Vietnam Academy of Science and Technology

Vietnam Journal of Marine Science and Technology

journal homepage: vjs.ac.vn/index.php/jmst

# Upwelling phenomenon in the marine regions of Southern Central of Vietnam: a review

**Bui Hong Long*, Phan Minh Thu**

*Institute of Oceanography, VAST, Vietnam*
*E-mail: buihonglongion@gmail.com

Received: 26 December 2021; Accepted: 30 March 2022

**ABSTRACT**

Upwelling is an oceanographic phenomenon that involves the physical process and contributes to changes in chemistry, biology, and natural resources. So, systematically, it is the particular ecosystems of whole marine regions with the upwelling. The strong upwelling waters in South Central Regions of Vietnam have uncertain features of the East Vietnam Sea (Bien Dong) and special characteristics of a coastal upwelling area, recorded in international scientific papers in the twentieth century. Their first signals were discovered in the early 1930s through conceptual ideas. The upwelling phenomenon is officially confirmed by scientific results of marine investigations of the NAGA Expedition (1959–1961). The paper aims to review and discuss the physical from Vietnamese investigation and results since 1990s. The following factors are the most contributing to forming and developing the strong upwelling in Southern Central Waters: (1) Influence scale (Mezo- and micro-scale); (2) Forming causes and developing mechanism of upwelling phenomenon, such as monsoon, morphography, shoreline, and western boundary current system of the East Vietnam Sea; (3) Influence of the water-mass from Mekong River on the upwelling area; (4) Ecological environmental consequences; (5) Impacts of the atmospheric-oceanic interaction processes on the western EVS on upwelling. Additionally, the review has targeted findings of upwelling phenomenon mainly in Vietnamese waters based on remote sensing analysis and reanalysis data series to simulate their forming, mechanizing, fluctuating models and the impacts of upwelling in the EVS on resources and ecosystems. The coupled atmosphere-ocean models resulted the upwelling mechanisms and formation. The long-time series of upwelling phenomenon (Macroscale) were evaluated by remote sensing and reanalyzed data series. It is also providing the supplementing and detailing causes and mechanisms of upwelling formation; impacts and interactions of upwelling on marine physics and hydrodynamics (ocean vortexes, seawater temperature), biochemical (nutrients, plankton organisms), and resources (fish, seafood). Within the framework of strong upwelling waters in the Southern Central Regions (Vietnam), the review has not only mentioned partly clarified scientific results but also indicates the limitations and challenges which were faced and encountered in the forecasters of upwelling phenomena in the future.

**Keywords:** Upwelling phenomenon, natural resources, East Vietnam Sea, Bien Dong.

*Citation*: Bui Hong Long, and Phan Minh Thu, 2022. Upwelling phenomenon in the marine regions of Southern Central of Vietnam: a review. *Vietnam Journal of Marine Science and Technology*, *22*(2), 103–122. https://doi.org/10.15625/1859-3097/17231

## INTRODUCTION

Upwelling is the upward movement of deep water to the surface in the ocean and semi-enclosed and open seas [1]. If only considering the formed location of the upwellings in the ocean, they are divided into types: coastal, equatorial, Southern Ocean upwelling, ones formed in the waters around offshore islands, ridges, or seamounts, in somewhere having tropical cyclone, and/or artificial upwelling. Coastal upwelling always comes with several results from ecology, physics, and hydrology, such as biodiversity changes, the abundance of marine resources, upwelled nutrient-rich, cool sea surface temperatures (SST), low dissolved oxygen, localized climate, fluctuating circulation, interacting water masses. Naturally, the boundary zone between upwelling and adjacent waters is often high in fish productions.

The upwellings are formed by several drivers, including (1) the combining wind, Coriolis force (in Northern and Southern Hemisphere), and Ekman transport causes the movement surface water from the shore to the sea, as the same time the upward water current from deeper or bottom layer to surface layer for a water balance; (2) the eddy effect of the wind field on the sea surface, the current systems on the deep layers of continental shelf could form water circulation as cyclones and anticyclones, which cause vertical movements of water rising (upwelling) and descending (downwelling); that is Ekman Pumping effect; (3) the interacting opposite directions of regular current systems, which forms dipole vortices, causing the flowed divergence effect between these vortices that lead to the surface water in coastal regions to be downwelling and the deeper water be rising upward for replacement; (4) Tidal front; and (5) The effect of fresh water-mass flow from the river affects current system on the edge of the continental shelf. Besides all these causes, the formed upwelling has to depend on coastal topography, shoreline direction, morphography, and slope of the seabed in waters. The upwelling is also influenced and affected by large-scale processes of climate, monsoon, ENSO (El Niño - Southern Oscillation), IOD (Indian Ocean Dipole), IOU (Indian Ocean Upwelling), trans-equatorial monsoon flow, the irregular cyclonic system in the western equatorial Pacific Ocean, and Gill response.

Several different scientific opinions exited, but they have a general mechanism for the upwelling phenomenon. The combining effects of wind, Coriolis effect, and Ekman transport are the main causes of upwelling, although they have different functions for diverse types of upwelling. Within the generally upwelling process, winds blow across the sea surface in one direction, producing a wind-water interaction. On account of the wind, the water is transported a net of $90^o$ from the wind direction by Coriolis forces and Ekman transport. Ekman transport causes the surface water to transfer at about a $45^o$ angle from the wind direction, and the friction between the surface water layer with its below layer results in the successive layers moving in the same direction, resulting in a spiral of water going downward in the water column. Formerly, due to Coriolis forces, the surface water transfers to the right of wind direction in the Northern hemisphere, whereas it has left of the direction wind in the Southern Hemisphere. As the net movement of water is divergent, deep water’s upwelling moves upward and replaces the lost water on the surface.

However, the mechanism of the upwelling phenomenon and its contributed factors, which can impact the forming, developing, and declining processes, are very complicated: They are multifactorial, multi-tempo-spatial processes to form a particular ecosystem, but do these geographic areas have typical organisms? This question has been discovered and clarified gradually. Nowadays, even in Vietnamese waters, the perception and understanding of upwelling still have several challenges for research and development.

Thus, this paper aims to collect national and international scientific material of the upwelling phenomenon and its related processes in the Vietnamese Sea and the East Vietnam Sea (EVS) (Figs. 1–3). Almost this material (a total of 371 CTD casts) could help to be detailed the strong upwelling phenomenon in the Southern Center Waters (SCW) of Vietnam.

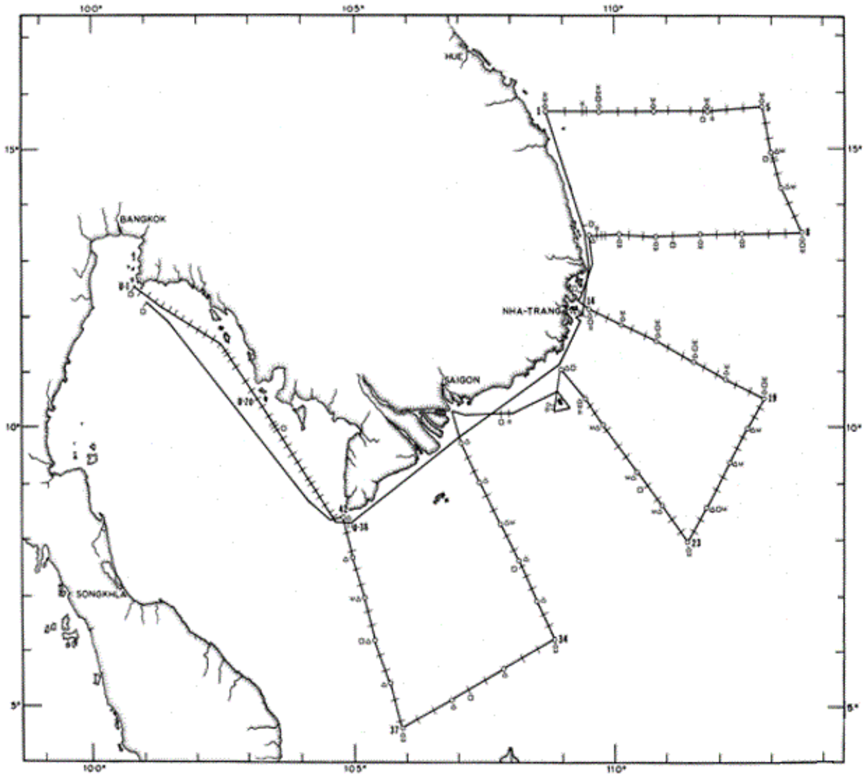



*Figure 1.* The station transects for physical and hydrological measurement in the NAGA expeditions in Vietnamese Sea (1959–1961)

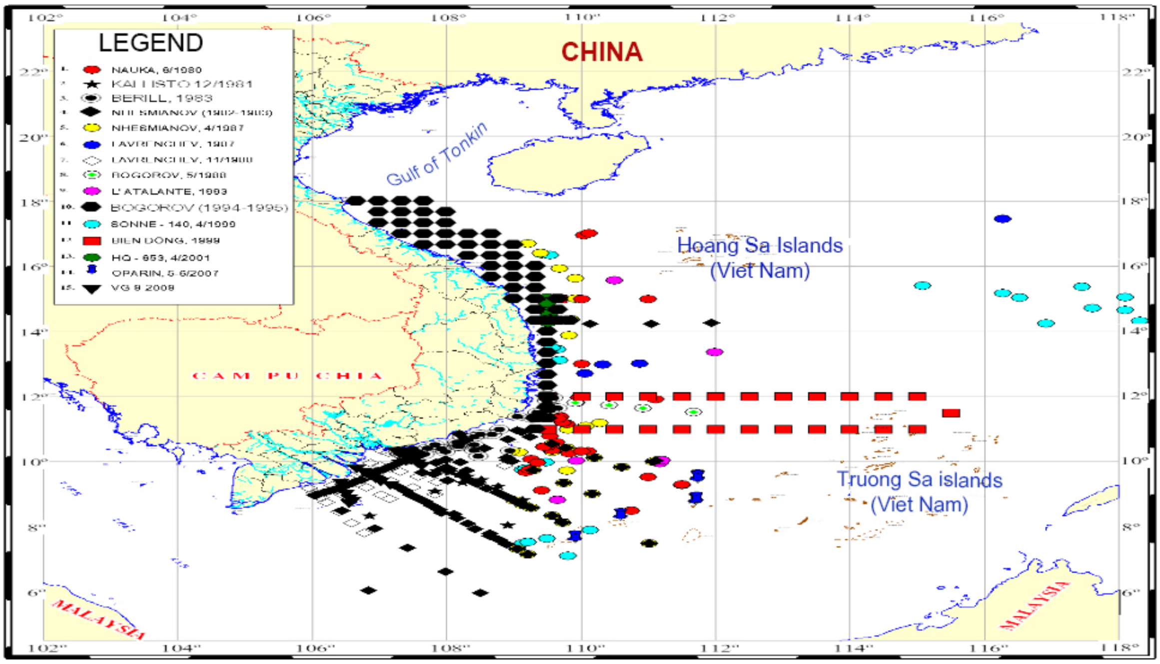



*Figure 2.* Diagram of main cruises for physical and hydrological measurement in continental shelf of Vietnam (1980–2009)

