Generation and Operational Application of Gridded Data from High-Frequency Surface Wave Radar （HFR）

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Outline

1 Overview of HFR Data

2 Verification and Evaluation of HFR Data

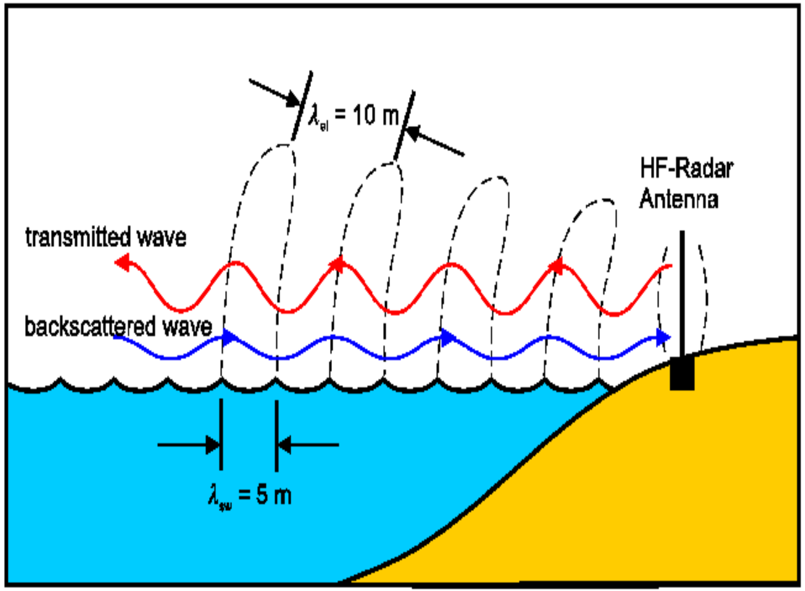
3 Quality Control and Grid Based Product Construction

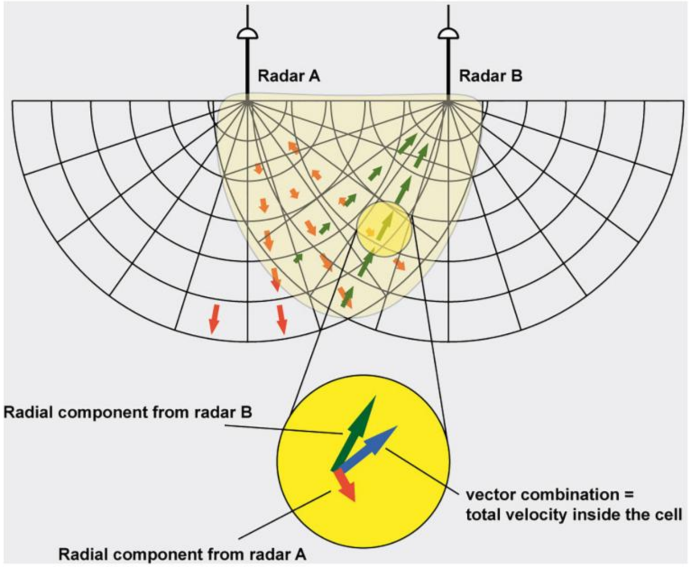
4 Application in Maritime Search and Rescue Forecasting

5 Research on Other Applications

1 Overview of HFR Data

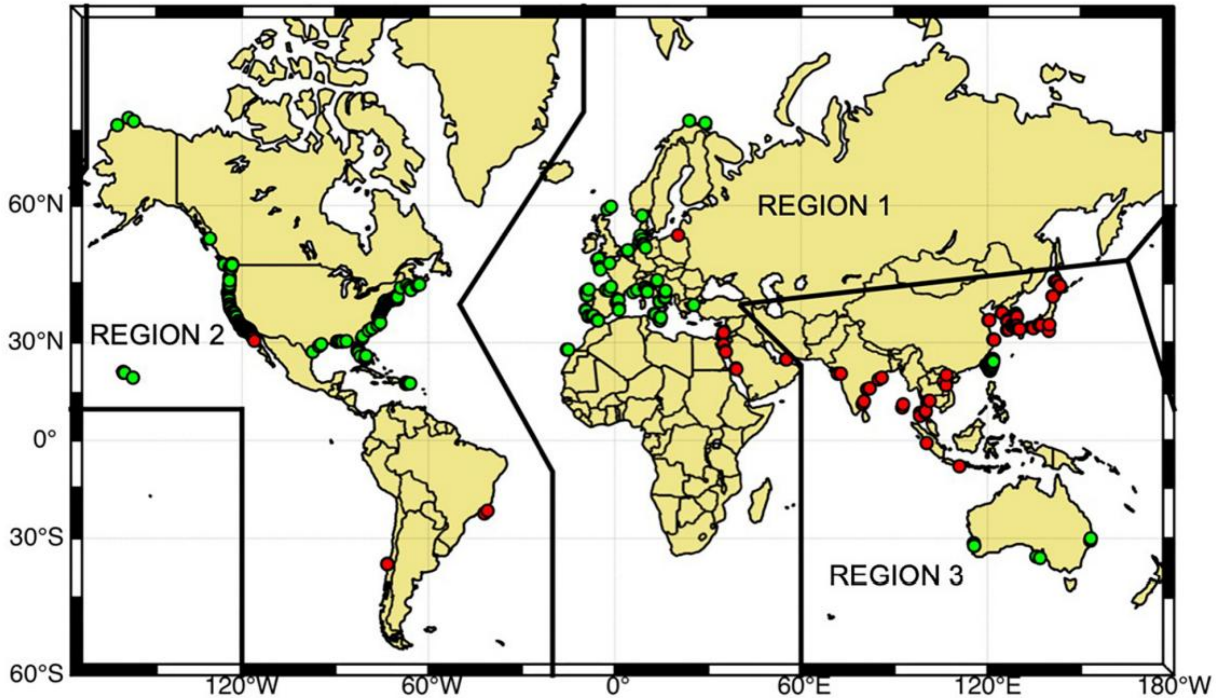
- **High-Frequency Surface Wave Radar (HFR)** has been applied in marine environmental monitoring due to its advantages of multiple functions, high cost-effectiveness, independence from weather and sea conditions, and all-weather continuous observation of large sea areas. The radial current velocity in the direction of the radar beam can be calculated by measuring the Doppler shift of the first-order spectral peak in the HFR echo Doppler spectrum (Barrick 1972a). The sea surface current field can be synthesized using vector principles based on radial velocities from two or more radar stations (Shay et al. 2007; Kim et al. 2011; Zhao et al. 2011).
- Since its advent in 1977, after decades of development, HFR has gradually become an important means of marine observation, with a coverage radius of up to hundreds of kilometers and a sampling interval as short as less than 10 minutes.
- The high spatiotemporal coverage makes HFR systems not only effective tools for coastal current monitoring and research but also applicable to marine target search, accident rescue, and marine scientific research.





1 Overview of HFR Data

- The HFR observation network in the United States has been operating for 18 years, bringing together more than 150 radars from 31 organizations.
- In the past decade, the number of radar observation systems in Europe has gradually increased, with more than 60 stations now.
- There are 110 radar stations in operation in Asia.



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2 Verification and Evaluation of HF Radar Data

- Observation accuracy

➢ The accuracy of ocean current observation has gradually been optimized from the initial 27 cm/s (Barrick et al. 1977; Paduan and Rosenfield 1996; Chapman et al. 1997).

➢ Liu et al. (2014) analyzed three portable SeaSondes systems and two WERA phased array systems in the United States and pointed out that the root - mean - square deviation between HFR and ADCP current measurements can reach about 4 cm/s.

➢ Lai Yeping (2020) compared the portable HFR and found that the root - mean - square error of the current velocity was 10.37 cm/s, and the root - mean - square error of the current direction was 15.12°.

