

REVIEW

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Remote sensing insights into ocean fronts: a literature review

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Abstract

By providing valuable data that allow scientists to study various oceanographic characteristics on a global scale, remote sensing techniques have considerably advanced our understanding of ocean fronts. Ocean fronts involve the interaction of water masses with specific physical properties such as temperature, sea color, salinity, and density. In particular, ocean fronts can act as barriers, impeding the movement of water masses and leading to the convergence or divergence of nutrients and marine species. Research on ocean fronts and their impact on marine biodiversity and physical environments has recently become popular. This paper introduces ocean front research progress based on remote sensing images, including research material, methods, limitations, and possible future research directions. The latest research on spatiotemporal variation in ocean fronts has substantially enhanced our understanding of the interaction of water masses with specific physical properties in the ocean.

Keywords Ocean front, Remote sensing, Oceanographic characteristics, Object detection, Image classification, Time-series prediction

1 Introduction

An ocean front, a typical dynamic feature of the ocean, is a region in the ocean where two water masses with different physical properties, such as temperature, salinity, and density, come into contact and interact. Ocean fronts play an important role in ocean circulation and the transport of heat, nutrients, and marine organisms (Chapman et al. 2020). Ocean fronts are integral to global ocean circulation patterns. Studying these features contributes to our understanding of large-scale ocean movements, which in turn influence climate regulation and the transport of heat and nutrients around the planet. In

addition to their physical importance, fronts have ecological value (Hense et al. 2003; Liu et al. 2018; Allen et al. 2020; Gangrade and Franks 2023). Ocean fronts play a pivotal role in influencing climate and weather patterns. Investigating these regions improves the understanding of how oceanic processes impact global weather systems. This knowledge is vital for predicting climate change and extreme weather events. In addition, ocean fronts are often biodiversity hotspots, hosting a rich variety of marine life. Understanding these dynamic boundaries is essential for understanding the intricate ecosystems in these regions. By studying ocean fronts, we gain insights into the interactions among different marine species and their dependencies on specific environmental conditions. Identifying and studying these areas can reveal critical information about species distribution, migration patterns, and the overall health of marine ecosystems. This knowledge is crucial for conservation efforts and sustainable management of marine resources. Human activities such as fishing and shipping are often concentrated around ocean fronts. Investigating the impact of these activities on the delicate balance of marine ecosystems

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helps in developing effective management and conservation strategies. This help is particularly important for ensuring the sustainability of fisheries and minimizing environmental degradation.

Satellite imagery enables the detection and monitoring of ocean dynamic features on a global scale, allows scientists to track the movement, size, and characteristics of these dynamic features, and provides valuable insights into their behavior and effect on oceanic processes, including the role of oceans in regulating the climate, supporting economies through fisheries and maritime activities, and highlighting the environmental challenges our planet faces. Understanding the complexities of oceans and their intricate interactions is essential for addressing environmental challenges and safeguarding the health and biodiversity of marine environments for future generations. This review uncovers a wealth of research focused on the application of remote sensing (RS) technologies to study ocean front dynamics and their vital role in various oceanic processes. Furthermore, this review highlights the advancements in machine learning techniques that have enabled the detection and analysis of ocean front characteristics.

The contents of this review are illustrated in Fig. 1. In Section 2, a brief description of the basic characteristics of ocean fronts is provided. In Section 3, we describe the data materials used in ocean front research. Section 4 elucidates recent research progress on ocean front spatial and temporal variation characteristics. These studies are crucial for understanding the interactions between water masses, including upwelling and downwelling processes. These interactions have considerable implications for marine ecosystems, fisheries, and climate patterns. Furthermore, studies covered in Section 5 demonstrate how ocean fronts can influence ocean ecology and the environment. Particularly, this review encompasses investigations into the influence of ocean fronts on the distribution of marine organisms, as they often act as primary habitats of biological productivity. In Section 6, the review discusses the challenges and limitations associated with more in-depth research on ocean fronts. In

Section 7, we conclude our review by highlighting the important contributions of RS technology to oceanography and underscore its crucial role in advancing our knowledge of ocean front dynamics and their far-reaching implications for marine ecosystems and climate systems.

2 General knowledge about ocean fronts

The fronts are regions where water masses with distinct characteristics, such as temperature, density, and nutrients, meet and interact. The interaction of these water masses forms strong and active fronts, which are often accompanied by horizontal shear and baroclinity instability. Horizontal shear refers to the change in the velocity or direction of ocean currents across a horizontal distance. In contrast, baroclinic instability is caused by horizontal density gradients between different water masses. These factors contribute to the generation of cyclonic (clockwise) and anticyclonic (counterclockwise) circulations or eddies on both sides of a strong front, with jets of water flowing between them.

2.1 Downwelling and upwelling of ocean fronts

Within a frontal zone are horizontal gradients of temperature, density, and nutrients. The water masses undergo deformation as they converge at the front, creating a flow with a steeply sloped isopycnal surface (surface of constant density). In geostrophic equilibrium, denser water flows downward along these isopycnals from the colder side of the front and spreads beneath the lighter water on the warmer side, which helps stabilize the front. The front characteristics are further shaped by the presence of downwelling and upwelling regions (Matano and Palma 2008). Downwelling occurs on the colder side of the front because of the convergence of water masses, leading to the sinking of water. On the warmer side, downwelling is less pronounced because of the negative divergence of the flow, which means that the water is spreading apart. These vertical motions are associated with secondary circulation across the isopycnals and are ecologically important because they transport nutrients to the sea surface.