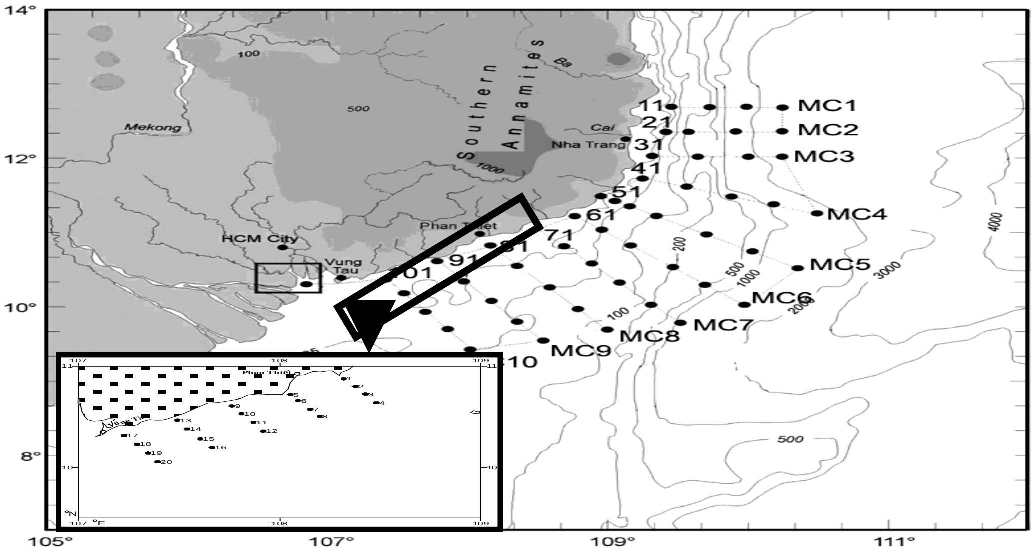



*Figure 3.* Diagram stations of VG3, 4, 7, 8 by R/V Marine Research (Ministry of Natural Resources and Environment) and R/V SONNE 187-2 (Joint Project of Vietnam - Germany, 2003–2006)

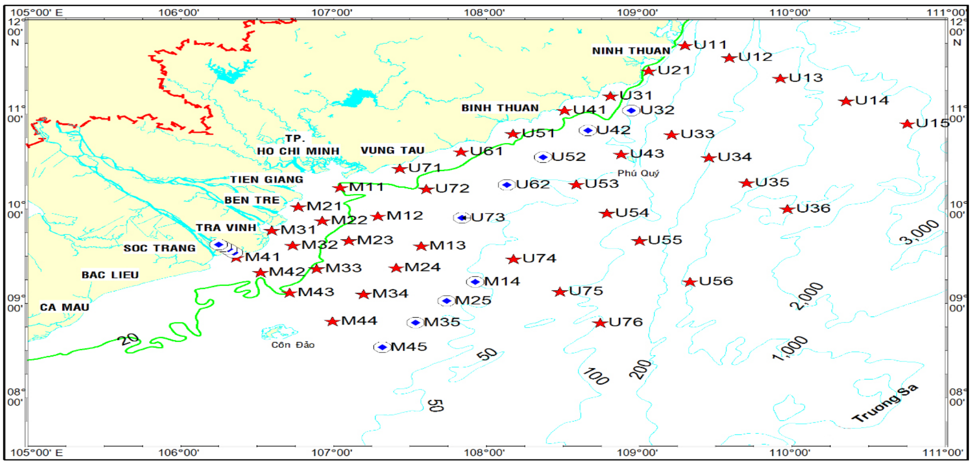



*Figure 4.* Stations in the general cruises of joint project of Vietnam - USA (2013–2015)

*Table 1.* General information of data for upwelling research

| Cruise | Sources | Period | Number of CTD casts | Model of CTD |
|---|---|---|---|---|
| VG3 | Vietnam - Germany | 8/7–28/7/2003 | 38 | SBE19+ |
| VG4 | Vietnam - Germany | 21/4–1/5/2004 | 38 | SBE19+ |
| VG7 | Vietnam - Germany | 8/7–26/7/2004 | 34 | SBE19+ |
| VG8 | Vietnam - Germany | 3/3–13/3/2005 | 22 | SBE19+ |
| SONNE | Vietnam - Germany | 12/4–21/4/2006 | 68 | SBE19+ |
| V.Ru11 | Vietnam - Germany | 28/4–06/5/2011 | 60 | SBE19+ |
| V.US-13 | Vietnam - Germany | 10/9–29/10/2013 | 28 | SBE19+ |
| V.US-15 | Vietnam - USA | 21/5–31/5/2015 | 51 | SBE19+ |
| DTCS-16 | Institute of Oceanography | 16/7–20/7/2016 | 17 | SBE19+ |
| DTCS-17 | Institute of Oceanography | 11–13/7&9–10/8/2017 | 15 | SBE19+ |

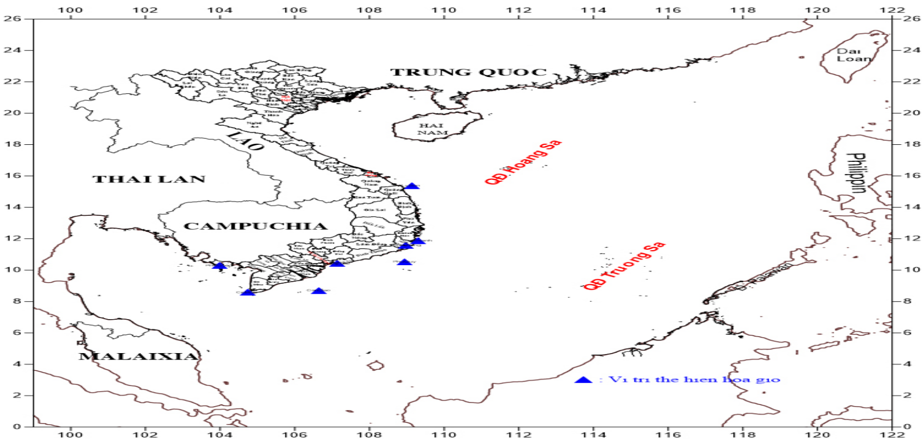



*Figure 5.* Stations for wind observation

## UPWELLING PHENOMENON IN THE EAST VIETNAM SEA AND VIETNAMESE SEA

### Upwelling in world oceans

The upwelling areas, famous high fishing production in the world, are located in Peru, Chile (South America), California, East Florida, Somalia, Ghine, etc., whereas in the East Vietnam Sea, the strongly one is notably in the Southern Center Waters (Vietnam) (Figurre 6).

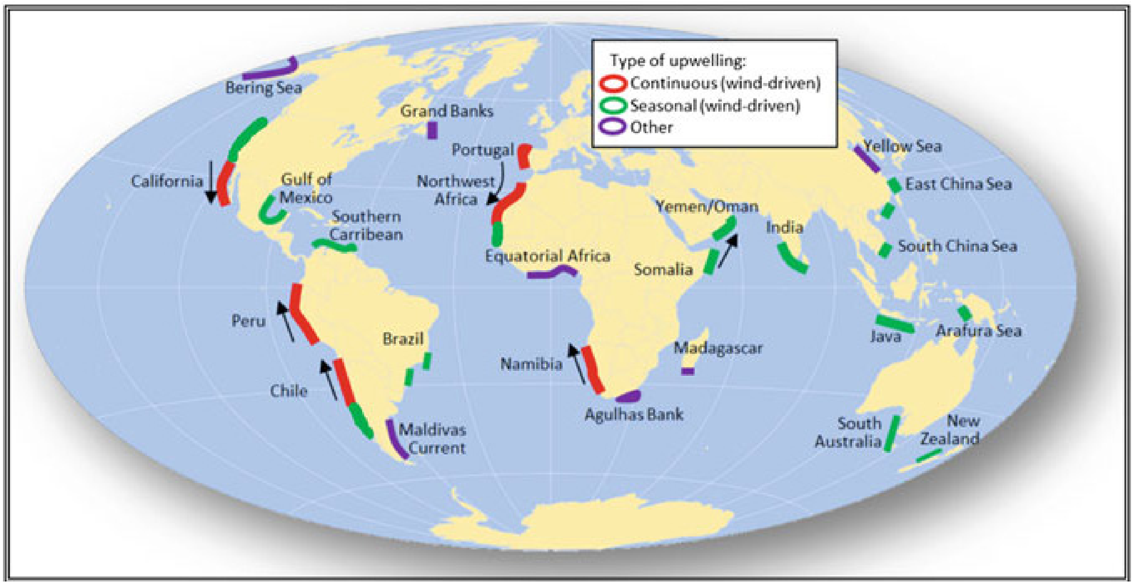



*Figure 6.* Strongly coastal upwelling regions in the world oceans [2]

### Upwelling in East Vietnam Sea

It has been recorded in 12 main upwelling ones (occurring frequently) and 4 weak upwelling ones (occurring infrequently) in the EVS (Fig. 8), with key features as follows:

1. In the northern part of the EVS, the upwellings in summer are distributed along the east coast of Hainan island and the east coast of Guangdong and southern Fujian.