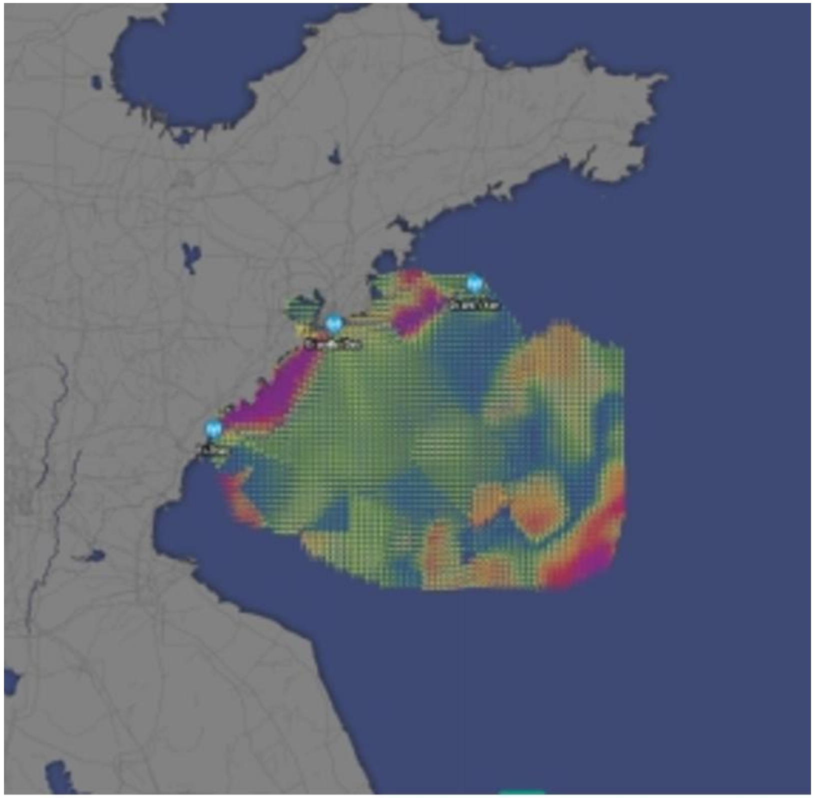
➢ Xie Xiaobai (2020) verified the high - frequency ground wave radar data in typhoon monitoring and found that the average deviation of the current direction was 22°, the correlation coefficient reached 0.83, the average deviation of the current velocity was 4 cm/s, and the correlation coefficient was as high as 0.9.

Reference	HF radar + Frequency (MHz)	Instrument	Area	Period + validation	RMSE+R
Chapman et al. (1997)	OSCR 25.4	ADCP	North Carolina, USA	1993.06 radials	8-15cm/s, 0.39-0.9
Graber et al. (1997)	OSCR 25.4-49.9	PCM	North Carolina, USA	1993.06 radials + totals	11-20 cm/s
Emery et al. (2004)	CODAR 13	PCM, ADCP	S. Barbara CA, USA	1997.06-1999.11 radials	7-19 cm/s, 0.39-0.77
Kaplan et al. (2005)	CODAR 12.5	ADCP	Bodega B., CA, USA	2001.05-12 totals	5-15cm/s, 0.59-0.92
Paduan et al. (2006)	CODAR 13-25	PCM	Monterrey CA, USA	2003.07-09 radials	9-28cm/s, 0.25-0.81
Alfonso et al. (2006)	CODAR 5	PCM	Galicia, Spain	2005.11-2006.02 totals	2-7cm/s, 0.6-0.9
Cosoli et al. (2010)	CODAR 25-36	ADCP	Venice, Italy	2005.08-09 radials	8-20 cm/s, 0.14-0.84
Rubio et al. (2011)	CODAR 4.53	PCM	Basque Country	2009 totals	8-13cm/s, 0.34-0.86
Solabarrieta et al. (2014)	CODAR 4.53	ADCP	Basque Country	2009.01-2011.09 totals	8-15cm/s, 0.27-0.67
Lorente et al. (2014)	CODAR 27	PCM	Strait of Gibraltar, Spain	2013.10-12 radials + totals	8-22cm/s, 0.31-0.81
Xu et al. (2016)	OSMAR 7.8	ADCP	Taiwan Strait, China	2013.01-03 totals	7.5-25.8cm/s, 0.69-0.98
Zheng et al. (2019)	OSMAR 13	ADCP	South China Sea, China	2015.06 15-23 totals	11cm/s
Lai et al. (2020)	OSMAR 25	PCM	Qiongzhou Strait, China	2019.05 30-31 totals + radials	10.37-13.5cm/s, 0.88-0.93
Jie et al. (2020)	OS0801H 10.75	ADCP	Jiangsu, China	2018.01, 2018.05, 2018.06, totals	4cm/s, 0.9

2 Verification and Evaluation of HF Radar Data

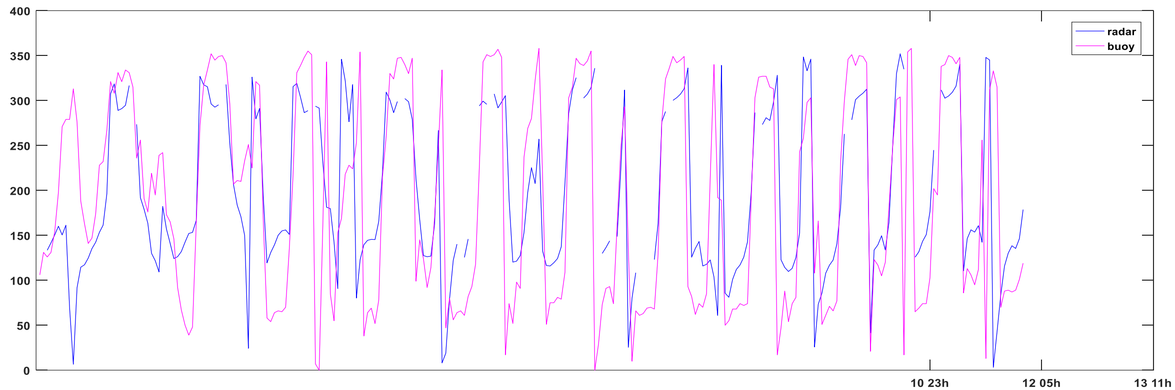
Taking the synthetic high - frequency ground wave radar from three stations in the North Yellow Sea as an example, the verification and evaluation of radar current data are carried out, and the evaluation methods include:

- Comparing with buoy current data for verification and evaluation
- Comparing with seabed – based and moored ADCP current data.
- Comparing with Vessel-mounted ADCP current data.



2.1 Comparison with buoys

Compared with the surface data observed by buoys, the absolute error of the current velocity observed by radar is 9.23 cm/s ~ 16.32 cm/s, the relative error of the current velocity is 59% ~ 130%, and the absolute error of the current direction is 46° ~ 60°. Considering that the relative error of the current velocity is large, after removing the buoy observation data with a current velocity of < 50 cm/s, the absolute error of the current velocity is 10.12 cm/s ~ 29.02 cm/s, the relative error is 15% ~ 35%, and the relative error of the current direction is 35° ~ 55°. It can be seen that when the ocean current data is small, the radar observation error is large, that is, when the current velocity is large, the radar observation error is relatively small.

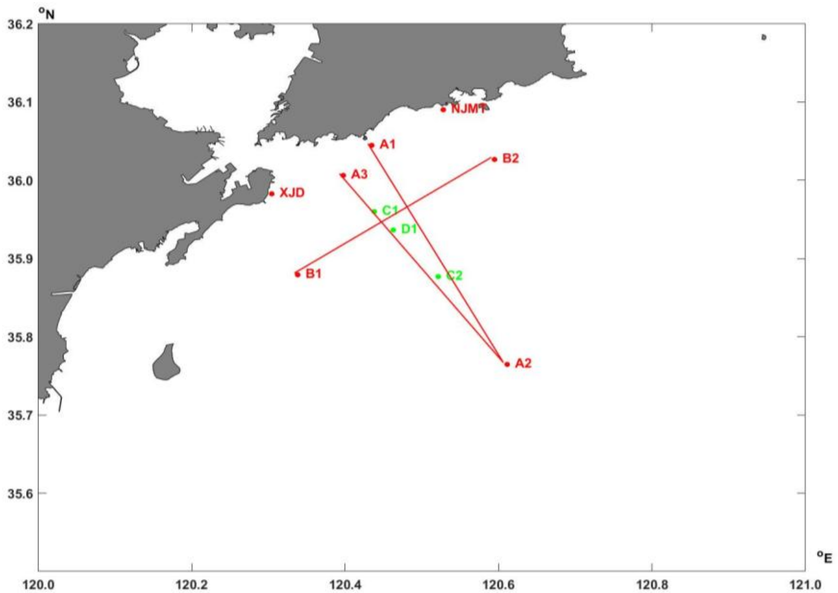


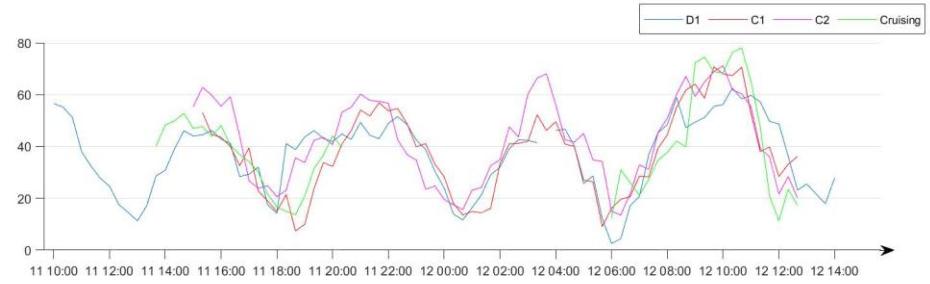
Station ID	Current speed		Current speed (>50cm/s)		Current direction	Current direction (Current speed >50cm/s)
	MAE (cm/s)	MRE	MAE (cm/s)	MRE	MAE (°)	MRE (°)
B1	9.23	59%	10.12	15%	46	37
	10.21	85%	14.49	20%	52	40
	11.62	93%	20.3	28%	52	35
	11.52	79%	22.29	29%	56	55
	16.32	130%	29.02	35%	60	45