General knowledge	Materials	Research progress	Influence on marine environment	Limitations and opportunities
	Sea surface temperature			Temperature reconstruction
Downwelling and upwelling	Sea surface height	Ocean front detection	Transporting nutrients	Abnormal climate events
	Sea surface density			Interdisciplinary research
Formation mechanism	Sea level anomaly	Ocean front classification	Concentrate plankton	Data resolution
	Sea surface salinity			
Physical characteristics	Chlorophyll concentration	Ocean front prediction	Alter fish community structures	Machine learning methods

Fig. 1 Summary of the entire article

Increased nutrient availability facilitates the growth and accumulation of plankton (plants and small zooplankton) in the front region.

2.2 Formation mechanism of ocean fronts

A strong front is visually represented as an inclined interface between waters with different characteristics that intersect with the sea surface to form a frontal area. These fronts are dynamic zones in which various oceanographic processes, such as nutrient transport, primary productivity, and the distribution of marine species, are strongly influenced. Particularly, the intensification of the horizontal density gradient during frontogenesis accelerates the geostrophic jet, disrupting the balance between the density gradient and the Coriolis force. Frontogenesis refers to the process by which a front intensifies or forms, typically because of the convergence of different water masses. In response to frontogenesis and the disruption of geostrophic balance, vertical nongeostrophic secondary circulations occur across the isopycnals (lines of constant density). These secondary circulations tend to reduce the slope or dip of the isopycnals, restoring equilibrium. This vertical nongeostrophic circulation plays a vital role in the transport of nutrients.

The frontal area is influenced by different types of instabilities. Mesoscale baroclinity instability causes the frontal jet to meander and form a frontal eddy. Symmetric instability releases the kinetic energy of the frontal jet, increasing the small-scale turbulence and vertical mixing levels at the frontal level. These instabilities contribute to increased biological productivity in the frontal area. In the geostrophic approximation, the horizontal density gradient is balanced by the Coriolis force, which results from the Earth's rotation. However, during frontogenesis and the occurrence of nongeostrophic secondary circulations, this balance is disrupted, leading to complex and dynamic processes within the front. Overall, the interaction of different water masses in the frontal area produces intricate physical and biological processes. Understanding ocean front dynamics is crucial for studying the interactions between different water masses, their impacts on marine ecosystems, and their role in shaping climate patterns and the Earth's ocean circulation. RS technologies have played an important role in advancing our knowledge of these complex features and continue to be instrumental in furthering our understanding of the dynamic ocean processes.

As shown in Fig. 2, ocean fronts are primarily driven by wind, which transports warm and cold waters between regions, leading to downwelling and upwelling. In addition, the sun's energy is also an important factor for ocean front formation, as it is unevenly distributed across the ocean's surface. This uneven heating results in

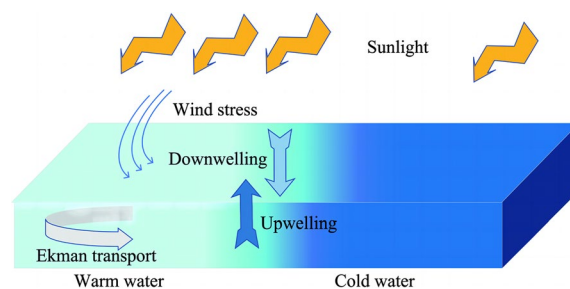


Fig. 2 Possible driving forces for ocean front formation

temperature gradients between the water masses. Furthermore, the Earth's rotation can alter the flow direction of water masses, prompting interactions between different water masses with varying nutrient levels and light availability. In summary, ocean front formation is a complex interplay between wind patterns, temperature gradients, Earth's rotation, and water masses.

2.3 Physical characteristics of ocean fronts

Oceanic fronts range in size from a few hundred meters to thousands of kilometers and exist in the surface, middle, and near-bottom layers of an ocean. Permanent fronts are associated with planetary circulation and strong currents, such as the Gulf Stream and Kuroshio Current (Belkin and O'Reilly 2009; Flor 2010; Kida et al. 2016). According to spatiotemporal scales, ocean fronts can be divided into the following types:

Planetary-scale fronts: Planetary-scale fronts, such as the Antarctic and subtropical fronts, have horizontal extensions of 10–500 km and are usually associated with Ekman transport. Planetary-scale fronts are closely related to the division of global climate zones and atmospheric circulation.

Mesoscale fronts (Xing et al. 2023): Mesoscale fronts are characterized by a relatively fixed position and a certain seasonal variation. For example, the temporal variation in tidal fronts is related to the tidal cycle and seasons. The spatial scale of mesoscale fronts usually ranges from tens to hundreds of kilometers and can persist for several weeks to months.

Mesoscale fronts contribute to ocean mixing and the exchange of materials between different water layers and are efficient transporters of water, heat, and nutrients in the ocean. They are critical components of the oceanic system and have far-reaching implications for ocean circulation, nutrient cycling, and the distribution of marine species.

Submesoscale fronts (Cao and Jing 2022): Submesoscale fronts are generated by the interaction of large-scale turbulence and mesoscale eddies (Thomas

et al. 2008; McWilliams 2016). The spatial scale of sub-mesoscale fronts ranges from several kilometers to tens of kilometers, and its temporal scale ranges from several days to tens of days.

Small-scale fronts: Small-scale fronts are very dynamic and flickering ocean fronts. The spatial scale of small-scale fronts ranges from several hundred meters to several kilometers, and their temporal scale ranges from several hours to several days.