2. In the western part of the EVS, the coastal upwellings in the summer often occurred along the coast of Vietnam, their features were the most vigorous intensity in August and an accompanying cold jet current

extending eastward from the coast to the sea. The cold vortexes are localized in the central coastal waters of Vietnam.

3. Large cold vortex is localized in Luzon Strait in winter.

4. Four upwellings are along the southwest and northwest coasts of Taiwan Strait, around Taiwan Bank, and Penghu islands.

5. Coastal upwellings at the estuary of the Yangtze river and along the Zhejiang coast are localized in the East China Sea. In addition, a cold zone also occurred in the continental shelf of the East China Sea and the marine area off the northeastern Taiwan island.

6. Furthermore, four other (infrequently and weak) upwellings in the EVS have irregularly appeared in northern Bohai Strait [3], offshore the southwestern Hainan island [4], along the eastern coast of Peninsular Malaysia [5], and nearby southeastern Sabah coast [6].

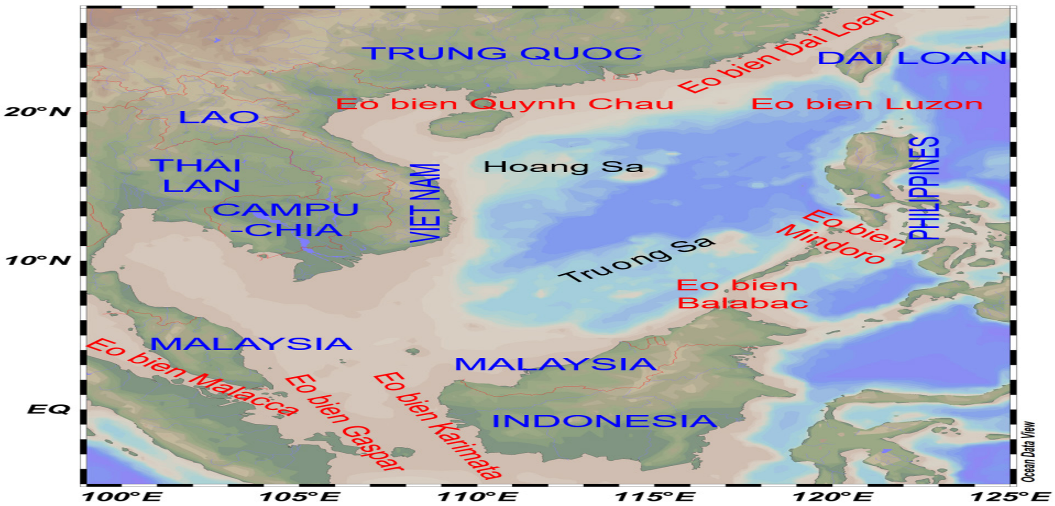



*Figure 7.* Geographical Features in East Vietnam Sea

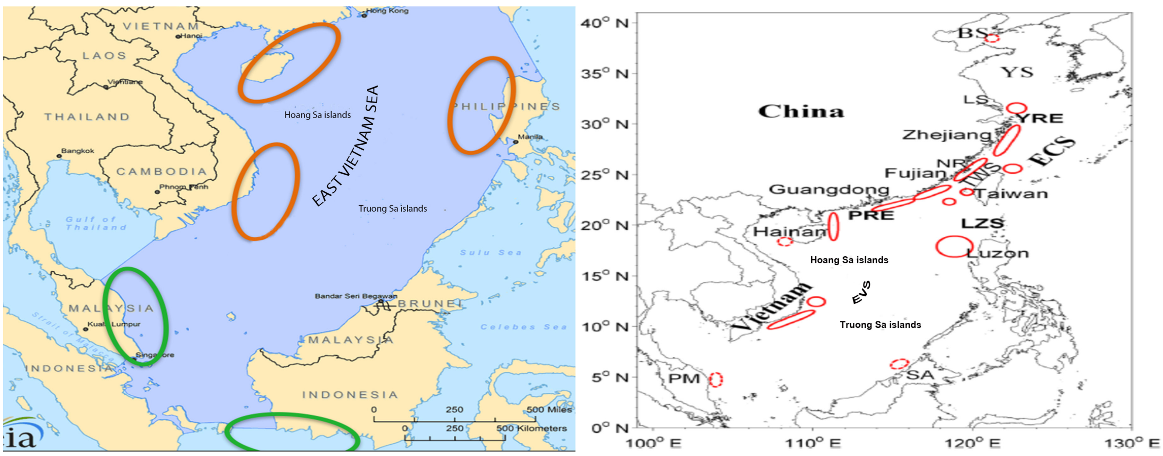



*Figure 8.* Distribution of upwelling regions in East Vietnam Sea [7]. Red ellipses or circles indicated the locations of large upwelling (occurring with intensity and frequency). Dashed lines of ellipses or circles are regions of the upwelling's occurring infrequently and weakly). Symbols of sea, strait and estuary: TWS (Taiwan Strait), LZS (Luzon Strait); and LS (Lüsi Strait), NR (Nanri) and SA (Sabah), East China Sea (ECS), Yellow Sea (YS) and Bohai Sea (BS), Yangtze estuary (YRE), Pearl estuary (PRE), PM (Peninsular Malaysia)

**Results of upwelling in Vietnamese marine regions**

The upwelling phenomenon in the waters of Vietnam has been mentioned in scientific reports and published articles based on remote sensing analysis of surface sea temperature and chlorophyll-a concentration, such as waters of Bach Long Vi islands, the Gulf of Tonkin, Con Dao, and Binh Cang bay (Nha Trang). However, these existing upwellings are only on a small/local scale, both in spatial and temporal existence. Therefore, this paper is targeted at the strong upwelling waters of Vietnamese SCW.

The coastal upwelling phenomenon in Southern marine regions of Vietnam was firstly discovered by NAGA Expedition by Vietnam and the United States in 1959–1960. Its result was detected by analyzing the spatial distribution and structure of hydrological factors (such as temperature, salinity, and density of seawater). As a result, the coastal and continental shelf waters in the southern center of Vietnam happened in regions of low temperature, high salinity, and high density that resulted from upwelling water from deep waters [8–10].

After the Liberation Day of South Vietnam, the coastal upwelling phenomenon in the SCW was continued by scientists of Nha Trang Institute of Oceanography under national projects on physical-hydrological conditions of the waters from Thuan Hai to Minh Hai (1978–1980); the physical-hydrological of waters in the continental shelf in Southern Vietnam (code 48.06.01, in 1981–1985); on the hydrological and dynamic structure of the EVS (code 48B.01.01, in 1986–1990); and especially, the project of strong upwelling phenomenon in the SCW (code KT03.05, in 1991–1995).

Until 2003, only 3 major projects had been investigated and studied in the fields of upwelling phenomenon in the SCW, including cruises of the NAGA Expedition (1959–1960), the Thuan Hai - Minh Hai Program (1978–1980), and the national project KT03-05 (1991–1995). The first two programs were general cruises, whereas the third project targeted the thematic subject of the strong upwelling phenomenon in the SCW, in which physical factors (meteorology, hydrology, and circulation), aquatic chemistry, geochemistry, and some special ecological effects were simultaneously observed to orient for finding geometric-physical features of the upwelling water as well as its ecological consequences. However, due to funding and scientific equipment limitations, the investigation of upwelling thematic could only be done in a very narrow region of the center of the strongest upwelling water in the Ninh Thuan - North Binh Thuan. As a result, the measured and observed data series were insufficient to study the upwelling. Thus, the upwelling characteristics in coastal and continental shelf regions of Southern Vietnam have been investigated by the Nha Trang Institute of Oceanography based on combining observed data and numerical hydrodynamic models.

***Main causes of upwelling water***

The main causes of upwelling in the SCW are the regularly and seasonally strong current systems in the Western EVS, the structural features of the shoreline - sea floor, the impact of the Southwest monsoon. During the summer, wind is dominated southwest and west directions. These wind directions interacted a favorable angle from the main direction of the shoreline are formed coastal upwelling phenomenon. Furthermore, the atmospheric vortex, existed fairly stable in the SCW, is capable of causing cyclonic circulation accompanied by upwelling phenomenon.

***Basic characteristics of upwelling***

*Influent boundary of upwelling*

Upwellings exist on the whole of coastal and continental shelf regions of the SCW, from Binh Thuan to Binh Dinh, but the strongest upwelling center is observed in the coastal and continental shelf waters of Ninh Thuan - North Binh Thuan. Upwelling water comes from deeper layers of approximately 200 m [11].

*Cycle of upwelling*

Upwelling is intensely active in the seasonal cycles and synoptic events. Every year, it occurs from May to September, and the strongest upwelling in the period of June–August. The synoptic event of current, being able to activate in from 2–3 days to 8–9 days, is following the synopsis of the southwest monsoon wind. However, the upwelling fluctuations in time, intensity, and boundaries have not yet been understood.

*Upwelling intensity*

At the center of the most vigorous upwelling (waters of Ninh Thuan - North Binh Thuan), the velocity of the upwelling current can reach $10^{-1}$–$10^{-2}$ cm/s within synoptic oscillation, whereas it is about $10^{-3}$–$10^{-4}$ cm/s for the seasonal cycle. The rate of upwelling currents has the highest value at the starting layer (deeper than 200 m), reduces to the surface layer and is zero at the sea surface. The area of high ecological efficiency is not placed at the center of upwelling, but at the southwest edge of the center of strong upwelling within the triangle regions of Ca Na - Phu Quy - Phan Thiet. The features of the upwelling regions are the morphography of significant roughness, a passing hydrological front, a thermocline/halocline layer on the continental shelf - accumulated suspended substances, nutrients, organic matters, and carbonate; and high primary production. Thus, these regions may become a fishing ground for marine resources.