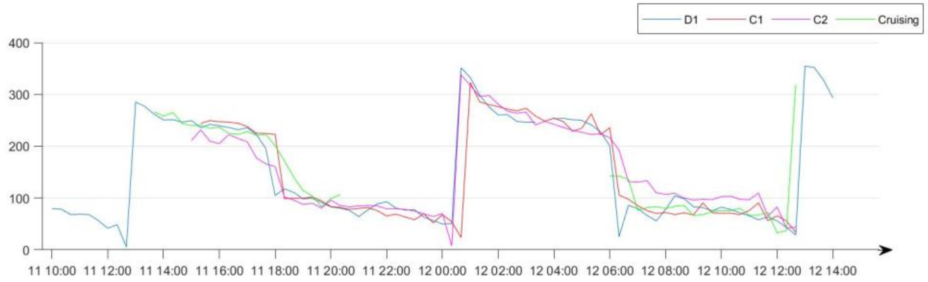
2.2 Comparison with Seabed - based, Moored ADCP and Vessel-mounted ADCP

Due to the small number of buoy stations, in order to further verify the high - frequency radar observation data, a marine test was designed: within the radar coverage, one seabed base (D1), two moored ADCPs (C1, C2) and three Vessel-mounted ADCP (A1 - A2, A2 - A3, B1 - B2) were designed.

Station ID	Time period
D1	11.11 10：00 ~ 11.19 09:40
C1	11.11 15：15 ~ 11.12 12：45
C2	11.11 15：00 ~ 11.12 12：40
Cruising (A1-A2-A3, D1-B1-B2)	11.11 13：40 ~ 11.12 12：40

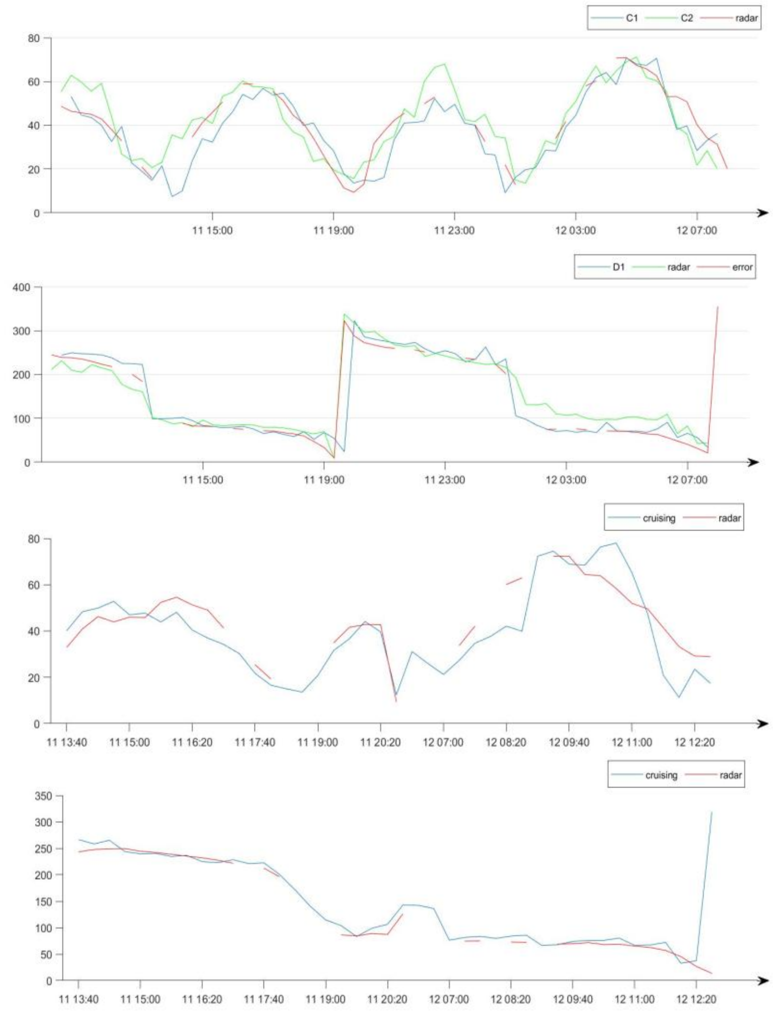






2.2 Comparison with Seabed - based, Moored ADCP and Vessel-mounted ADCP

- For station C1, the RMSE and correlation coefficient are 7.6 cm/s and 0.89, respectively, and the average flow direction difference is 11°.
- For station C2, the RMSE and correlation coefficient are 11.5 cm/s and 0.80, respectively, and the average flow direction difference is 21°.
- For station D1, the RMSE and correlation coefficient are 10.1 cm/s and 0.82, respectively, and the average flow direction difference is 11.7°.
- For the underway ADCP, the RMSE is 8 cm/s, and the average flow direction difference is 11°.



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3.1 Purpose of Gridded Data Production

Although HFR ocean current observation data have passed verification and evaluation, in practical applications, such data are affected by factors such as solar radiation, electromagnetic environment, and diurnal variations in ionospheric intensity. As a result, the quantity and quality of the synthesized ocean current data obtained in time and space are unstable, leading to discontinuities in the spatially detected ocean currents. The lack of data volume makes HFR ocean current data unsuitable for direct application in subsequent fields such as flow field characteristic analysis, model assimilation, and multi-source data fusion. Therefore, based on long-term radar observation data, through the analysis of data quality, spatiotemporal distribution characteristics, and basic movement laws of ocean currents, spatiotemporal interpolation algorithms have been developed to effectively quality-control and "patch" the observed ocean current data. This process constructs regular gridded ocean current observation data products with different resolutions, ensuring as much as possible the completeness and accuracy of regional data. These gridded products will be directly applied to marine search and rescue, prediction of marine pollutant drift, analysis of sea surface flow field characteristics, and safety assurance for maritime navigation..

3.2 Research Status

- In 2007, Kaplan applied the Open-boundary Modal Analysis (OMA) method to ocean current observation data for spatial interpolation of high-frequency radar observation data. This method is relatively complex and requires analysis of radial currents and their errors.
- In 2016, Saha used high-frequency surface wave radar observation data from five different locations to evaluate the interpolation effects of two common interpolation methods. The results showed that the inverse distance weighting statistical method and the artificial intelligence network method are more suitable for spatial interpolation of radar observation data, as they can effectively fill in observation gaps.
- Huang Qihua adopted the BP neural network method for spatial interpolation of ocean currents, and demonstrated that the BP neural network method is significantly superior to the inverse distance weighting method and linear interpolation method.