According to the physical properties of water masses, ocean fronts can be divided into the following categories:

- (1) Thermal fronts are defined by sharp temperature contrasts between adjacent water masses. They typically occur where warm and cold water masses meet, resulting in a substantial temperature gradient across the front.
- (2) Salinity fronts are characterized by differences in salinity between the two water masses. They form where waters with different salinities mix, creating a distinct boundary.
- (3) Density fronts are defined by variations in the water density. These fronts are influenced by temperature and salinity differences and are crucial for understanding ocean circulation and mixing processes.
- (4) Chlorophyll fronts exhibit an important change in the concentration of chlorophyll-*a*. Chlorophyll fronts are of particular interest to oceanographers and marine scientists because they often coincide with areas of increased biological productivity.

3 Materials acquisition

Temperature, density, salinity, and chlorophyll concentration are basic physical properties of seawater. The geophysical characteristics of ocean processes, such as ocean circulation, ocean fronts, eddies, and other related studies, rely on the physical properties of seawater. The observation of these properties can be divided into two types: on-site observation and remote observation using RS technology. On-site observation is the most direct and accurate means of obtaining observation data; however, because of the constraints of equipment and environmental factors, the spatiotemporal scope of its observation is greatly limited. In comparison, satellite RS technology can provide long-term observations covering the whole world.

Currently available satellite RS data include sea surface temperature (SST), sea surface height (SSH), sea surface density (SSD), sea level anomaly (SLA), sea surface salinity (SSS), photosynthetically active radiation, surface flow, and chlorophyll concentration. SSH data are available from the National Center for

Environmental Information (NCEI, <https://www.ncei.noaa.gov/>) of the National Oceanic and Atmospheric Administration (NOAA). SSD data are estimated based on SST, SSS, and atmospheric pressure data. SSS and SSD data were obtained from the Soil Moisture and Ocean Salinity (SMOS) Earth Explorer mission (<https://www.catds.fr/Products/Available-products-from-CPDC>).

SST data are available from the NASA moderate-resolution imaging spectroradiometer (MODIS) satellite at 9 km resolution, from the advanced very-high-resolution radiometer (AVHRR) at 5 km resolution, and from the Physical Oceanography Distributed Active Archive Center, which can provide multiscale ultrahigh resolution SST data with a resolution of 0.01×0.01 degrees. SST data can be acquired using infrared sensors (MODIS and AVHRR Pathfinder), such as spectroradiometers, and passive microwave sensors, such as the advanced microwave scanning radiometer. Generally, a spectroradiometer can capture high-resolution data, but these data are contaminated by clouds, whereas the microwave scanning radiometer can capture data with lower resolution, but these data are unaffected by clouds. Therefore, microwave scanning radiometers are often used to supplement spectroradiometers, particularly in areas where cloud cover is a severe problem, such as high latitudes and polar regions.

Nevertheless, current RS observations cannot address the need for the study of submesoscale oceanic dynamics and small-scale air-sea interactions. In response to this problem, many countries jointly proposed the SEASTAR mission, which intends to provide data at a resolution of 1 km. In addition, to achieve higher resolution SST and ocean color data, hybrid datasets are proposed to fuse on-site observations and satellite RS observations. The fused data with a temporal resolution of one day can be accessed from NOAA, the National Environmental Satellite, Data, and Information Service (NESDIS), and the NCEI (<https://www.ncei.noaa.gov/>).

4 Research progress on ocean front spatiotemporal characteristics

Part of the research on ocean front spatiotemporal characteristics is classified and illustrated in Table 1. The current research directions on ocean front spatiotemporal characteristics mainly include ocean front detection, classification, prediction, and analysis. Popular ocean front detection methods mainly include analysis-based methods and data-driven methods. Analysis-based methods, such as microcanonical multifractal formalism (MMF) (Tamim et al. 2015; Yang et al.

Table 1 Methods proposed for analyzing ocean front spatiotemporal characteristics

	Detection	Classification	Prediction	Analysis
Ten years ago	Belkin and O'Reilly 2009	—	Griffa et al. 2007	Mahadevan and Tandon 2006; Flor 2010; Ferrari 2011; Taylor and Ferrari 2011; Lévy et al. 2012
Recent 10 years	Tamim et al. 2015; Yang et al. 2016	Prants et al. 2014b; Lima et al. 2017	Yang et al. 2017; Zhang et al. 2017	Prants et al. 2014a; Baltar et al. 2016; Kida et al. 2016; Kahru et al. 2018; Lévy et al. 2018; Scales et al. 2018
Recent 5 years	Sun et al. 2019; Li et al. 2021; Wang et al. 2023; Xing et al. 2023; Zhu et al. 2023	Kim et al. 2022; Yang et al. 2022	—	de Verneil et al. 2019; Archer et al. 2020; Belkin 2021; Prants 2022

2016) and the Lagrangian method (Prants 2022), rely on analyzing the singular index of RS images.

4.1 Analysis-based ocean front detection methods

To detect the location and track the evolution of ocean fronts in the ocean, Prants et al. (2014a, b) and Prants (2022) propose computing Lagrangian indicators. Lagrangian indicators contain not only information about the current characteristics of water masses, such as their temperature, salinity, and density but also information about their origin. Such information includes the trajectory and time of existence of ocean fronts.