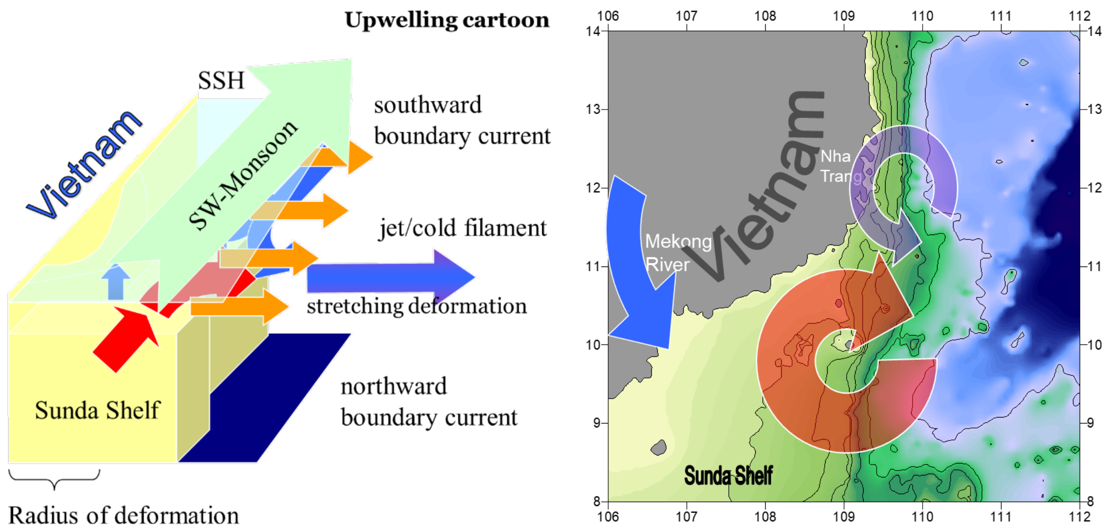



*Figure 9.* Mechanism of formation of strong upwelling waters in the south central sea of Vietnam (Vietnam - Germany Joint Project in 2003–2006)

Figure 10 shows the feature of upwelling phenomenon in the SCW of Vietnam, following:

The current regime, due to the influence of the southwest monsoon, typically from June to August 2005, presented the upwelling phenomenon in the SCW (Fig. 10).

The upwelling was most intense in June 2005, although in July 2005 the surface current speed reached the highest value of 61.2 cm/s in the direction of 107.763$^{o}$. The average current velocity is 7.4 cm/s in the study area [12].

The cause of formation, variation in intensity, and physical boundary of upwelling waters have local characteristics and are resulted from interactions of physical processes (Atmosphere - ocean interaction and interacting with bottom - coastline topography). Ekman transport, the interaction between the two strong current systems, one going down the south in the Western EVS and another going upward the north from the Sunda shelf, affects the Coriolis transform coefficient in the coastal regions. These results are the scientific foundation for achieving numerical models to assess the upwelling quickly.

Provision of a scientific basis and data sources helps to divide the water mass into the upwelling regions and to estimate the interaction between the water masses of the Mekong river and the upwelling of SCW.

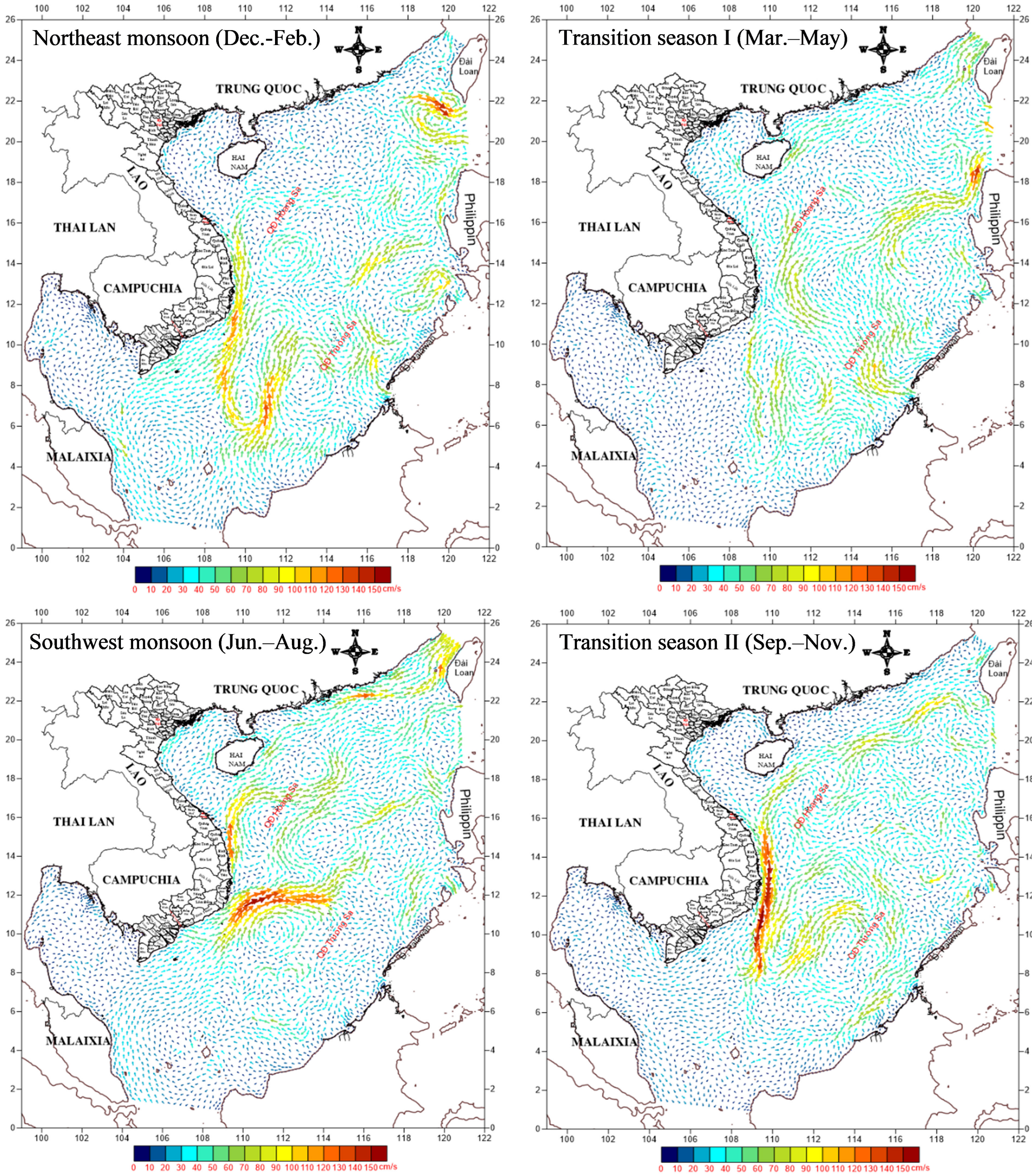



*Figure 10.* Distribution of averaged seasonal surface currents (3D model) (Vietnam - Germany Joint Project in 2003–2006)

In addition, the results of the Vietnam - USA Joint Project "Variation in the seasonal, annual, and interannual cycles of physical and biogeochemical processes of the EVS, Vietnam, including the changed from the NAGA Expedition". (2013–2017) done in the strong upwelling of the SCW indicated that:

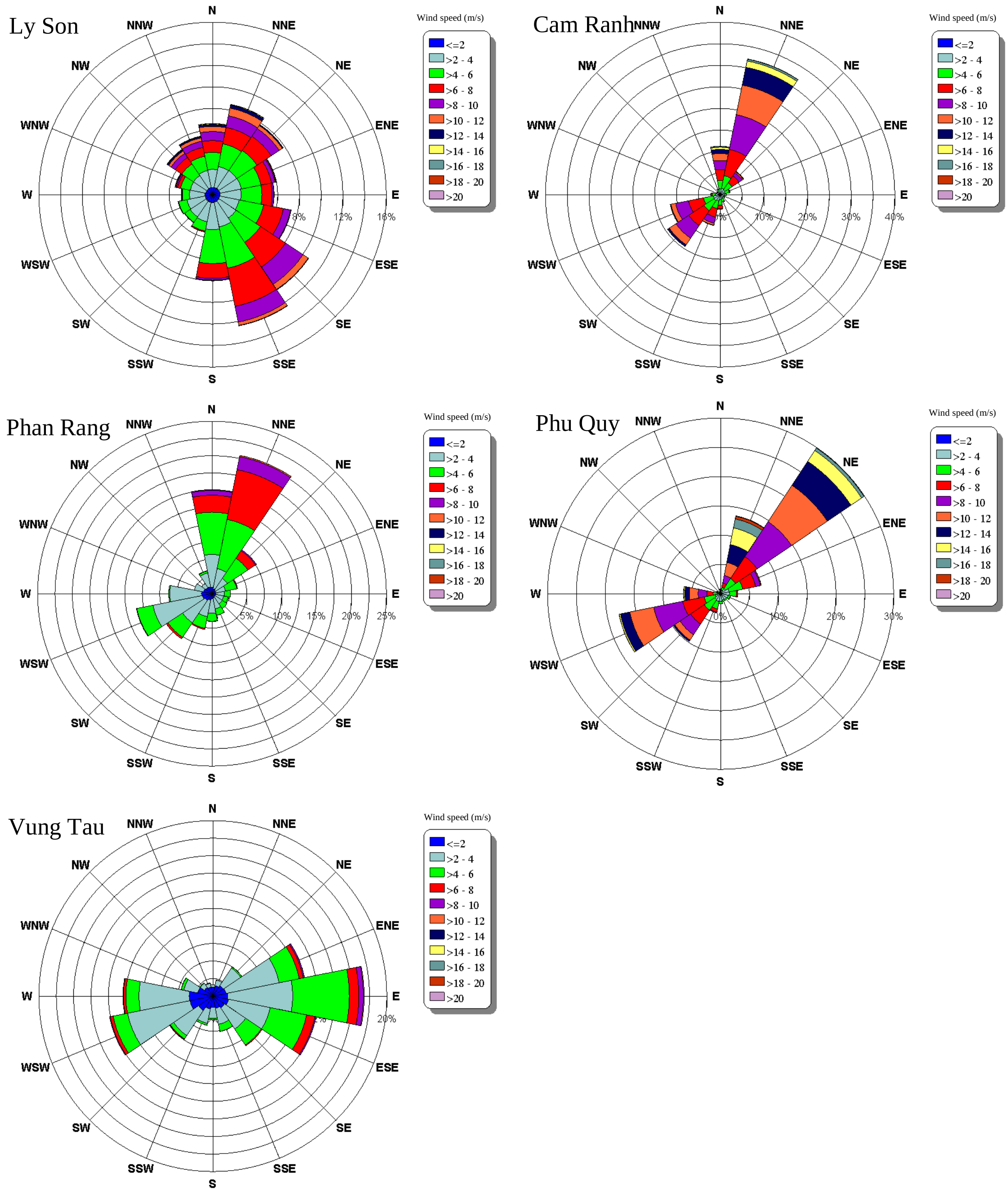



*Figure 11.* Wind diagram in studied stations using NCEP CFSR dataset (1979–2015), Unit: Averaged Wind Speed (m/s)

