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Assessments of surface current variability along the mid-southern coast of Vietnam from high-frequency (HF) radar measurements

Thanh Huyen Tran
Helzel Messtechnik GmbH
Kaltenkirchen, Germany
tran@helzel.com

Alexei Sentchev
Laboratory of Oceanology and
Geosciences UMR8187
Univ. Littoral Côte d'Opale
Wimereux, France
alexei.sentchev@univ-littoral.fr

Manh Cuong Tran
Laboratory of Oceanology and
Geosciences
Univ. Littoral Côte d'Opale
Wimereux, France
trancuong205@gmail.com

Dinh Duc Dang
Center for Environmental Fluid
Dynamics
VNU University of Science
Hanoi, Vietnam
dangduc@hus.edu.vn

Thomas Helzel
Helzel Messtechnik GmbH
Kaltenkirchen, Germany
helzel@helzel.com

Abstract— Characteristics of the coastal surface currents in Vietnam are often challenging to be well-described due to the lack of reliable data. Thus, a remote sensing technology – high-frequency (HF) Wave RADar (WERA) has been implemented to monitor the surface currents along the mid-southern coast of Vietnam, which is largely influenced by the strong South China Sea Western Boundary current system (SCSWBC). The HF radar data obtained from a measurement campaign in May, 2019 were checked for outliers through variance-filters. Thereafter, the velocity fields were reconstructed using 2DVar-EOF gap filling and interpolation method [1, 2] for further analysis. The reconstructed surface current maps showed that the main current direction in this area during summer was northeast and the flow was driven by the southwest monsoon which usually starts from May [3]. The eastern sector of the domain was noticed with remarkably strong northeast current. At the onset of summer monsoon, the jet was weakened and deviated, thus, strongly modified the dynamics of the region [4]. A current divergence was observed in the northeastern and eastern parts of the study area. Some other interesting features of surface circulation were revealed during the second week of measurements, on 9-10 of May. Those features are characteristics of the east Vietnam cyclonic eddy and the southeastward offshore current [3–5]. On May 9, the cyclonic eddy expanded further to the south and prevailed over the entire area within a week. Spectral analysis was performed to identify the dominant frequencies of the surface current variability. The results demonstrated the capability of HF radars in monitoring such sub- and meso-scale motions of near-shore surface currents.

Keywords— sea surface currents, HF radar, mesoscale divergence, pollution monitoring, disaster prevention

I. INTRODUCTION

Large scale surface ocean circulation is governed mostly by winds and thermohaline gradient and subtly changes over time

scales of months to years [8]. Meanwhile, at meso- to sub-mesoscales in coastal regions, it becomes more interesting since other local driving forces including effects of bathymetry, the presence of inland sources (river discharge) and tides lead to more complicated and dynamic motions which change rapidly over a time scale of several days to several weeks. The coastal waters of Vietnam are located in the West of the South China Sea (SCS). At monthly to yearly scales, the area is mostly governed by monsoon winds. The main current direction in this area during summer is northeastern associated with the presence of south-wester monsoon. The summer monsoon starts from May [3]. The prominent circulation which influences other oceanic properties (i.e. nutrients, momentum, energy) in the SCS is the SCS Western Boundary current (SCSWBC) [9]. This current is strong and stable over the year and flows along the Vietnam middle-southern coasts. Notably, during summertime, at approximately 11°N, the northeastward current diverges easterly to form a distinctive circulation called SE Vietnam Offshore Current (Fig. 1). These circulation features in the SCS have been characterized in several previous studies e.g. [7], [9]–[11]. However, it is very challenging in characterizing the ocean current variability at smaller scales at coastal regions of Vietnam, especially along the coasts since the existing observations are insufficient both in terms of temporal and spatial scales [10]. The majority of studies of coastal dynamics in this region have been undergone using modelling with few and discrete oceanic data. The lack of high-resolution coastal data leads to the inability of detecting sub- to mesoscale dynamics. It is worth noting that the complex bathymetry and fresh-water input also contribute to very high uncertainties and the inaccuracy in model results. Especially, the middle southern coast of Vietnam, characterized by a steep and short continental shelf, is the location of upwelling and downwelling during the two monsoon seasons. Therefore, in order to understand

thoroughly how sub- and mesoscale motions at the coastal regions develop, expand and join with regional and global circulations, nearshore surface currents need to be monitored using intensive and advanced measurement technics. Amongst others, high-frequency (HF) Radar appears to be a robust technology for surface current monitoring.