The Lagrangian method is based on a singular expansion of the evolution matrix computed by linearized advection equations. In contrast to invariant manifolds in the theory of dynamical systems, manifolds in ocean flows exist for a finite time. They can be approximately located using the extrema of the scalar fields of the finite-time Lyapunov exponent (FTLE) accumulated over a certain period, and the finite-size Lyapunov exponent (FSLE) accumulated until a certain specified distance between pairs of initially proximal particles is reached. FSLE and FTLE diagnostics are used to analyze the dynamics of a strong front, revealing a fine structure that indicates the convergence of different water masses from separate sources. In this method, the FTLE is calculated as follows:

$$\lambda = \frac{\ln \sigma(t, t_0)}{t - t_0}, \quad (1)$$

where $\sigma(t, t_0)$ is the maximum singular value of the evolution matrix, and $t - t_0$ is the integration time. The FSLE is calculated as follows:

$$\lambda_s = \frac{\ln(\sigma_f/\sigma_0)}{\tau}. \quad (2)$$

The values of λ are calculated by integrating the advection equations until time τ , when two particles, initially

separated by a distance σ_0 , diverge over a distance σ_f from each other.

Compared with the Lagrangian method, the MMF method not only considers the local maximum gradient but also comprehensively considers the context information of the area. The MMF method can not only obtain the global maximum gradient but also avoid local optimal errors. In the MMF algorithm, a Fourier transform is used to obtain the frequency domain of the SST image. Then, based on the context information of the detection area, a wavelet transform is applied to calculate the singularity index at each pixel of the image. The key point of MMF is the accurate computation of the singular exponent (SE) value $h(\vec{x})$ at each pixel. The formula for calculating the SE at each pixel x is as follows:

$$h(\vec{x}) = \frac{\log(\tau_\psi \mu(\vec{x}, r_0))}{\log r_0} + o\left(\frac{1}{\log r_0}\right), \quad (3)$$

where N and M are the size of the image, and $r_0 = \frac{1}{N \times M}$ is used for image normalization. $\tau_\psi \mu(\cdot, r_0)$ represents the wavelet projection. $h(\vec{x})$ represents the SE at pixel x that is the strongest temperature variation and is used for analyzing the ocean front. Figure 3 displays the detection results of ocean fronts in major ocean current regions.

4.2 Data-driven ocean front detection methods

In recent years, data-driven methods have been proposed to detect ocean fronts (Sun et al. 2019; Li et al. 2021; Wang et al. 2023; Zhu et al. 2023). These methods are designed to learn the mapping relationship between the input and output data so that the detection result can meet certain requirements. Several classic deep learning models are listed as follows:

- (1) The fully convolutional network (FCN) (Long et al. 2015) represents a convolutional neural network architecture that eschews fully connected layers in favor of an exclusive reliance on convolutional

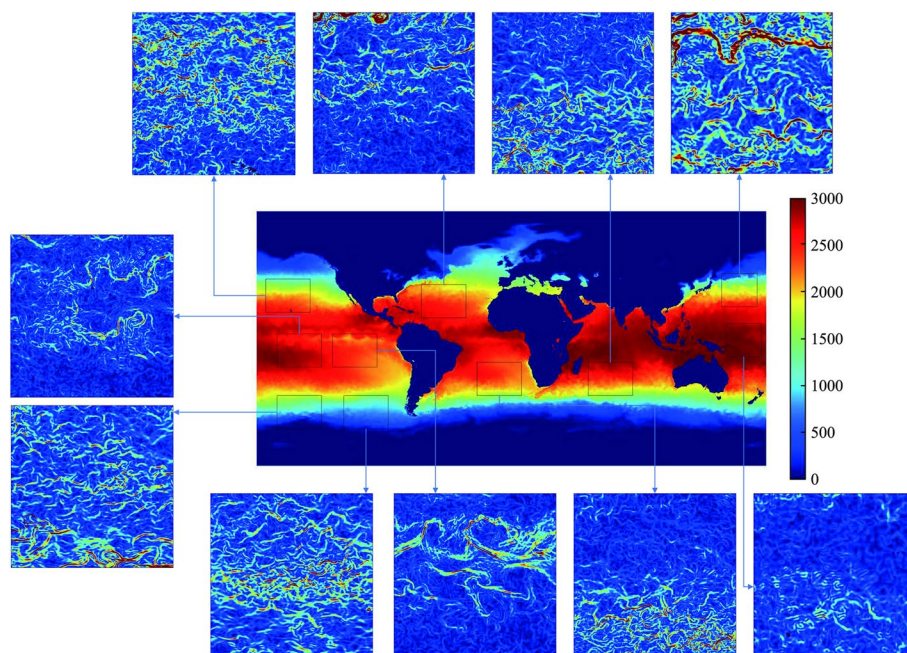


Fig. 3 Ocean front detection result, the color bar represents the temperature of sea surface (100/°C). The central image displays the global SST image, and the surrounding images show the ocean front images detected in the corresponding regions

operations. The integration of convolutional layers within the FCN framework augments spatial dimensions, thereby amplifying the size of the feature maps. This augmentation is instrumental in producing refined and detailed output, thereby enhancing the network’s ability to yield high-resolution results.

- (2) U-Net (Ronneberger et al. 2015) is a popular convolutional neural network (CNN) architecture that is commonly used for image segmentation tasks. A network based on U-Net is designed and applied to identify and delineate front boundaries from satellite images.
- (3) SegNet (Badrinarayanan et al. 2017) employs max-pooling indices as a strategic mechanism for preserving crucial location information about the maximum pixels within a network. This innovative approach effectively mitigates the issue of information loss that may arise during the pooling process, ensuring the retention of spatial details critical for accurate segmentation tasks.
- (4) SPNet (Zhao et al. 2017) incorporates a pyramid pooling module as a pivotal component to aggregate contextual information from varying scales. This sophisticated module facilitates the integration of background knowledge, which proves highly instrumental in semantic segmentation. The widespread adoption of PSPNet within academia under-

scores its efficacy and utility in addressing the intricacies associated with semantic segmentation tasks.