Spatial, seasonal and interannual variation of wind regime: Based on the reanalysis series of wind in NCEP CFSR in the period 1979–2015, features of wind in coastal and island stations were analyzed and presented as followings: (1) The impact of the Northeast monsoon was greater than that of the Southwest monsoon. The influence of the Northeast monsoon had gradually decreased from North to South, which might affect Vung Tau further. In contradiction to the Northeast monsoon, the Southwest monsoon's wind was strongest in

Vung Tau (dominant whole year), reduced to the north, but was not clear at Ly Son station (Figure 11). (2) At stations on offshore islands (e.g. Ly Son, Phu Quy, Con Dao), the annual and seasonal average wind speed may be more than 1.5–3 times stronger than coastal stations. (3) In the El Niño year, the prevailing wind direction was the NE and ENE, whereas the prevailing wind direction changed to the SW and WSW in the La Niña year. In a regular year, there seems to be no difference between the two monsoon wind fields. And (4) toward the south direction, the influence of ENSO phases (El Niño and La Niña) on the wind regime is reduced. Generally, the wind regime was strongly influenced by seasons and spatial distribution. This influence of the Northeast monsoon was more significant than that of the Southwest monsoon and gradually decreased from North to South for the Northeast monsoon and vice versa for the Southwest monsoon. The average annual and seasonal wind speed gradually increase from coastal waters to offshore regions, and it did not seem to be influenced by ENSO phases (El Niño and La Niña).

Seasonal fluctuations of some mainly hydrological factors: The thermo-saline relationship allows to determine the upwelling occurs in the SCW during the Southwest monsoon, whereas fresh water from the Mekong and Dong Nai river systems can affect the SCW in the Northeast monsoon. The thermocline layer may move from a water layer of 10–20 m to a water layer of 30–50 m. In addition, fluctuations in seawater temperature and salinity indicate the impact of climate anomalies. In terms of interannual changes, SST has increased over the past few decades. The annual average SST reached a high and abnormal value in 1987 (the development of strong El Niño), 1998 (the decline of strong El Niño), and 2010 (the end of the El Niño and development of strong La Niña). From the drop of weak La Niña to the development of moderate El Niño, the current velocity rapidly changed and increased abnormally in opposite directions. In terms of seasonal changes, temperature fluctuations have a lag phase of salinity. Salinity drops from March to October and increases from October to coming March. The unusually high salinity occurred during the year of the weakly El Niño, whereas the abnormally low salinity is in the decline during the weak La Niña. In the period of October and coming February, current direction is from North to South, whereas it has a path from South to North in the period of April–August. In March and September, the current direction of North-South axis is relatively weak.

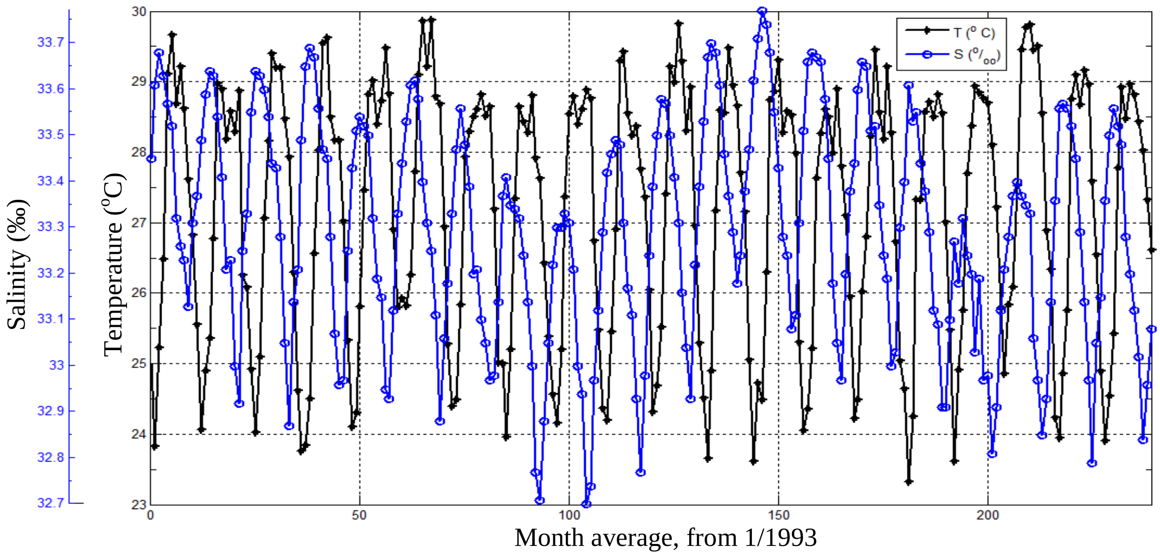


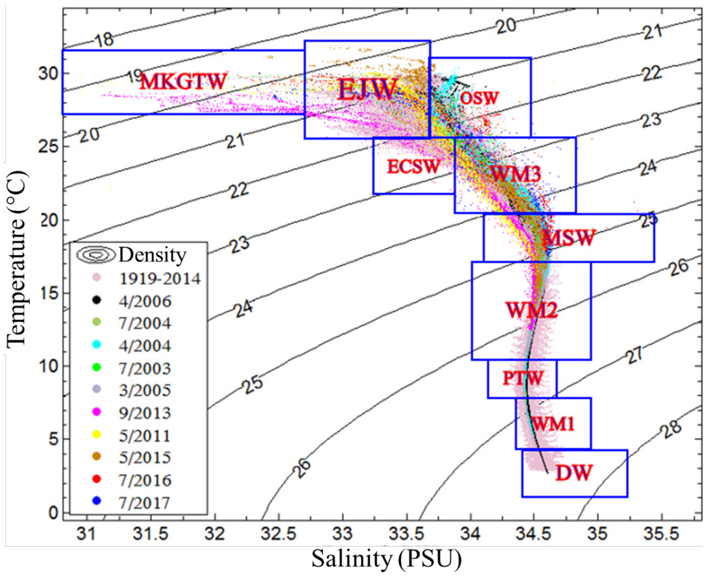

*Figure 12.* Monthly sea surface temperature and salinity (1993–2010) (Vietnam - USA Joint Project in 2013–2017]

In more future, material from the Pacific Ocean through the Luzon Strait can affect the center of the EVS. In contrast, they, from the Mekong river, can be transported along the shore and moved towards the Cape of Ca Mau (Southern current) or transported towards the strong upwelling waters of the SCW (Northern stream), depending on the intensity and duration (seasonal cycle) of the Southwest monsoon.

**Features of strong upwelling in the South-Central Waters and the changes under the influence of long-period interactions**

Generally, strong upwelling in the SCW is coastal with spatial distribution from coastal water to 300–400 km-offshore and from latitude 11–13$^o$N. The upwelling occurs in the Southwest monsoon (from June to September). The wind stress and eddy play a decisive role in forming and developing strong upwelling in coastal and offshore regions of the SCW. The double-layer current system changes seasonally in the coastal waters of Vietnamese SCW (the outer boundary of 80 km-shore from the coastline, the separation depth of the double-layer current system is about 50–100 m-depth. As the Southwest monsoon blows parallel to the shoreline, due to the Coriolis effect, Ekman Transport to the sea causes a volume of deeper water to rise to compensate for the surface water going offshore. In the upwelling regions, divergent currents exist towards the sea where two current systems (regular current from the North down and the wind current of the Southwest monsoon going from the South) meet and create a pair of dipole vortices (Figures 9, 10). This movement is based on the principle of water balance from the deeper layer to compensate for the amount of upper water going to the sea. The strong upwelling is located in the South of latitude 12$^o$N, whereas the waters in the North of latitude 12$^o$N and offshore of 200–400 km distance from the coastline are weaker upwelling. In addition, a hydrological front zone exists in the waters of Southern Ninh Thuan and Northern Binh Thuan, which have a high potential for fishing resources.

The SCW has seven main water masses, including deep water (DW); permanent thermocline water (PTW), maximum salinity water (MSW), offshore water (OSW), Mekong river and Gulf of Thailand water (MKGTW), Equator and the Java Sea water (EJW) and East China Sea water (ECSW), and three mixing masses, such as Mixing of DW and PTW (WM1), Mixing of PTW and MSW (WM2) and Mixing of MSW and OSW (WM3) (Figure 13, Table 2 [13]).