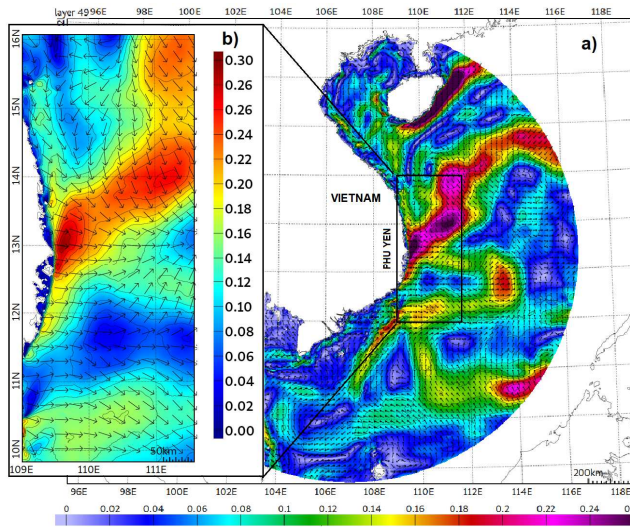


Fig. 1. a) Surface circulation in the Western SCS in April-May, from modeling results. 3D SYMPHONIE model was used to generate current velocity fields for the 9-year long period, 2008-2008, which have been averaged. .. b) The study region, Phu Yen, located in the middle of Vietnamese coast. A large upwelling occurs at latitudes 10-14°N formed by the persistent monsoon wind in summer..

HF Radar (HFR) is a land-based remote sensing technology which is capable of measuring surface currents and waves. It is well known for monitoring the ocean state along coastal regions with high resolution and wide range up to 200km or more. There are two types of techniques used in HF Radars to determine the direction of arrival (DOA) i.e. azimuth and range, namely direction finding (DF) (i.e. compacted array) and beamforming (BF) (i.e. phased array) [12]. DF technique uses some fitting algorithms, best-known is Multiple Signal Classification (MUSIC) [13], to find the incident angel matching the set of received sea echoes [14]. Meanwhile, in BF algorithm, the beam is steered to a desired direction through a phase shift between arrays. Therefore, this technique allows the HF radar to capture the whole echoes coming from the sea [14]. The HF Radar system commonly known for DF technique is CODAR SeaSonde and for BF is WERA [12], [14]. In a research of [15], WERA and CODAR systems were compared with moored ADCPs in monitoring sea surface currents. The results showed that both systems were capable in surface current mapping, both for radial currents and total velocity vectors.

Three HF Radar systems from CODAR have been deployed in the north of Vietnam providing with better knowledge on general circulation and sea surface current variability in this area [16]. Notwithstanding, their operating frequency was rather low, resulting in a coarse resolution of the data, thus likely incapable to capture small-scale local motions occurring in the coastal regions. Differ from CODAR, WERA

can be more flexible in implementation since it is a mobile system and can be deployed both in DF or BF technique. The operating frequencies of WERA can be setup flexibly or at dual frequency. Therefore, the implementation of WERA HF Radar systems in Vietnam can resolve the problem of coastal data inadequacy and coarse spatial resolution. However, the data obtained from HF Radar need to be post-processed to remove noise and spikes as well as to fill gaps in the data. Within the scope of this paper, the surface current velocities were reconstructed from WERA measurements performed in 2019, along the middle southern coast of Vietnam (offshore of Phu Yen). The acquired data are used to assess the variability of sea surface currents in this region.