- (5) DANet (Hu et al. 2018) demonstrates a notable capability in capturing intricate pixel-level correlations by employing two distinctive attention mechanisms: channel correlation and position correlation. These sophisticated attention mechanisms serve the purpose of dynamically weighting the importance of channels and positions within a network, thereby enabling enhanced modeling of intricate relationships between pixels. The integration of such attention mechanisms into DANet exemplifies its adeptness in leveraging contextual information to discern and exploit pixel-wise correlations, contributing to its efficacy in diverse image analysis tasks.
- (6) HANet (Fu et al. 2019) introduces a height attention mechanism to augment its feature extraction capabilities. This augmentation facilitates the model in discerning and incorporating the nuanced relationships between the vertical dimension (height) and semantic classes. By integrating this height attention mechanism, HANet achieves an enhanced capacity to capture and exploit vertical contextual information, thereby elevating its proficiency in understanding the vertical distribution of semantic elements within the input data. The strategic incorporation of height attention within HANet underscores its commitment to refining the modeling of

spatial dependencies across different dimensions, contributing to improved performance in tasks involving semantic segmentation.

- (7) LSENet (Xie et al. 2022) utilizes a channel supervision unit structure and a location attention mechanism to improve ocean front detection accuracy. The data and code are available at <https://github.com/liusha1155/LSENET>.

An evaluation and comparison of these object detection methodologies are presented in Table 2. The fundamental concept underlying intersection over union (IoU) lies in quantifying the relationship between the intersection and union of two sets, the ground truth and predicted-object boundaries. A widely employed derivative of the IoU is the mean intersection over union (mIoU), which serves as a prevalent evaluation measure. mIoU provides a comprehensive assessment of the overall accuracy of detection tasks by averaging the IoU scores of the background and ocean front. As shown in Table 2, the ocean front detection accuracy requires ongoing refinement and enhancement. The results contribute to validating the efficacy of these methods, providing valuable insights into their capabilities and suitability for accurate ocean front detection. More recently, some researchers have explored the use of a feature transformation mechanism for object detection (Shi et al. 2020). These methods show great potential for improving ocean front detection accuracy.

4.3 Ocean front classification

Ocean fronts can be conveniently classified into strong and weak fronts according to their intensity. Generally, the stronger the ocean front, the longer its existence, and the higher the possibility of having abundant fish resources. Therefore, classifying ocean fronts is of great importance for ocean fisheries.

Lima et al. (2017) propose employing a CNN for ocean front classification. In detail, they apply a transfer network to classify ocean fronts and fine-tune the network structure to further improve the classification performance. As shown in Fig. 4, their model can classify regions of weak and strong ocean fronts. The classification accuracy achieved using their method is higher than 86%.

Through comprehensive consideration of the position, intensity, and lifetime, an ocean front can be divided into two evolution stages: the enhancement and attenuation stages. To study ocean front evolution, Yang et al. (2022) propose a deep neural network that can recognize and track ocean front evolution processes. Particularly, their method can not only accurately classify the ocean front enhancement and attenuation processes but also record the position variation in the ocean front. Moreover, ocean front evolution includes more than enhancement and attenuation processes. Figure 5 displays four typical ocean front evolution processes: ocean front enhancement, attenuation, splitting, and merging. Overall, ocean front evolution is a new research field with tremendous developmental potential.

Table 2 Performance of different ocean front detection methods evaluated by IoU

	FCN	U-Net	SegNet	PSPNet	DANet	HANet	LSENet
Background	97.70	98.56	97.84	97.93	98.57	98.37	98.59
Front	54.23	66.38	54.31	57.84	66.64	62.71	68.76
mIoU	57.85	69.06	57.94	61.18	69.30	65.68	71.25

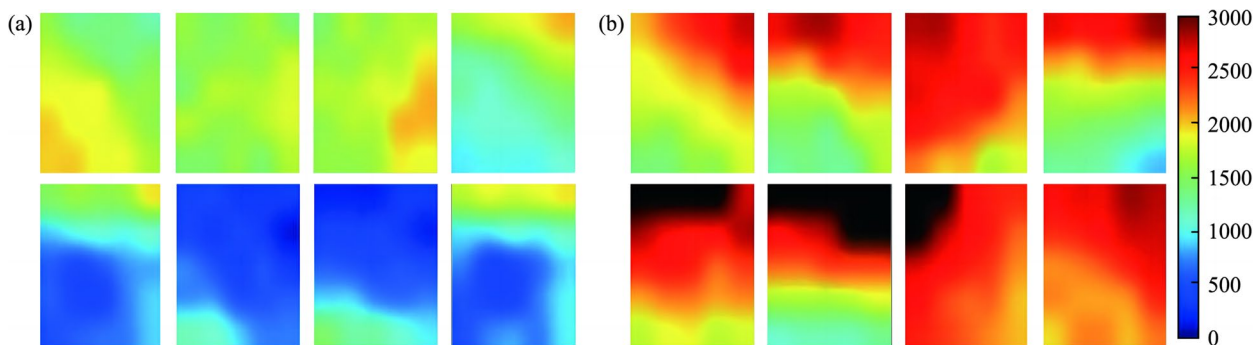


Fig. 4 Ocean front classification result, the color bar represents the temperature of sea surface (100/°C). **a** weak ocean front and **b** strong ocean front