*Hình 13.* TS-diagram and typical distribution of water masses [13]

*Table 2.* Characteristics of water mass in South Central Marine of Vietnam [13]

| No. | Watermasses | Temperature ($^{o}$C) | Salinity (PSU) | Layer depth (m) |
|---|---|---|---|---|
| 1 | Deep Water (DW) | < 4.0 | > 34.4 | > 1,200 |
| 2 | Permanent Thermocline Water (PTW) | 7.0–10.0 | 34.2–35.0 | 400–700 |
| 3 | Mixing of DW and PTW (WM1) | 4.0–7.0 | 34.3–35.8 | 700–1200 |
| 4 | Maximum Salinity Water (MSW) | 16.5–20.0 | > 34.1 | 50–250 |
| 5 | Mixing of PTW and MSW (WM2) | 10.0–16.5 | 34.1–35.0 | 100–450 |
| 6 | Offshore Water (OSW) | 25.0–30.5 | 33.7–34.5 | 0–90 |
| 7 | Mixing of MSW and OSW (WM3) | 19.0–28.0 | 33.9–34.8 | 0–180 |
| 8 | Mekong River and Gulf of Thailand Water (MKGTW) | 27.0–31.5 | < 32.9 | 0–60 |
| 9 | Equator and Java Sea Water (EJW) | 25.5–31.0 | 32.5–33.7 | 0–80 |
| 10 | East China Sea Water (ECSW) | 21.0–25.0 | 33.2–33.9 | 0–80 |

## SCIENTIFIC QUESTIONS AND OUTLOOKS FOR UPWELLING IN EAST VIETNAM SEA

### Current system in western boundary of the East Vietnam Sea in the Southwest monsoon season

The interaction of two current systems: The results of research and simulation of the upwelling phenomenon have not yet discussed the consensus on the convergence and divergence regions of the above current systems in the western boundary of East Vietnam Sea under impacts of the Northeast and Southwest monsoons.

Generation of pair of vortex dipoles and their role: Vortex dipoles are generated in the SCW and fluctuate temporally and spatially but are still unclear. The question is whether the current divergence of this current system overlaps with the offshore diversion area due to Ekman Transport? This question has not been agreeably answered with specific scientific evidence.

Future, the properties, causes, and extent of formation of a vortex of the South Central Coast still need scientific evidence to elucidate.

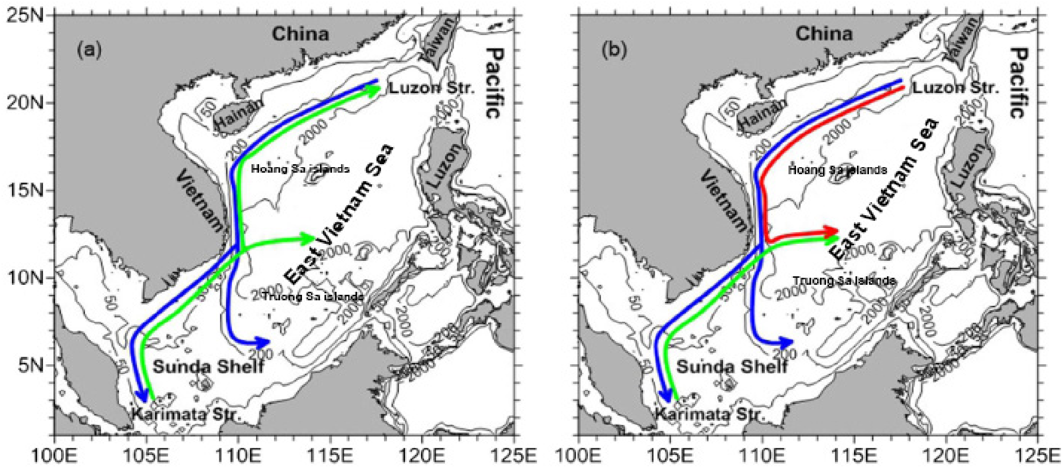



*Figure 14.* Current systems in western boundary of East Vietnam Sea. (a) Winter (blue) and summer (green) (e.g., [14–18]; Fangetal (2009); (b) The same as (a) (e.g., [19–23]) but having the eastward jet current in summer (red) existing in the adjacent regions of latitude 12$^{o}$N [11, 12, 24–28]

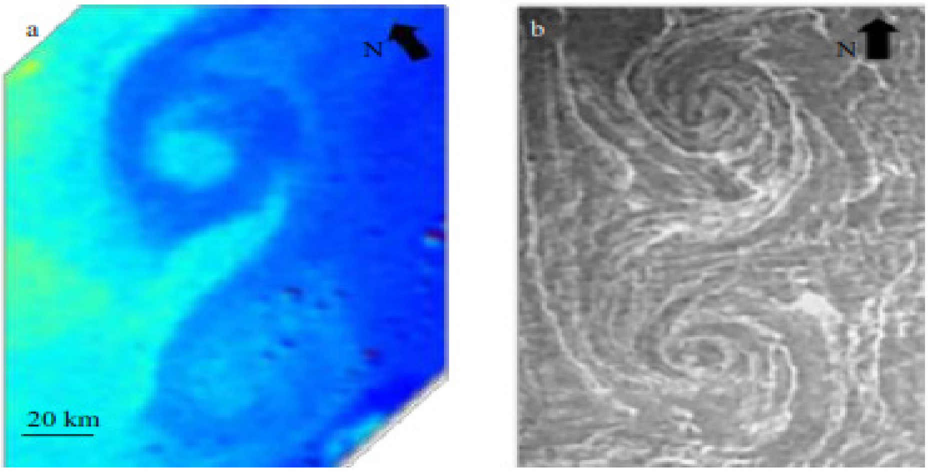



*Figure 15.* Comparison of a MERIS image of vortexes associated with a jet current off the Vietnamese coast of on July 29, 2009 (a) and spiral vortex train off the North coast of Africa in the Mediterranean Sea, taken from a spacecraft shuttle STS41G-35-94 (NASA) (b) [29]

**Origin of water masses formed the upwelling**

The origin of water masses is a very complex issue. Based on the results of dynamic studies, analysis of water masses, and properties of physical and chemical factors in the upwelling water, it is found that:

Bolton et al., [30] indicated that using radioisotope analysis ($\Delta^{14}C$) from Massive Porites in Nha Trang bay, the upwelled water from the deeper basin in the EVS originated from the surface and intermediate water masses of the Pacific Ocean via the Luzon Strait. Upwelling is generated by rising deeper water from depths below 200 m [11].

Results of water mass analysis show that the distinctive depth of deeper water masses of the SCW changes as occurred the upwelling there.

**Role of Ekman Transport and Ekman Pump in the formation of upwelling**

The coastal upwelling is mainly caused by Ekman Transport due to the Southwest monsoon blowing along the shoreline combining with the morphography suitable for the upwelling generation. The offshore upwelling is caused by the Ekman Pump formed by wind stress vortex. In terms of physic basic, however, the principle of balance and conservation of matter in offshore upwelling has not been consistently explained.

**Impact of large-scale processes of sea - atmosphere - land interaction on the strong upwelling in the central waters**

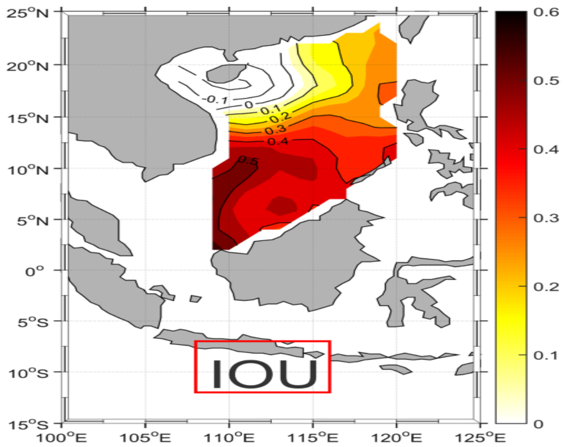



*Figure 16.* Correlation diagram between Indian Ocean Upwelling Index (IOU, 108–116°E, 7–12°S) and variation of sea surface temperature in the EVS with a phase lag of 2 weeks for the period from 1948–2017

Roles of the trans-equatorial wind and IOU (Indian Ocean Upwelling Index) to the upwelling of the SCW can be realized after the years having strong El Niño (e.g., 1998 and 2010). As a result, in the summer, especially in August, the current, in the direction perpendicular to the shoreline, is not clear compared to the regular year (e.g., 2005) [12, 26, 27]. Wu et al., [31] indicated that the IOU and the central coastal upwelling index of Vietnam in August have a correlation coefficient of 0.41 (with a confidence level of 99%). Thus, the trans-equatorial winds, originating from the Indian Ocean and especially off the Northwest coast of Australia blowing directly Northwestward, could act as a direct driver of summer upwelling in the EVS. Based on an analysis of wind trajectory from 1948 to 2017, two main trans-equatorial wind trajectories to the upwelling regions in August were eastern and western orbits. During El Niño (summer of 1998), the west rotation was replaced by the East orbit, resulting the wind blowing the EVS through the Sulu Sea. In contrast, winds over the EVS became more turbulent due to the intensively eastern wind currents, leading to a decrease in upwelling in the summer of 1998. Thus, is it generalized for all the cases of years having El Niño?