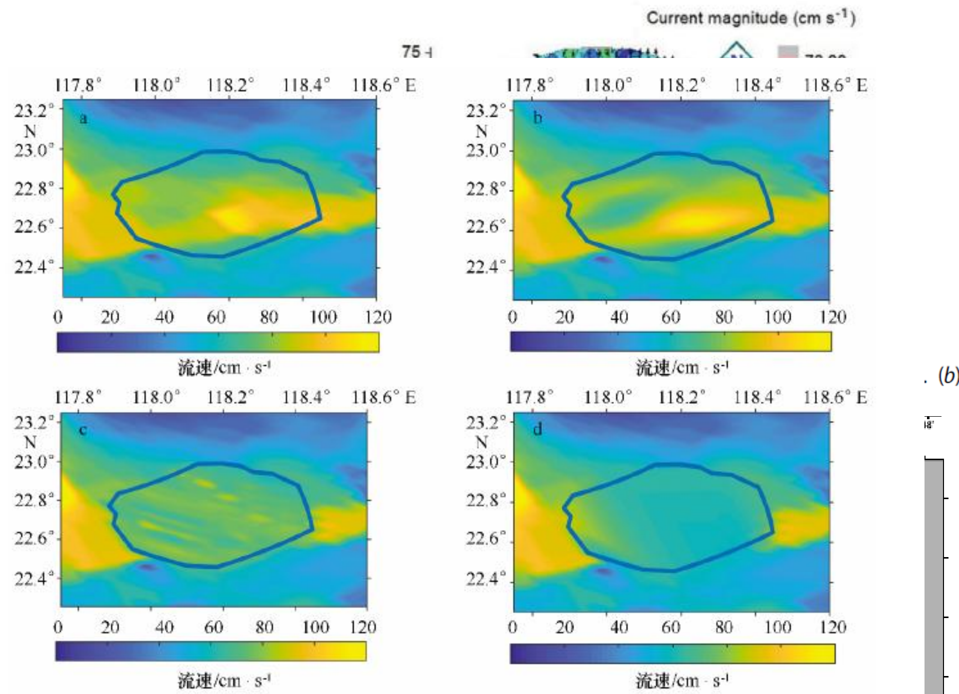


图 4　3 种方法插值结果与原始数据的对照

Fig.4　Comparison of the interpolation results of three methods with the original data

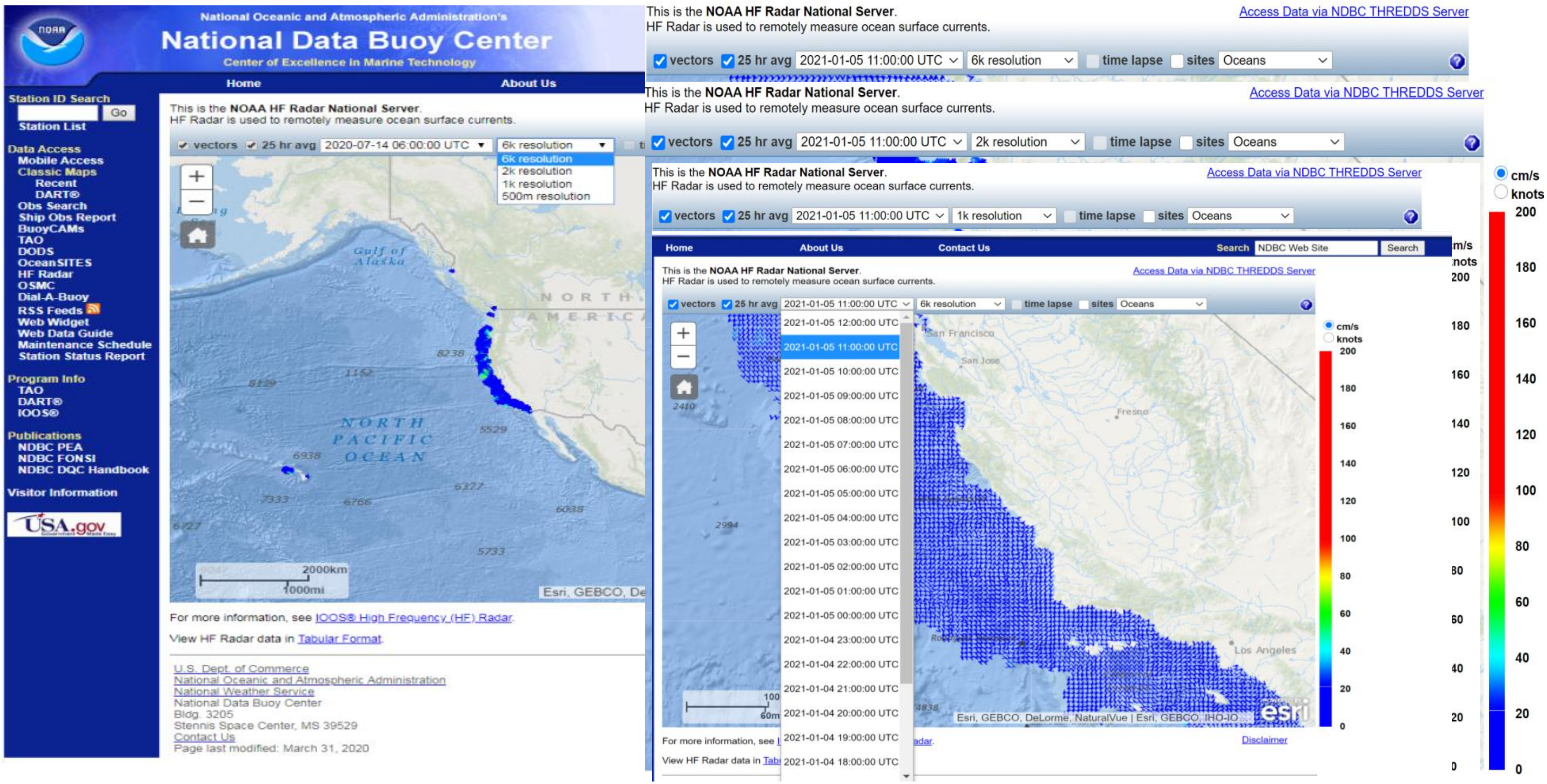
a.原始数据;b.BP 法插值结果;c.IDW 法插值结果;d.LI 法插值结果

a.The original data; b. the result of BP method; c. the result of IDW method; d. the result of LI method

Figure 7. Current maps (*a*) Observed (*b*) Interpolated.

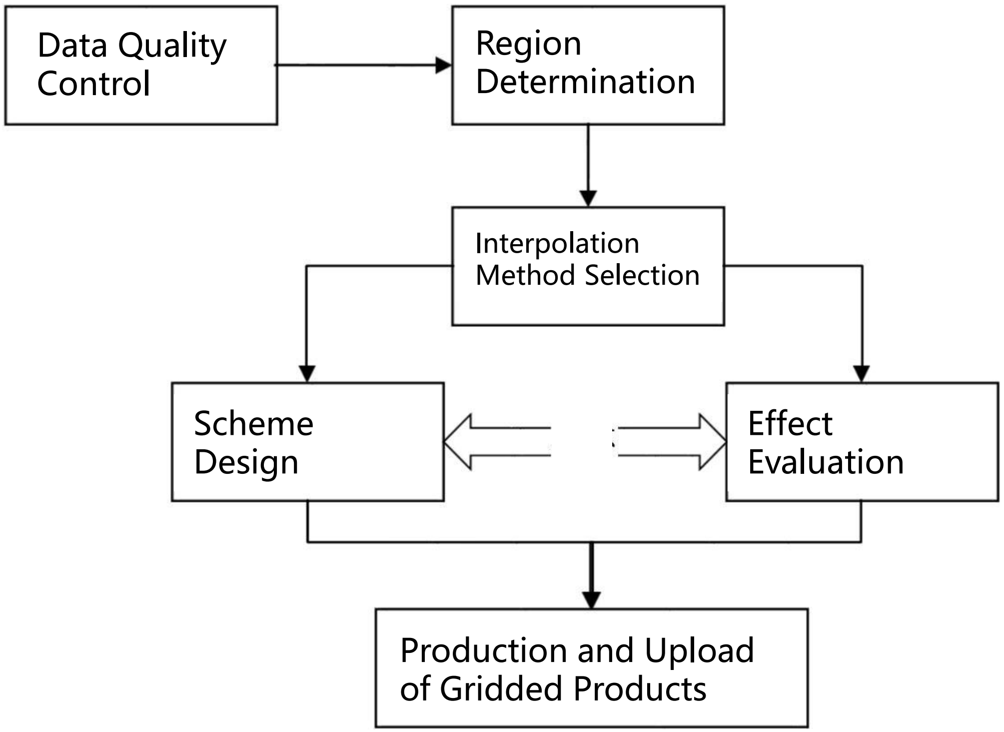
3.2 Research Status

The NOAA Data Center in the United States has produced high-frequency surface wave radar ocean current data along the U.S. coast into observation data products with different resolutions, which are classified into 500m, 1km, 2km, and 6km based on the radar's own performance.



3.3 Technical Route for Gridded Data Production

Based on the characteristics of high-frequency surface wave radar observation data, a method for producing gridded products is designed, which includes six aspects: quality control of flow field observation data, determination of the gridded product area, selection of interpolation methods, scheme design, evaluation of fitting effects, and production and upload of gridded products. The specific technical route is shown in the figure below.



3.4 Data quality control

Considering that the coverage of synthesized current data is affected by factors such as wireless signals, sunspot activities, and sea surface conditions, first, quality control is performed on the radar data to eliminate outliers. The quality control methods include the threshold method, eliminating outliers and jump values, and calculating the vorticity of the flow field to eliminate

(1) Threshold Method
Taking the historical maximum value of ocean current velocity in this sea area as the threshold, the threshold elimination method is adopted to remove abnormal values from the observation data.