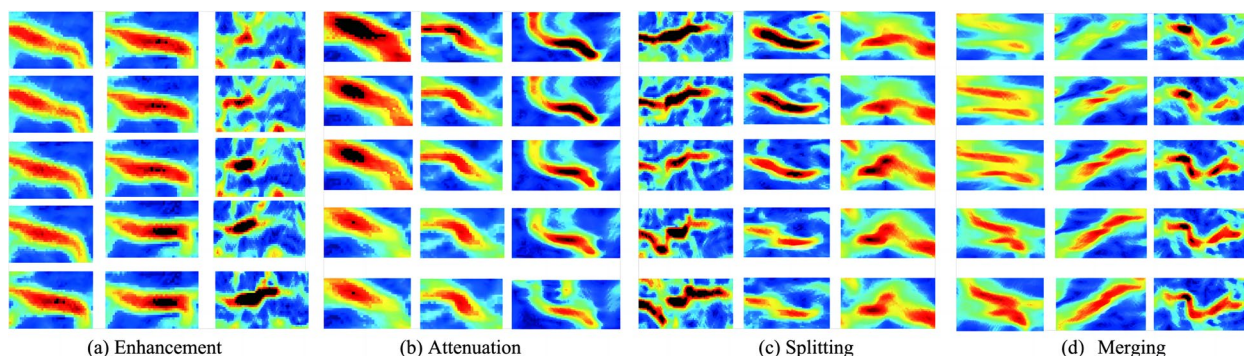


Fig. 5 Typical ocean front evolution processes: **a** enhancement process, **b** attenuation process, **c** splitting process, and **d** merging process

4.4 Ocean front prediction

Data-driven time-series prediction is an active field (Qiu et al. 2019; Wang et al. 2021). Accurate prediction of SST can provide a technological foundation for ocean front prediction. As shown in Fig. 6, the spatial and temporal variation in the SST fronts corresponds to that of the SST.

On the basis of historical SST time series and through continuous automatic iterative updates of parameters, machine learning methods have been successfully applied to predicting the spatial and temporal variations in SST. Based on the historical SST in the previous year, a CNN and long short-term memory (LSTM) network are proposed for SST prediction (Yang et al. 2017; Zhang et al. 2017). In Fig. 7, the first row shows the ground-truth ocean front images, and the second row shows the prediction ocean front images. In summary, the prediction results are consistent with the ground-truth images.

However, the prediction performance decreases with increasing prediction length. As technology advances and our understanding of ocean dynamics improves, ocean front prediction methods will continue to evolve, leading to more accurate and reliable predictions of these essential features in the Earth’s oceans.

5 Influence of ocean fronts on marine environments and marine life

In addition to ocean front observation and identification, recent research has focused on understanding the influence of ocean fronts on marine life and environments (Polovina et al. 2006; Godo et al. 2012; Lévy et al. 2012, 2018; Lehahn et al. 2017; Scales et al. 2018; Belkin 2021; Lu et al. 2022). Previous studies have linked the anomalous warming climate phenomenon in southern California to oceanic winds, surface heat flux, and warm advection, but few studies have considered its

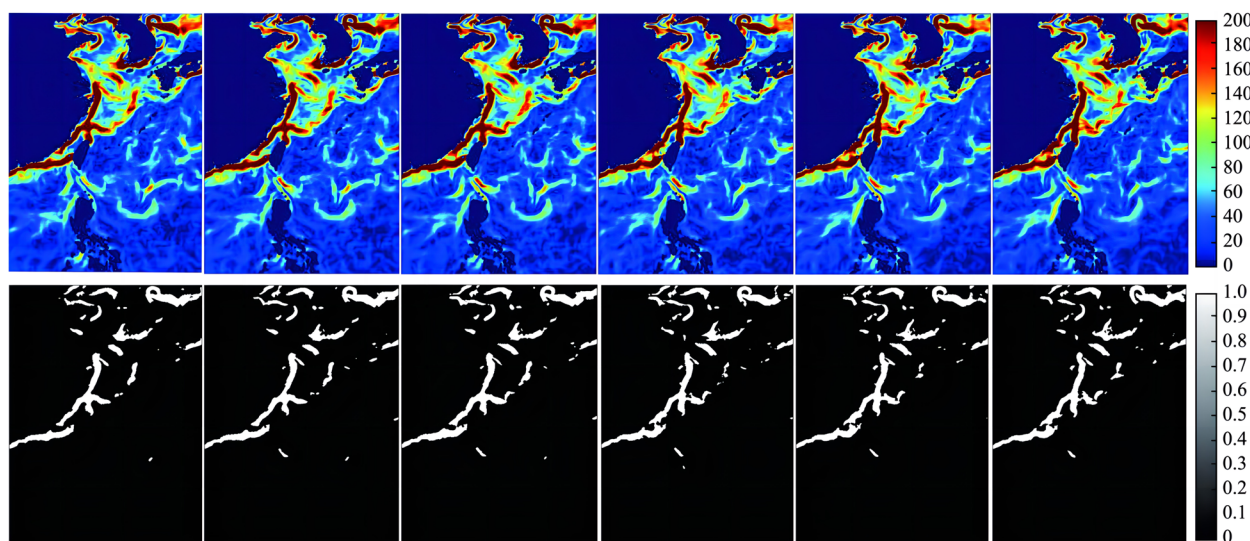


Fig. 6 Spatial and temporal variation in ocean fronts along the China coast, the color bar represents the intensity of ocean front. The first row shows the SST images, and the second row displays the corresponding SST fronts