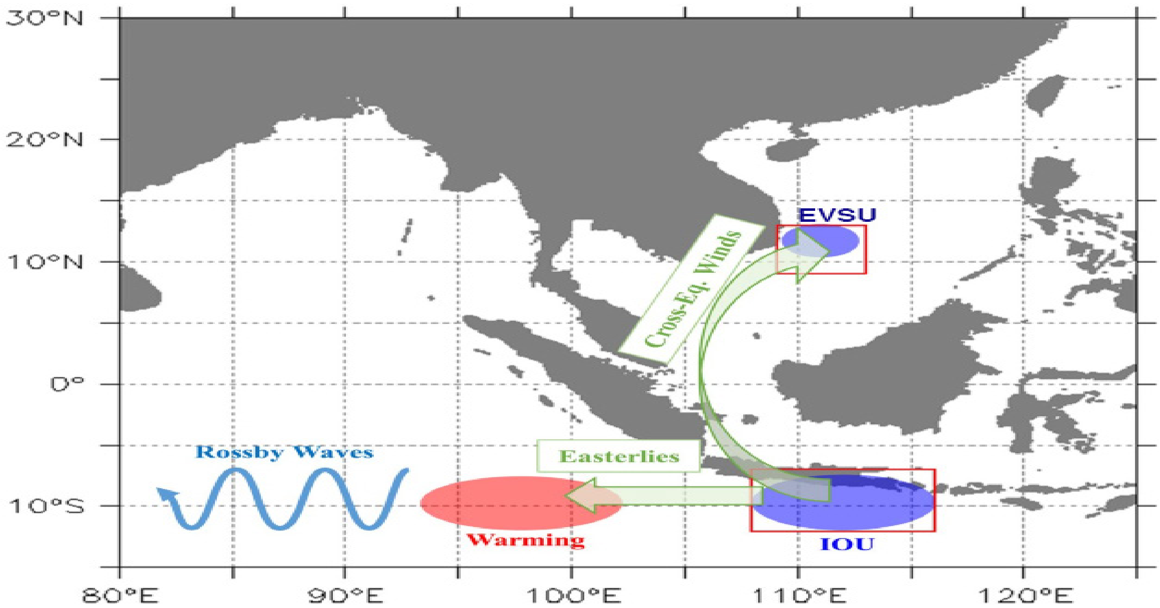



*Figure 17.* Diagram of depicting the sequence between IOU (Indian Ocean Upwelling Index) and atmospheric/oceanic variability in the Pacific and Indian Oceans

Abnormally strong upwelling (post-El Niño) off the southeastern coast of Vietnam in late summer 2016, compared with the case of 1998.

The traditional opinion indicates weak upwelling is commonly observed off the southeastern coast of Vietnam during the summer after El Niño. According to Xiao et al., [32], based on assessing an algae bloom off the southeast coast of Vietnam in August 2016 and comparing it with a case another in 1998 (Figure 18), results of the structure and mechanism analysis of upwelling indicated the abnormally strong upwelling in August 2016 was caused by strong winds that generated by Ekman transport to the sea and Ekman pump. On a large scale, it was caused by a southwesterly anomaly located in the southern tropical anomaly cyclone (AC) over the Northwest Pacific (WNP), which is exactly the opposite of August 1998. This anomalous southwest wind associated with AC over the WNP cannot be explained by the La Niña, the negative Indian Ocean Dipole, or Pacific meridian positive-mode events. In 2016, nine tropical cyclones formed and developed on the WNP, resulting in an excessive amount of rainfall occurring there.

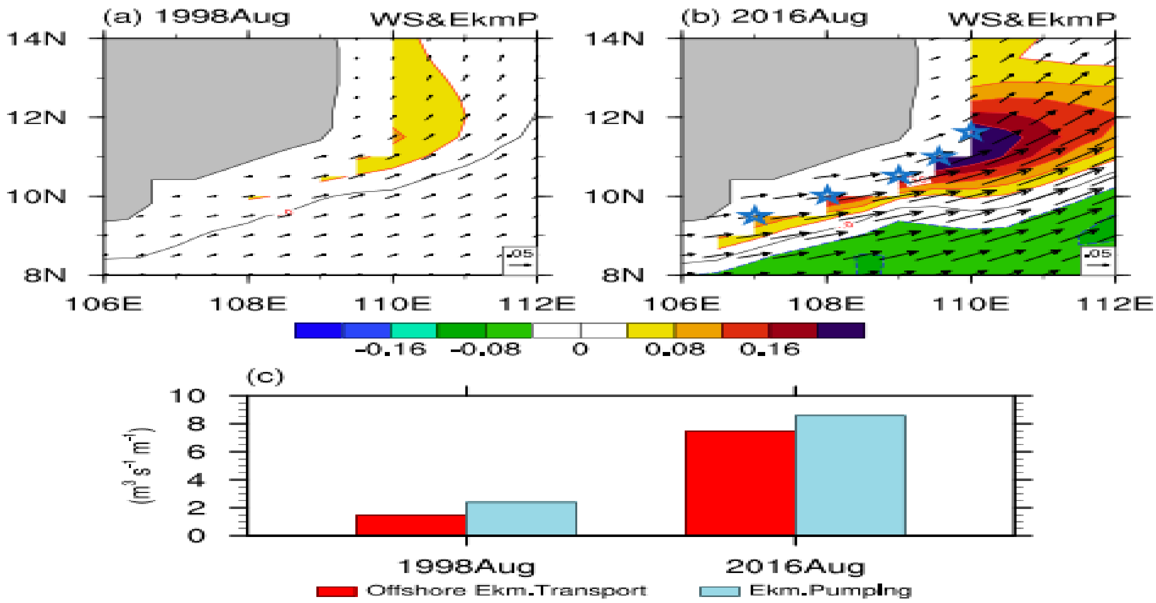



*Figure 18.* Distribution of wind vector and intensity Ekman Transport (red) and Ekman Pump (blue) in August 1998 and August 2016 over the South Central Waters [32]

Hence, ENSO is not the only cause affecting the appearance or disappearance of strong upwelling in the SCW. Therefore, it is necessary to consider the climate change effect to identify the causes, mechanisms, and predictability of upwelling fluctuations in the EVS. This action aims to detail the large-scale processes of sea-atmosphere interaction in the Western Pacific, such as the AC over the WNP; it also needs to consider atmospheric exchanges between the Indian Ocean and the equatorial region and the trans-equatorial wind regimes.

**Interaction of upwelling with natural hazards (hurricane, typhoon,...)**

Based on the satellite data, and in-situ temperature and salinity observations, and the United States Joint Typhoon Warning Center for a one-dimensional mixed model, the role of the summer upwelling in Northern EVS in TCs (Tropical Cyclone), self-induced sea surface cooling mechanism was discovered (Figure 19) [33]. Its amplitude of TCs is 50% larger in the upwelling than without, resulting in the upwelling of EVS. It is possible to increase the amplitude of TCs self-induced cooling and play a negative role in TCs weakened before landfall.

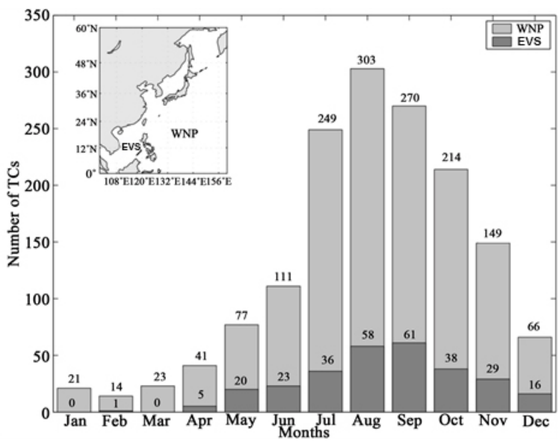



*Figure 19.* Number of typhoons by month forming over the North Pacific region (gray column) and the EVS (black column) for 1945–2010 [33]

Figure 20 shows that in non-upwelling regions, the surface temperature is reached to 29°C, but the surface temperature averaged at 27–28°C in upwelling. When having a typhoon, the mixing layer could go down to 100 m depth. The salinity was insignificantly changed as the storm passing the regions with and without upwelling.

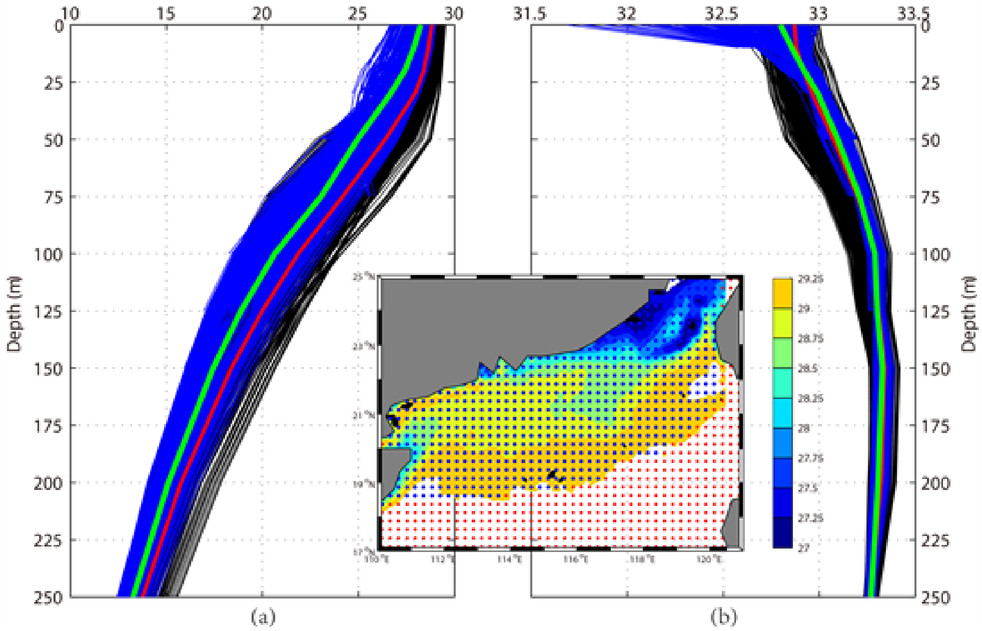



*Figure 20.* Temperature-salinity profiles and average in the upwelling (blue and green lines) and non-upwelling (black and red lines) from the database WOA09. In the subplot, blued dots area is upwelling, whereas red dots area is without upwelling. (a) Temperature profile; (b) Salinity profile [33]

**Impact of upwelling on coastal climate (local wind, temperature and humidity regime,...)**

Zheng et al., [34] demonstrated by numerical evidences about the relationship between coastal upwelling and reducing wind forcing. Given the existence of a typical cold zone with a temperature drop of 3–5°C, the local wind speeds can drop to < 70% of initial levels. The mechanism of wind forcing reduction responded to coastal upwelling in the SCW is caused by development of sea-breeze winds. Coastal sea breezes will increase, whereas the difference between land and sea is even greater due to the contribution of a unique coastal current system (Figure 21). Thus, the air-sea-land interaction controls the processes of the local wind system in response to the existence of coastal upwelling. That is to take account to clarify the process of air-sea interaction in the EVS basin.