(2) Singular Value Method
Eliminating singular values in the observation data.

$$y(t_n)-\bar{y} > 3\delta, \delta = \sqrt{\sum \Delta y^2/(M-1)} \quad (n = 1,2,\cdots,M)$$

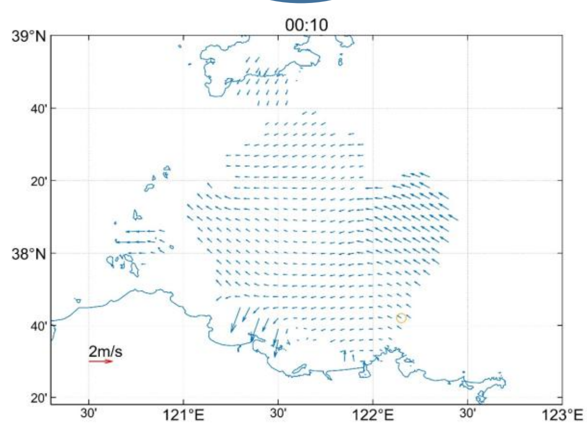
(3) Jump Value Method
Eliminating Jump Values in Data

$$|y(t_n) - y(t_{n\pm1})| > 3\delta$$

其中，y 为观测数据，t_n 为观测时刻，δ 为标准差。

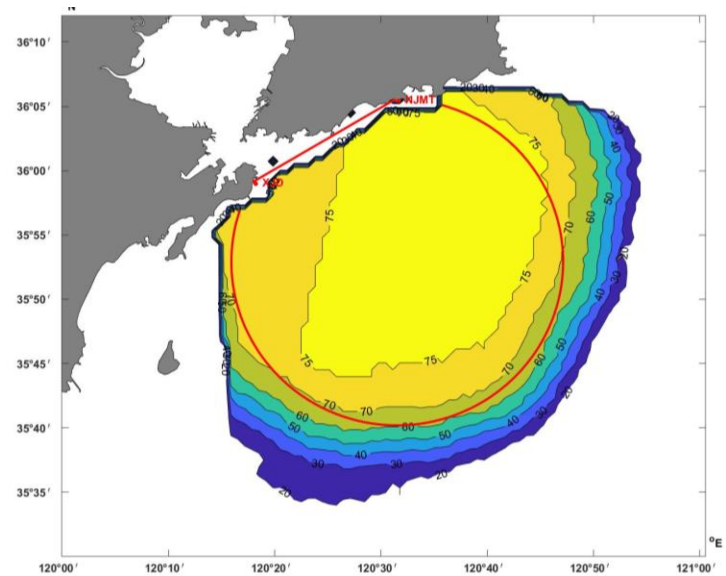
(4) Flow Direction Conflict Method
Eliminating areas with conflicting flow directions
Eliminating areas with excessively high vorticity in the field

Data quality control



3.5 Determination of the Gridded Region

The spatiotemporal discontinuity of flow field data synthesized by high-frequency surface wave radar is characterized by the spatial average sampling rate (point density) and temporal average sampling rate. Based on the distribution of sampling rates and the intende interpolation method, the region for producir regular gridded products is demarcated, as shown by the red line in the figure. To maximize the coverage of observation data as much as possible, the gridded product region is set to the range where the spatial coverage rate reaches 70%.



3.6 Interpolation methods

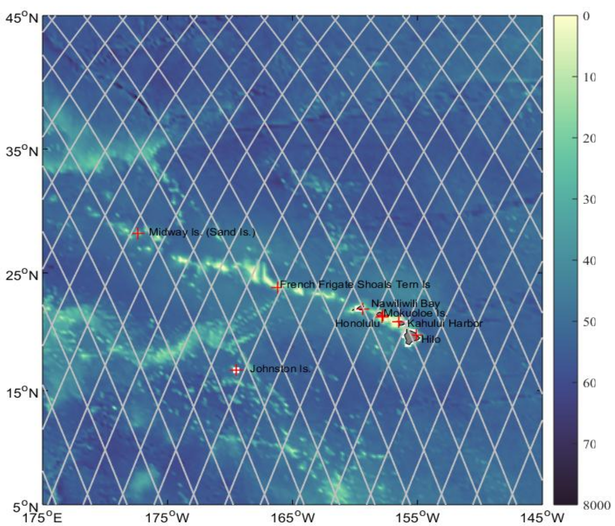
- Inverse Distance Weighting (IDW)
- Kriging Interpolation Method
- Minimum Curvature Method
- Natural Neighbor Interpolation Method
- Multiple Regression Method
- Radial Basis Function (RBF) Method
- Linear Interpolation Method
- Polynomial Interpolation Method
- Artificial Neural Network (ANN)
- Support Vector Machine (SVM) and Generative Adversarial Network (GAN) Method

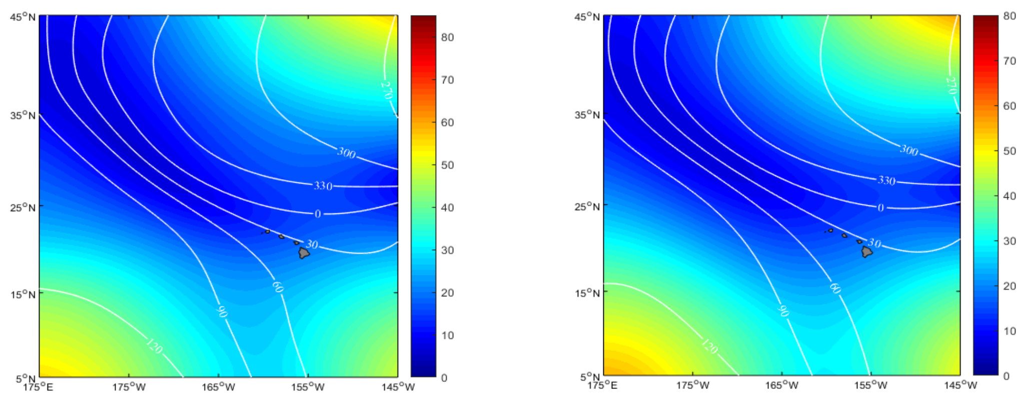
Considering the universality of interpolation methods across different radar data and sea areas, as well as the characteristic of spatial distribution continuity in ocean current flow fields, we adopt the radial basis function fitting method based on the principle of least squares fitting. This method treats the two-dimensional space as an integral function, avoiding issues such as spatial extrapolation and the selection of interpolation radius in ordinary interpolation methods.

3.6 Interpolation methods

- Radial basis functions have been widely applied in data analysis

- Tidal fitting in the Hawaiian sea area（Xu M , Wang Y , Wang S , et al. Ocean Tides Near Hawaii from Satellite Altimeter Data I[J]. Journal of Atmospheric and Oceanic Technology, 2021.)