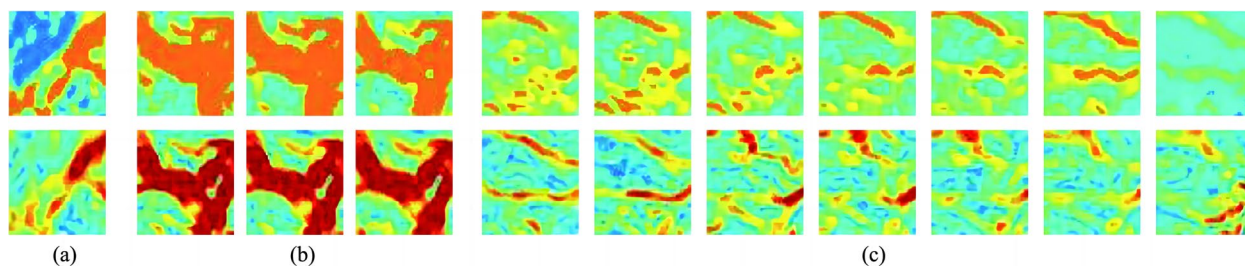


Fig. 7 Ocean front prediction. The first row shows the ground-truth ocean front images, and the second row displays the corresponding prediction results. **a** one-day prediction, **b** three-day prediction, and **c** seven-day prediction

link to the atmosphere of the equatorial Pacific Ocean. Recent research has revealed that well-connected atmospheric forcing from the equatorial Pacific exacerbates the anomalous climate phenomenon in southern California. Satellite RS data quantitatively showed that this well-connected climate forcing affects SST, chlorophyll concentration, and ocean front frequency along the California coast through El Niño, subsequently affecting the local marine fishery industry. A study of the California ocean current system during the abnormal warming period from 2014 to 2016 revealed that El Niño reduced the frequency of ocean fronts and chlorophyll concentration in the region, leading to dramatic changes in phytoplankton abundance and community composition. These dramatic changes then resulted in changes in the range and number of fish populations, leading to the closure of sea fisheries and reduced production capacity.

In addition to its influence on the marine environment, ocean fronts have an important influence on marine ecosystems. Marine ecosystems are intricate systems shaped by the interplay of physical, chemical, and biological processes, creating a delicate balance that sustains diverse life in the ocean. Ocean fronts, tides, and eddies are physical processes that transport nutrients and oxygen to support marine life. Chemical processes promote primary productivity and the growth of phytoplankton, whereas biological processes convert sunlight into energy and produce organic matter for the food web. These interactions create complex marine habitats and contribute to biodiversity and resilience.

Phytoplankton is the foundation and key element of the marine food chain (Griffa et al. 2007). Phytoplankton are microscopic algae that consume sunlight, carbon dioxide, and inorganic nutrients. Phytoplankton convert these entities into organic molecules during photosynthesis (primary production). In addition to primary production, phytoplankton produces almost half of the planet's oxygen and is a key player in the carbon cycle, depleting atmospheric carbon dioxide and reducing its concentration (de Verneil et al. 2019). Sunlight penetrates seawater

to a depth of no more than 150 m, the lower boundary of the photic zone where phytoplankton reside. In open oceans away from coastal upwelling zones, plankton abundance depends on the availability of nutrients. Many studies (Mahadevan and Tandon 2006; Lévy et al. 2012, 2018) have noted that chlorophyll can accumulate at ocean fronts, thereby delivering additional nutrients to areas with sufficient light to support photosynthesis, which is particularly important in subtropical waters. At high latitudes, primary production growth is limited by insufficient light rather than nutrient availability. At these latitudes, fronts also contribute to increased primary production due to subduction, geostrophic circulation, and submesoscale turbulence (Taylor and Ferrari 2011).

Ocean fronts concentrate nutrients and plankton, fostering rich ecosystems and providing important feeding grounds for marine predators and other species. Recent studies have shown that ocean fronts trigger mesoscale eddies and affect the behavior and distribution of marine species (Archer et al. 2020; Dai et al. 2021). Particularly, horizontal agitation by mesoscale currents was found to distort large-scale phytoplankton landscapes into sub-scale patches delineated by sharp horizontal gradients. Mesoscale fronts were found to organize and structure phytoplankton communities into groups with distinct plankton species separated. The phytoplankton communities within these groups may move away from areas of primary production, potentially changing their community structure. These groups have a lifespan comparable to the duration of phytoplankton flowering and transform over time into filaments hundreds of kilometers long.

Furthermore, changes in the duration and location of ocean fronts considerably alter fish community structures. To study the quantitative correlation between ocean fronts and fishing activities, related studies adjusted RS images of SST, chlorophyll concentration, and fishing data to the same resolution to ensure geographical consistency (Lehahn et al. 2018). After adjusting the data, the fishing intensity was graded, and weights

were assigned according to the spatial distance between the fishing ground and the ocean front. The correlation between ocean fronts and fishing activities was calculated on the basis of the graded fishing intensity and spatial proximity to the ocean fronts. To verify the correlation, the observed and expected numbers of fishing events within each ocean front area were compared. The correlation between the frontal areas and fishing effort was evaluated in percentages. This quantitative assessment revealed a positive correlation between oceanic frontal regions and fishing activities. The correlation between ocean front distribution and the frequency of fishing events highlights the importance of ocean fronts in attracting fish groups. These findings emphasize the critical role of ocean fronts in shaping marine ecosystems and supporting fisheries.