II. HF RADAR MEASUREMENT

Two WERA stations, operating at frequency 16.15MHz, were installed in Phu Yen, Vietnam from the middle of April to the end of May, 2019. The 1st site (denoted as V1) was located at [13°10'11"N 109°17'42"E] and the 2nd site (denoted as V2) was located at [13°00'13"N 109°22'46"E] (Fig. 2). The range of this setup for radial currents can reach 80km in favorable weather conditions. The data integration was 2048 samples and at an acquisition interval of 30 minutes. In that campaign, surface currents and wind waves have been measured.

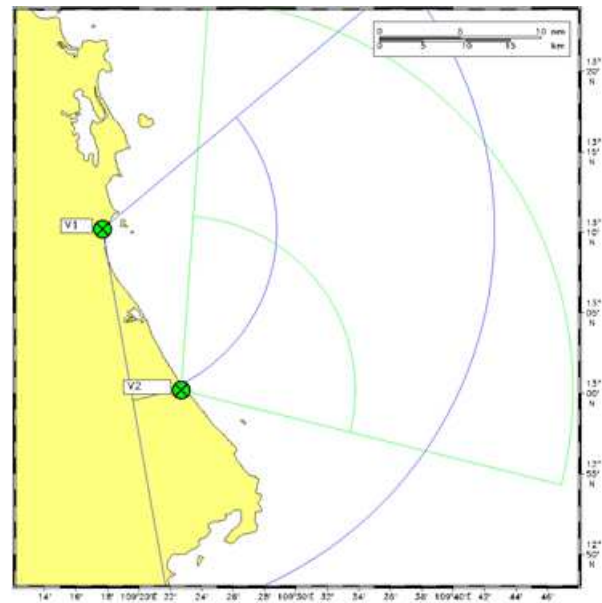


Fig. 2. Spatial coverage by WERA radars installed in May 2019 in Phu Yen, Vietnam. The radar site locations are shown by green circles.

The surface radial currents obtained at each site were calculated from the 1st order peaks in the power spectrum density of received signals from the sea [17]. Although most of the radial current data mapped by WERA were good, some locations were still disturbed by noise occurring within certain range cells (Fig. 3-left). These noise is the result of radio frequency interference (RFI) due to power supply, radio on ships, or other sources of electromagnetic interference. The RFI noise is inevitable and dependent on the deploying location. However, it can be filtered through several noise-filtering methods which are explained in Section III.A.

III. RECONSTRUCTION OF SURFACE CURRENT VELOCITIES

A. Despiking radial currents

Before being reconstructed with a more sophisticated gap filling method, firstly, outliers had to be removed from the datasets. Subsequently, an upper threshold for radial velocity accuracy i.e. RMSE was set to remove leftover spikes in the data. The radial velocity accuracy was calculated by WERA software from set of samples over an integration time of 30 minutes. It should be noted that the chosen threshold depends on the characteristics of the datasets, which can vary with features of the location and installation i.e. other sources of noise and the magnitude of sea currents. At the two radar locations, the noise along some range cells at a distance of more than 25km is the effect of the 50-60Hz interference caused by electrical devices or cables. Thus, the second filter was implemented only for ranges more than 25km from the coastline. In this research, the threshold was empirically chosen at 0.45 m/s. Fig. 3-right show the radial currents have been freed of noise.

B. 2DVar-EOF

1) Method in summary

The 2D variational interpolation in conjunction with empirical orthogonal function decomposition (2DVar-EOF) was introduced by [1] as an improved method for HF radar's radial current interpolation in comparison to the 2DVar method alone, proposed in [2]. In this paper, the 2DVar-EOF was used for the reconstruction of radial current velocity vector fields. The method can be summarized in sequencing steps below:

- 2DVar-EOF firstly decomposes the covariance matrix of radial current velocities on the orthogonal function basis.
- The covariance matrix (C) of the data after spectral decomposition is separated into two components: the noise and signal, determined by using a set of EOFs (modes) which demonstrated the variability fractions of the radial currents. Well-resolved data in line with EOF modes are identified as signal and the unresolved data are considered as the noise. Radial velocities missing in the time series are reconstructed using the former set of modes.
- The final step is the current vector map reconstruction using 2DVar interpolation technique. This is a non-local method of spatial interpolation which means that the velocity vector reconstruction in one point requires the observed radial velocities from the whole domain. The interpolation is performed by minimizing a cost function (J). This cost function includes additional terms (penalty terms) which account for smoothness, vorticity (*curl*), and divergence (*div*) of the current field.