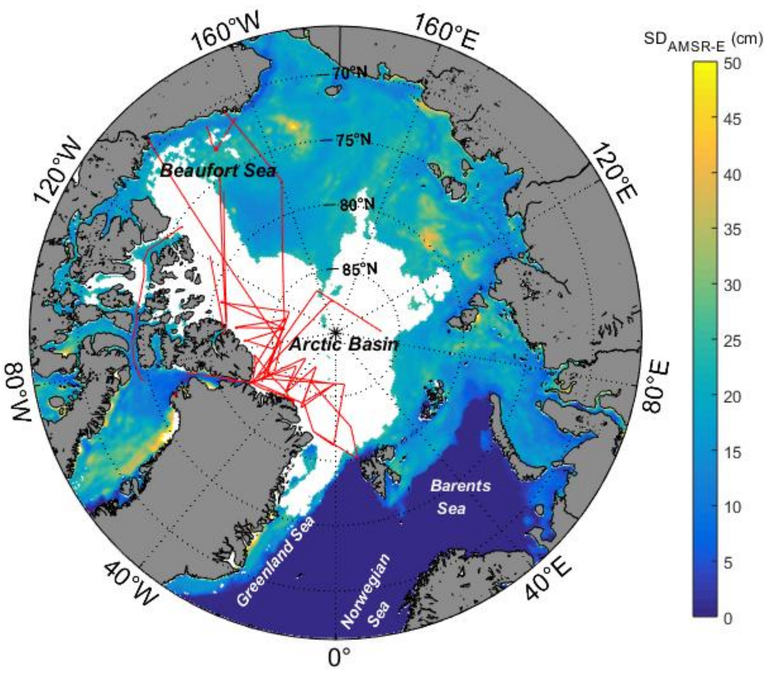


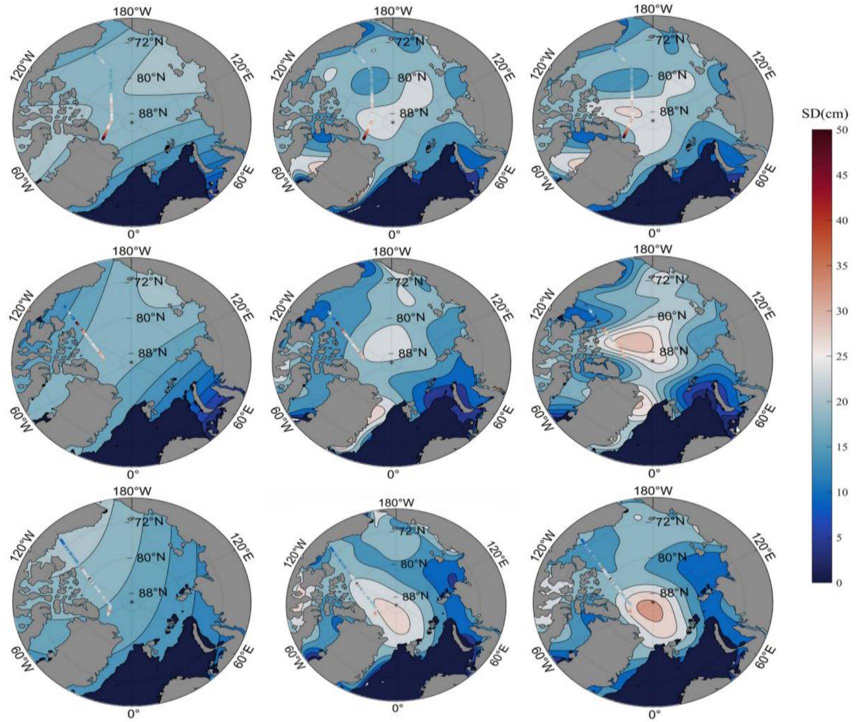
Cotidal charts of fitting results for the M2 tidal constituent (Left: Chebyshev polynomial fitting; Right: Cubic B-spline surface fitting)

3.6 Interpolation methods

- Radial basis functions have been widely applied in data analysis

  - Spatial Fitting of Arctic Snow Cover Thickness



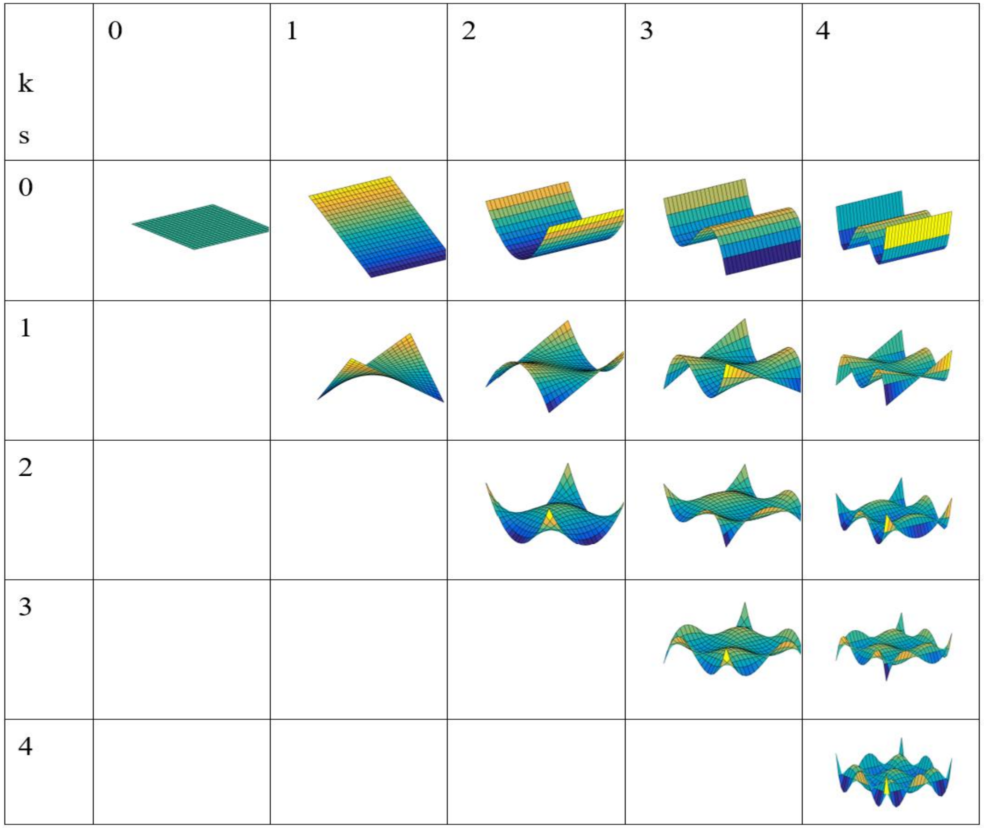


AMSR-E snow cover thickness and trajectories of the OIB cruises from 2009 to 2011; the blank areas represent the missing parts of AMSR-E data.

3.7 Scheme Design

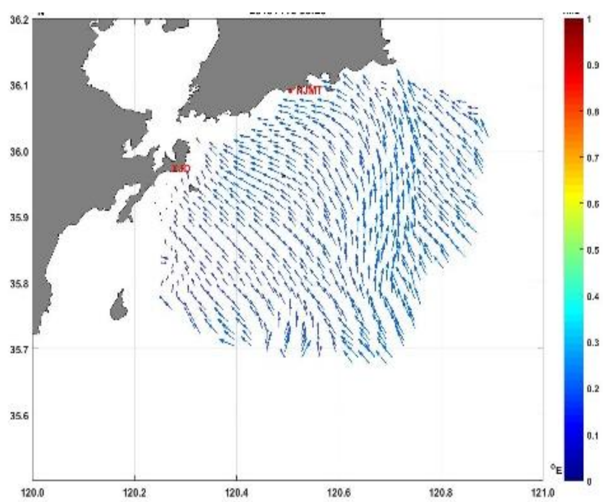
- After selecting the interpolation (fitting) method, different interpolation (fitting) schemes are set. This step requires scheme design based on the actual conditions of radar data and error distribution.
- For different interpolation methods, considerations are given to setting different interpolation parameters, such as interpolation radius, number of samples, and fitting order. Meanwhile, combined with the effect evaluation of interpolation products/fitting products, the interpolation methods and scheme design are optimized and improved.