6 Limitations and future opportunities

The limitations of current research on ocean fronts and future research opportunities include the following components:

- (1) The vertical movement of fronts has a greater ecological impact than horizontal movement because of more pronounced vertical gradients in temperature, salinity, density, nutrient concentration, sunlight brightness, etc. However, to our knowledge, little effort has been devoted to mapping the vertical structure of temperature in the presence of fronts based on satellite SST data. Temperature reconstruction techniques estimate the ocean temperature and salinity at different depths. However, existing models rarely consider the influence of ocean fronts on temperature reconstruction. Recent research reveals that regions with large deviations between in-situ observations and reconstructed data align with regions with ocean fronts. Therefore, a reasonable strategy is to include frontal features in the temperature reconstruction function. The useful frontal features include not only the intensity of the ocean front and the distance of the ocean front to the reconstruction location but also the commonly used SST and SLA features. This strategy might improve projection performance, particularly in areas affected by strong ocean fronts.
- (2) The Northeast Pacific Warm Anomaly from 2014 to 2016 resulted in high SST and low chlorophyll-*a* in the California Current System. During the same period, the frequencies of SST fronts and chlorophyll fronts decreased significantly (Kahru et al. 2018). Studies on ocean anomalous climate phenomena, such as El Niño and La Niña, have revealed their considerable impacts on the global environment (Mezzina et al. 2022). However, the relationship between ocean fronts and abnormal climate events has been less explored. Whether abnormal climate events represent the beginning of a long-term change in frontal frequency merits investigation.
- (3) Understanding how the behavior of individual marine predators is regulated by surrounding structures is the key to assessing the health of open-ocean ecosystems (Jacox et al. 2015; Henson et al. 2016). Baltar et al. (2016) propose using oceanic fronts as key features that influence marine microbial distributions. Despite the well-established role of ocean fronts in influencing events ranging from fisheries productivity to biogeochemical cycles (Worm et al. 2009; Chassot et al. 2010; Ferrari 2011), the effects of submesoscale and small-scale fronts still need to be measured. Furthermore, more interdisciplinary research is required to identify the factors driving microbial communities and their associated ecosystem services. Linking physical oceanography with molecular ecology could further demonstrate the importance of oceanographic characteristics for the distribution of marine microorganisms and contribute to the design of effective marine conservation policies in a changing climate.
- (4) Surface ocean dynamic processes, such as ocean fronts, occur and interact at multiple scales in the upper ocean, down to several kilometers or even fractions of a kilometer (Mettes et al. 2015). Submesoscale fronts are ubiquitous in the ocean and are important for tracer velocity and scaled energy cascades from large-scale forcing to dissipation. However, the low resolution of the available data makes the effect of submesoscale fronts on phytoplankton productivity difficult to analyze. Current observation systems cannot adequately address these scale issues (Zhi et al. 2021), and the effective resolution of interpolated data is limited to several kilometers because of the orbital crossing distance of satellites in orbit and the repeatability of satellite acquisition. A possible solution for this problem is to employ image processing techniques, such as superresolution and image enhancement techniques (Ju et al. 2022, 2023a, b), to develop innovative neural network architectures specifically designed to improve the reconstruction performance of surface ocean dynamics. Learning from high-resolution satellite observations is a reasonable approach to compensating for interpolation limitations. Further research, such as superresolution and image enhancement methods for RS data, is

required to improve our understanding of the effect of ocean fronts on phytoplankton productivity.

- (5) The machine learning method shows tremendous potential in analyzing the relationship between different types of ocean fronts. For example, in the Yangtze River, machine learning identifies four types of ocean fronts: ocean fronts detected based on chlorophyll-*a* concentration (chlorophyll front), SSS (salinity front), SST (temperature front), and SSD (density front). Recent research reveals that chlorophyll fronts are spatially well matched with salinity fronts, and density fronts are spatially well matched with temperature fronts (Kim et al. 2022), suggesting that chlorophyll changes are highly correlated with salinity and density changes are highly correlated with temperature. In addition, the machine learning method can also be applied to analyzing ocean structure characteristics (Franzke et al. 2022; Thomas and Müller 2022; Qi et al. 2023). Particularly, the clustering of ocean structures shows that each class of ocean structure can be associated with a well-known ocean region. For example, unsupervised clustering of temperature and salinity data reveals the impact of changes in the Kuroshio extension on the distribution of vertical structures (Sambe and Suga 2023).

7 Conclusions

The continuous and extensive data provided by RS techniques have enabled researchers to investigate complex ocean processes, contributing to our understanding of marine ecosystems, climate patterns, and interactions between oceans and the atmosphere. Ocean fronts are crucial in driving various oceanographic phenomena, including upwelling, heat transportation, and the distribution of marine life. Recent research based on RS images has advanced our understanding of the spatiotemporal variation characteristics of the ocean front and revealed the influence of the ocean front on the abundance and diversity of phytoplankton, zooplankton, and higher trophic level species. However, limited by data resolution, research methods, and related theories, current research cannot discover all the potential variation patterns of ocean fronts, necessitating further investigation to uncover new insights into the complex dynamics of water masses in the world's oceans.

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Authors' contributions

Yuting Yang: Conceptualization, Methodology, Formal Analysis, Resources, Supervision, Writing-Original Draft; Yakun Ju: Methodology, Software, Validation, Data Curation, Writing-Original Draft; Ying Gao: Software, Methodology, Validation, Data Curation; Cong Zhang: Software, Validation, Data Curation; Kin-Man Lam: Conceptualization, Methodology, Supervision.

Availability of data and materials

Not applicable.

Code availability

The code presented in this study is available from the first author upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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