Details of the formulation and further explanations are described in [1].

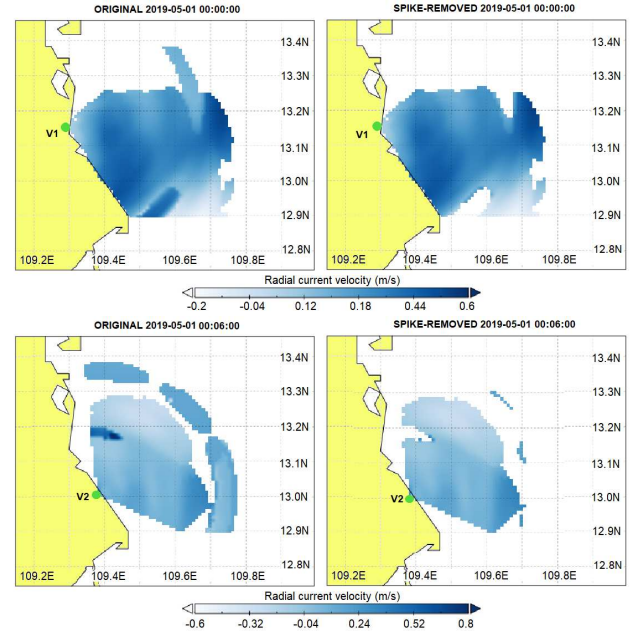


Fig. 3. Radial current velocities from the individual radar measurements before (left) and after (right) spike removal. Radar location is shown in green.

2) Reconstruction of surface current velocities

The radial velocities at the two stations after de-spiking step was ingested in 2DVar-EOF. The configuration of the 2DVar-EOF is described in TABLE I.

The interpolation of surface currents was implemented on an area, where the available data concentrated at most, including the overlapping area between two radar stations, illustrated in the Fig. 4 below.

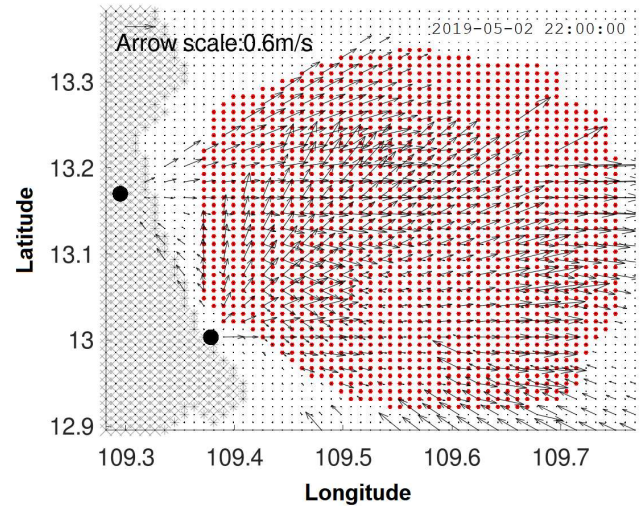


Fig. 4. Vectors of the radial current velocities at two WERA stations after spike removal (black arrows) and the velocity interpolation grid used in 2dVar. The land is illustrated in gray in the left side of the domain. The interpolation area is marked as red. Black dots show the two radar location on the seashore in Phu Yen.