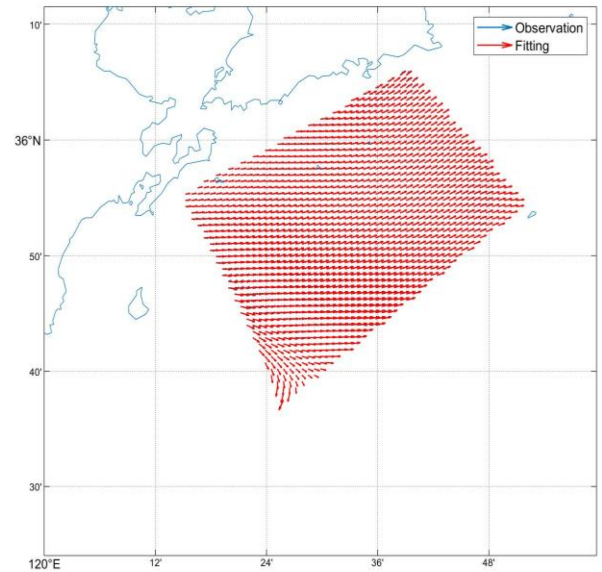
表 1. 各阶二维 Chebyshev 多项式曲面

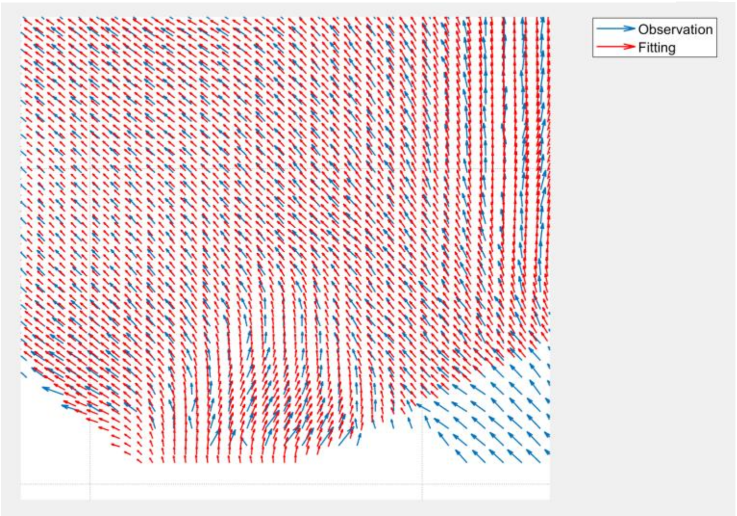


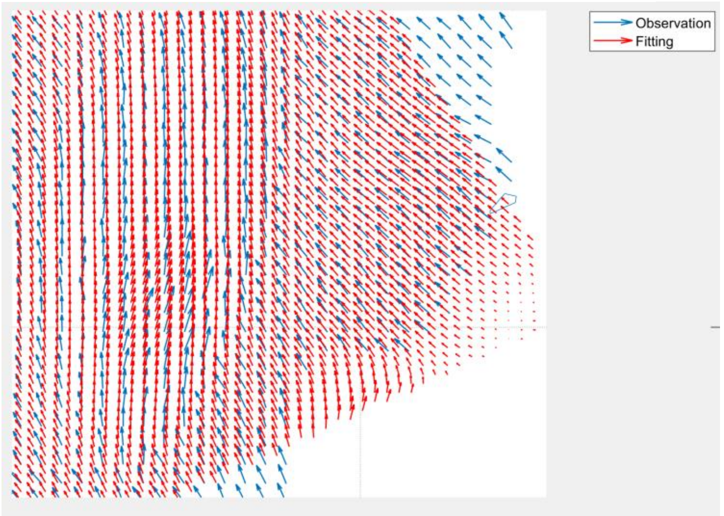
3.7 Scheme Design

Presentation of High-Frequency Surface Wave Radar Ocean Current Data After Interpolation







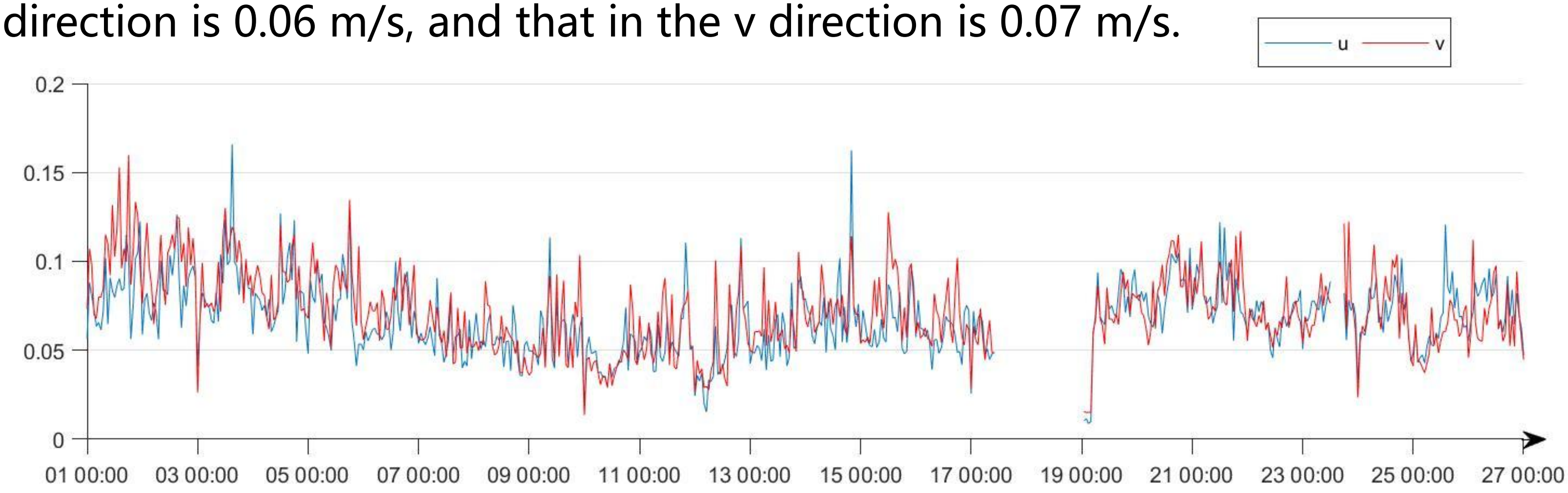


3.8 Evaluation of Fitting Effect

The error analysis method is adopted to evaluate the fitting effect of the fitting method.

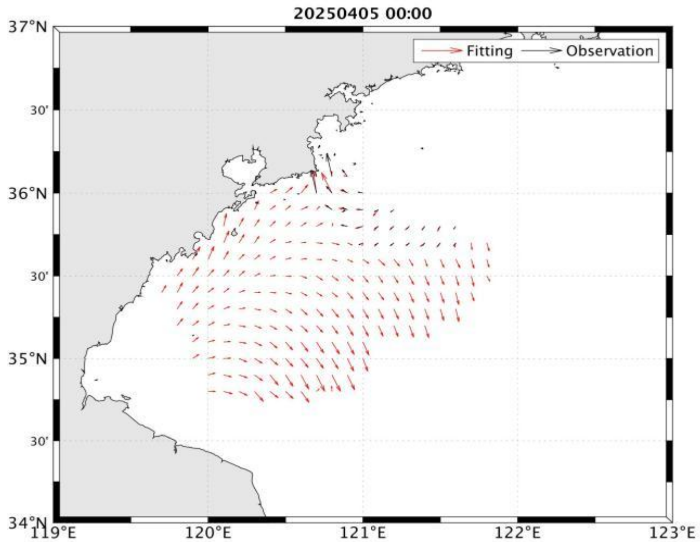
Root Mean Square Error (RMSE): Reflects the sensitivity and extreme value conditions of simulated values.

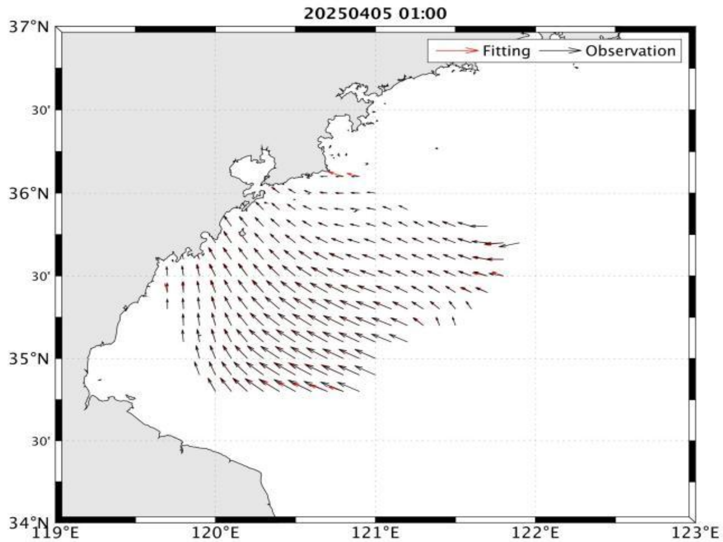
The hourly distribution of root mean square errors in the u and v directions after fitting is shown in the figure. It can be seen from the figure that the root mean square fitting errors in both directions are basically below 0.1 m/s. Through calculation, the average root mean square fitting error in the u direction is 0.06 m/s, and that in the v direction is 0.07 m/s.



3.9 Production of Regular Gridded Products

The reconstructed products of high-frequency surface wave radar sea surface observation data that have passed the effect evaluation are produced into gridded products with different spatiotemporal resolutions in accordance with the requirements for data products and image products. Additionally, the format of high-frequency surface wave radar flow field reanalysis data is standardized to form gridded products with different resolutions. From the comparison between the fitted flow field (black arrows) and the measured data (red arrows), it can be seen that the fitted flow field is in good agreement with the original observation data, and can well express the flow field characteristics of the region at different moments such as flood tide, ebb tide, flood transition, and ebb transition. Moreover, after calculation using the fitting method, the blank areas in the original data are reasonably filled, and the observation data at each moment is maintained within the maximum observation range of the radar.





