ST dependencies within ocean data for solving the challenging problems in ocean science. This survey provides a comprehensive overview of the existing STDM studies for ocean science, including the available ST ocean datasets and their unique characteristics, data visualization tools, data quality enhancement methods, and the methodologies for different categories of STDM tasks. In addition, some promising research opportunities for future research are also pinpointed. We hope that this survey can help computer scientists identify important research issues in ocean, and inspire researchers in ocean science to apply advanced STDM techniques to a variety of ocean applications.

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