TABLE I. CONFIGURATION OF THE 2DVAR-EOF PROGRAM

Item	Value	Item	Value
Domain resolution	1 km	Smoothing factor (<i>div</i>)	10^3
Domain size (rows x columns)	55 x 55	Smoothing vorticity factor (<i>curl</i>)	1.0
Number of interpolation grid cells	1696	Smoothing velocity factor (<i>uv</i>)	0.1
Number of EOF modes (K_r)	2556	Noise level in data	20%

IV. SURFACE CURRENT VARIABILITY

The coastal circulation observed by the radars and reported hereafter is strongly influenced by the large-scale SCSWBC which is characterized by an intense flow with magnitude exceeding 1 m s^{-1} (Fig. 6). Interestingly, the surface current fields observed by the WERA radars during 15 days of study period indicate two distinct pictures occurring in sub-periods with different wind forcing: north and eastward flow during the southern wind (Fig. 6a, d) and southward flow in the calm wind period (Fig. 6b, c). As already pointed out in [4], the monsoon wind plays an important role in the variation of the SCSWBC. In mid-winter, the SCSWBC is strong and flows southwestward along Vietnamese coast. During summer, the SCSWBC is degraded along with the complete reversal of the northeastern to southwestern wind generating a strong upwelling. Therefore the summer circulation is characterized by a rather complex pattern. Along the coasts of Vietnam from above 14°N to the north, current fields have a bimodal behavior: weakening the southward coastal current and meandering current motions. Meanwhile, in the southern segment from below 14°N to the south, the flow is northward from the Karimata Strait up to about 13°N , where it separates from the coast forming an eastward offshore current which can be found from the model field shown in Fig. 1. The presence of this offshore current together with the feature of a short continental shelf result in a deep bathymetric profile which then lead to the displacement of water nearshore. This could be the reason for the later formation of the large upwelling during the summer monsoon, while the southwest monsoon wind becomes dominant over the region. This conclusion however needs to be further studied with longer measurement time-series.

In addition to quantifying the mean flow field, it is of great interest to explore the role of small-scale processes which control the variability of the regional circulation. Here, we quantify the radius of deformation (R_d), which roughly estimates the spatial dimensions of small motions,

$$R_d \approx \sqrt{\left(\frac{g'h}{2}\right)/f}$$

by assuming a two-layer flow, with the reduced gravity $g' \approx 10^{-2} \text{ m s}^{-2}$, and the water depth $h \approx 20 \text{ m}$ from Fig. 10 of [18] and the Coriolis force $f \approx 0.327 \times 10^{-4} \text{ s}^{-1}$. The estimated $R_d \approx 9 \text{ km}$ was roughly equal to one third of the domain size. The Rossby number, $R_o = U / (f R_d)$, was estimated with by taking the velocity $U = 0.4 \text{ m s}^{-1}$ thus yielding $R_o \approx 1.35$. This value of Rossby number in oceanic systems indicates that small-scale

processes might play an important role, and the resulting flow field is largely influenced by the local forcing.