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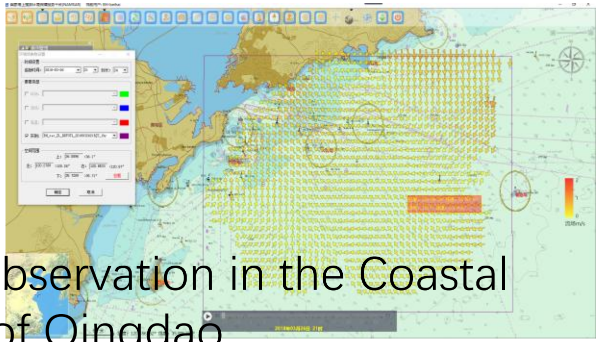
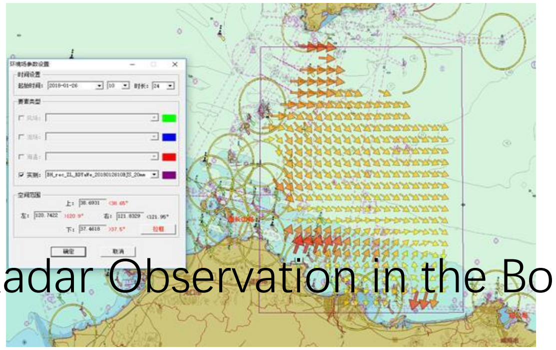
4 Application in Maritime Search and Rescue Forecasting

- The U.S. Coast Guard's SAROPS has been adopting ocean current data from various sources since May 2009. From 2016 to 2017, the flow field data provided by HFR data and statistical forecasts ranked sixth in the application of the SAROPS system, while the flow field results of the ROMS model after assimilating HFR data ranked fourth.
- Studies have shown that compared with HYCOM data, HFR surface layer data reduces the effective search area by 1/3 after 96 hours and achieves higher scores than global models.
- Europe has also carried out a series of applications of HFR data in search and rescue systems, such as the ongoing CMEMS User Uptake IBISAR project and the previous Tosca Project.
- We have integrated the HFR data from Qingdao and the Bohai Strait, as well as the forecast data after assimilating HFR data, into the "National Maritime Search and Rescue Support System".



Radar Observation in the Coastal Waters of Qingdao



Radar Observation in the Bohai Strait

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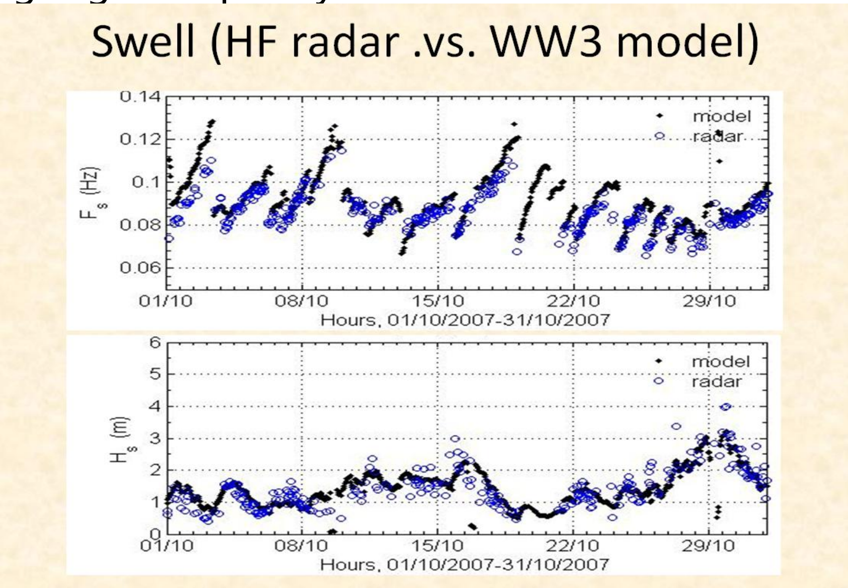
5.1 Research on Wave Inversion Algorithms

- The separation of wave components and research on swell components have increasingly become frontier topics in wave analysis research. Theoretically, the ocean wave spectrum can be retrieved from the second-order spectrum of HFR echoes. However, the corresponding relationship between the two is extremely complex, and the inversion calculation of ocean waves is highly dependent on the quality of echo data.
- In the calculation process of significant swell wave height, combined with the discussion on the radar second-order cross-section integral equation, a local swell inversion optimization model will be proposed from both theoretical and empirical perspectives. The research content has been approved as a Youth Fund project of the National Natural Science Foundation of China: Study on Inverting Swell Parameters Using High-Frequency Surface Wave Radar in the Northern China Sea Area.

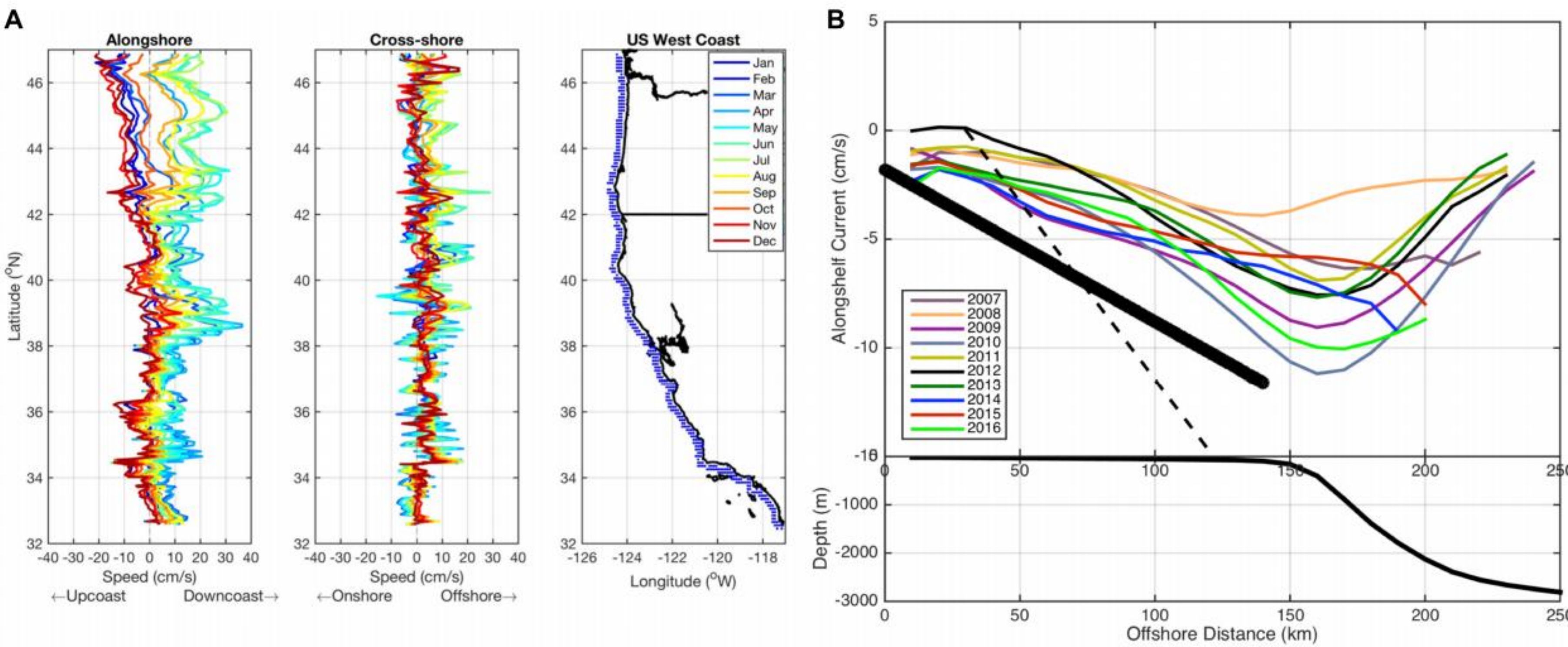


5.2 Disaster Early Warning - Tsunami Wave Identification

- the velocity of the orbital long waves caused by tsunamis can be detected by HF radar, based on the spatial and temporal scales of the characteristics of slowly varying ocean currents.
- The theory of HFR tsunami detection was first developed in the 1970s. The first detected tsunami occurred in Japan in March 2011. However, HFR at that time did not have real-time detection capability, and the tsunami could only be detected through post-analysis of data.
- The real-time tsunami detection radar was implemented by the WERA radar installed in Tofino, Canada. During the tsunami that occurred in October 2016, it was detected by HFR at a location 60 km offshore, 45 minutes before it reached the shore.
- Oman and the Philippines have also installed radar systems for identifying tsunami and storm surge hazards to protect their coasts.
- It should be noted that in the application of this field, it is necessary to improve the data transmission of HFR (including power equipment and the Internet) under the conditions of earthquakes and severe weather.

5.3 Coastal Circulation Identification

- HFR can identify seasonal variations of coastal currents, including the identification of upwelling, western boundary currents, eddies, etc.



Thank you