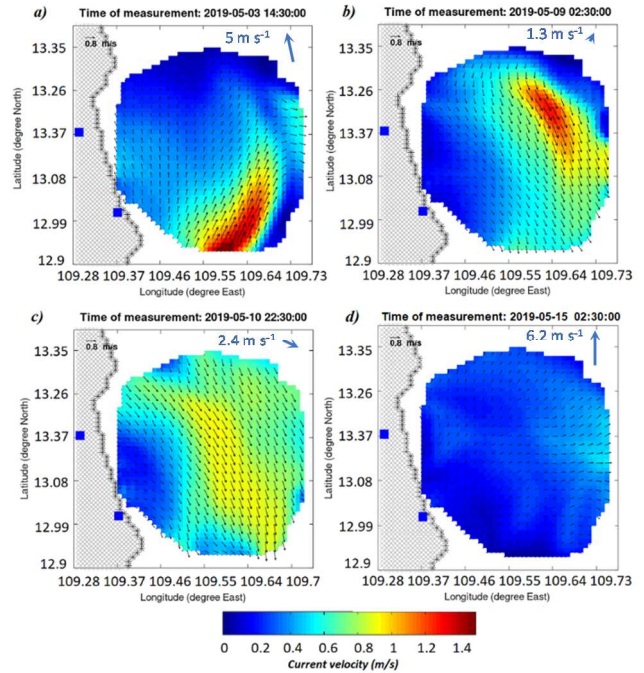


Fig. 5. Surface current velocities measured by HF radar and reconstructed by 2DVar method demonstrated some prominent features of coastal circulation in the South China Sea (SCS) region: a) SCSWBC intrusion; b-c) Longshore current intruded from the north of the domain and expanded over the entire area for several days; d) An occurrence of an offshore current corresponding to the upwelling was detected in Fig. 1 during April-May in the area. Blue squares show the radar site location. Renalysis wind (Era-interim) during the same periods are denoted by the blue vectors in the upper right corner.

To assess the variability of the surface currents, we conducted the rotary spectral analysis (hereafter referred to as RSA) of the HFR data to retrieve the major modes of the flow field variability. The method was used to process a 1.5-month long of HFR data during the whole measurement period. Fig. 7 shows the results of the spectral analysis for a point located in the middle of the radar domain. The spectrum shows significant peaks in the power spectral density (PSD) at tidal diurnal (25-hr period) and semi-diurnal (12.5-hr period) frequencies that dominate the flow variability (Fig. 6). The other significant peak corresponds to the period of 50 hours which matches the frequency of inertial motions. In the spectrum, energy of the diurnal tidal constituents is the highest and one order of magnitude larger than the other two peaks, suggesting that diurnal tide dominates the current variability in the area of study. In addition, there are smaller peaks toward the higher frequencies of variability observed in the spectrum. However, the short period of analysis (1.5 months) could not resolve these signals from the noise unequivocally.

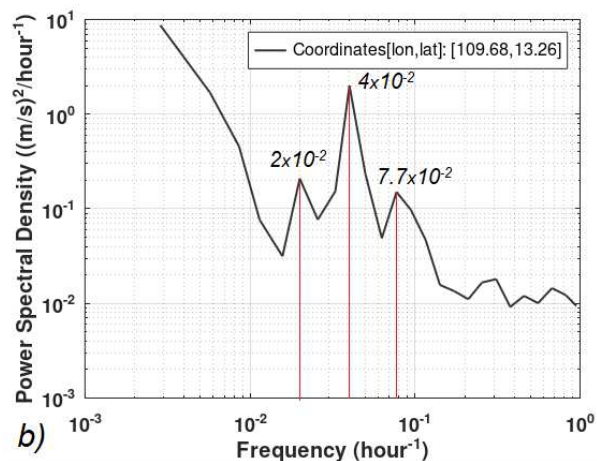


Fig. 6. Power spectral density (PSD) at: a) point [109.41°E, 13.16°N] located in the middle of the domain. A broad peak is identified at frequency 4×10^{-2} (hour⁻¹), corresponding to a period of 25 hours which concentrated the most energy and at 13 hours (7.7×10^{-2} hour⁻¹) explained the semidiurnal and diurnal tidal components. The peak at 50-hour period (2×10^{-2} hour⁻¹) represents the inertial motions. Their contribution to current velocity variability appears larger than that of semi-diurnal tidal constituents in the area.

V. DISCUSSIONS AND FINAL REMARKS

The results proved the capability of HF radars in monitoring surface ocean currents and the current variability within coastal areas. The reconstructed sea surface current velocities obtained from 2DVar-EOF can be a reliable input for further modelling approaches including Lagrangian transport simulation to predict the track of objects or substances in the ocean. This is a helpful application in search and rescue services and environmental protection.

Although the radar measurement campaign was conducted within only one and a half month, the measured data still delivered satisfied results to capture the sea surface current patterns at the beginning of summer monsoon. In order to acquire a comprehensive understanding of the dynamics in the area, another measurement campaign during winter monsoon is recommended and with a longer period of measurement. In addition, together with the installation of HF radars, *in situ* measurements such as moored AWAC or drifting buoys should be used to validate and compare with the HF radar measurements.

Last but not least, this preliminary research can be a basis for other possible deployment of HF radar systems along coastal regions of Vietnam.

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