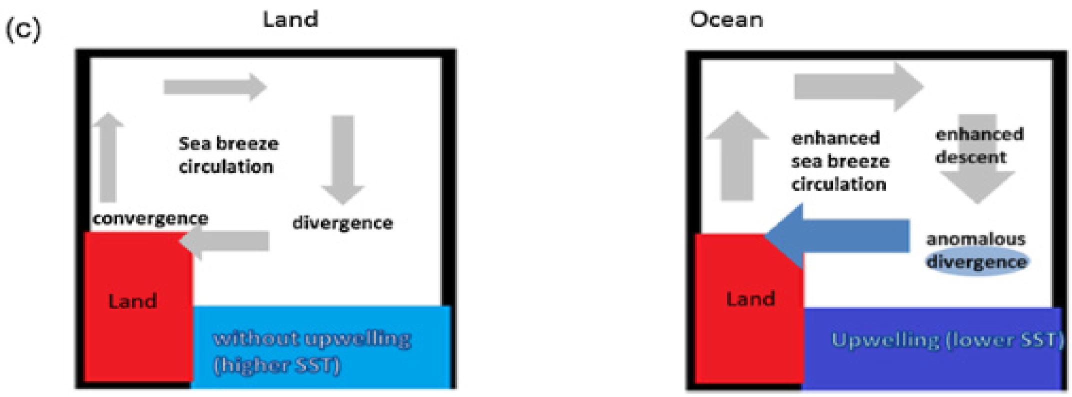



*Figure 21.* Diagram of the sea breeze mechanism in the coastal area: normal case (left) and increasing inshore wind in case of upwelling (right)

## CONCLUSIONS

The summer upwelling on the waters and offshore of Southern Vietnam is the most critical oceanographical feature in the EVS. The upwelling is generated by the pressure of local wind along the coast, resulting in the Ekman transport to move surface water mass to the sea, which is the crucial factor in controlling the annual variation in coastal upwelling. In addition, the improved the wind dipole vortex systems off the coast of South Vietnam as well as the scale expansion of the vortex to the east coast of Vietnam, the Southward shift of the jet current toward of eastward direction, and the strengthening of the cyclone of the Southward currents along the coastline are responsible for the increasing upwelling current in the Southern upwelling center, but for the reducing upwelling current in the northern center. The strongly developed dipole vortexes are the necessary conditions for forming of cold waters offshore the study area.

The frequency and intensity of summer upwelling in Vietnam vary considerably depending on the location and distribution. It is essential to clarify the roles of wind forces (including wind stress and wind vortex) and eastward currents in summer in the Southern waters of Vietnam with the variation in the frequency of occurrence and intensity of upwelling in the area.

As it was first observed in the 1950s, many coastal upwelling systems have been identified. They have studied within the continental shelf of the EVS, Vietnam, predominantly the strong upwelling in Southern Vietnam and the adjacent Luzon Strait. It is necessary to identify the standard upwelling index in sufficient detail (based on upwelling index derived from sea surface temperature - SSTUI) to determine the intensity (strong, weak), scales and fluctuations of the upwelling.

Coastal upwelling areas, involved in many national and international research, are generated mainly in seasons and driven by wind force along the shore, wind vortex, bottom morphography, coastline axis, circulation in the continental shelf, water vortex, islands, and the shape of coastlines. The current results, however, suggest focusing on localized and seasonal features based on upwelling indexes such as the anomalies of sea surface temperature (SST), sea surface salinity (SSS), nutrients, and chlorophyll-a; upwelling studies were difficult to quantify the phenomenon directly. The phenomenon’s long time series are not abundant in the EVS, whereas they are contributed to most other adjacent seas, resulting from the analysis of long-term dynamics is impossible. Furthermore, this phenomenon has been basically ignored despite the vital importance of the downwelling current.

However, the causes, formation mechanism, and variability of strongly coastal upwelling of Vietnam still needs to be detailed and quantified for the following reasons: (1) Analysis of long-term data series from remote sensing products; (2) Lack of observed in-situ data to calculate and validate modeling and remote sensing analysis; (3) Lack of upwelling indexes (being still mainly used sea surface temperature); (4) Original upwelling water masses and causes of fluctuations of strongly upwelling center in Southern Vietnam (large, medium and small scale); (5) Sea-land and sea-atmospheric interactions; and (6) Lack of scientific results of parallel consequences of upwelling within processes of physics, hydrology, ecology, and natural resources.

## REFERENCES

[1] Fairbridge, R. W., 1966. The Encyclopedia of Oceanography, Reinhold Pub. *Corp. NY*. 1021 p.

[2] Kämpf, J., and Chapman, P., 2016. Upwelling Systems of the World: A Scientific Journey to the Most Productive Marine Ecosystems. *Springer*.

[3] Zexun, W., Chunyan, L., Guohong, F., and Xinyi, W., 2003. Numerical diagnostic study of the summertime circulation in the Bohai Sea and the water transport in the Bohai Strait. *Advances in Marine Science*, *21*(4), 454–464.

[4] Lü, X., Qiao, F., Wang, G., Xia, C., and Yuan, Y., 2008. Upwelling off the west coast of Hainan Island in summer: Its detection and mechanisms. *Geophysical Research Letters*, *35,* L02604. doi: 10.1029/2007GL032440

[5] Malaysia, P. T. S., Daryabor, F., Tangang, F., and Juneng, L., 2014. Simulation of Southwest monsoon current circulation and temperature in the east coast of Peninsular Malaysia. *Sains Malaysiana*, *43*(3), 389–398.

[6] Abdul-Hadi, A., Mansor, S., Pradhan, B., and Tan, C. K., 2013. Seasonal variability of chlorophyll-a and oceanographic conditions in Sabah waters in relation to Asian monsoon—a remote sensing study. *Environmental Monitoring and Assessment*, *185*(5), 3977–3991. https://doi.org/10.1007/s10661-012-2843-2

[7] Hu, J., and Wang, X. H., 2016. Progress on upwelling studies in the China seas. *Reviews of Geophysics*, *54*(3), 653–673. https://doi.org/10.1002/2015RG000505

[8] Wyrtki, K., 1961. Physical oceanography of the Southeast Asian waters. Naga Report Volume 2: Scientific Results of Marine Investigations of the South China Sea and the Gulf Of Thailand 1959–1961. *UC San Diego, SIO, La Jolla, California*.

[9] Robinson, M. K., 1974. The physical oceanography of the Gulf of Thailand, Naga Expedition; Bathythermograph (BT) temperature observations in the Timor sea, Naga Expedition, Cruise S11. *Scripps Institution of Oceanography, UC San Diego*, Naga Report 3 part 1. pp 27–28.

[10] Lafond, E. C., 1963. Physical oceanography and its relation to the marine organic production in the South China Sea. In *Ecology of the Gulf of Thailand and the South China Sea. A report on the results of the NAGA expedition, 1959–1961, Southeast Asia research program, University of California, Scripps Institution of Oceanography, La Jolla, California*. pp. 5–33.

[11] Lanh, V. V., An, N. T., Luc, N. V., Trinh, L. P., Phung, N. H., and Vinh, N. K., 1997. The collection on strong upwelling waters in the South Central region. *Science and Technics Publishing House*. (in Vietnamese).

[12] Long, B. H., and Van Chung, T., 2010. Some experimental calculations for 3D currents in the strong upwelling region of Southern Central Vietnam using finite element method. *Marine biodiversity of East Asian Seas: Status, challenges and sustainable development*, 165–177.

[13] To, D. T., Bui, H. L., Nguyen, V. T., Nguyen, C. C., Phan, T. B., Nguyen, T. T. H., Nguyen, D. T., and Nguyen, T. T. D., 2018. Some study results on the characteristics and variability of water masses in the South Central Vietnam. *Vietnam Journal of Marine Science and Technology*, *18*(4A), 1–12. https://doi.org/10.15625/1859-3097/13632

[14] Shaw, P. T., and Chao, S. Y., 1994. Surface circulation in the South China sea. *Deep Sea Research Part I: Oceanographic Research Papers*, *41*(11–12), 1663–1683. https://doi.org/10.1016/0967-0637(94)90067-1

[15] Chu, P. C., Edmons, N. L., and Fan, C., 1999. Dynamical mechanisms for the South China Sea seasonal circulation and thermohaline variabilities. *Journal of Physical Oceanography*, *29*(11), 2971–2989. https://doi.org/10.1175/1520-0485(1999)029<2971:DMFTSC>2.0.CO;2

[16] Li, L. (2000). Seasonal circulation in the South China Sea-a TOPEX/POSEIDON altimetry study. *Acta Oceanol Sin*, *22*(6), 13–26.

[17] Yang, H., Liu, Q., Liu, Z., Wang, D., and Liu, X., 2002. A general circulation model study of the dynamics of the upper ocean circulation of the South China Sea. *Journal of Geophysical Research: Oceans*, *107*(C7), 3085. https://doi.org/10.1029/2001JC001084

[18] Xue, H., Chai, F., Pettigrew, N., Xu, D., Shi, M., and Xu, J., 2004. Kuroshio intrusion and the circulation in the South China Sea. *Journal of Geophysical Research: Oceans*, *109*(C2). https://doi.org/10.1029/2002JC001724

[19] Qiu, D., Yang, T., and Guo, Z., 1984. A westward current in the northeastern part of the South China Sea. *Tropic Oceanology*, *33*, 65–73.

[20] Huang, Q. Z., 1997. A westward current that flows through the north of the

Dongsha Islands in summer. *Tropic Oceanology*, *16*(2), 58–66.

[21] Jilan, S., 2004. Overview of the South China Sea circulation and its influence on the coastal physical oceanography outside the Pearl River Estuary. *Continental Shelf Research*, *24*(16), 1745–1760. https://doi.org/10.1016/j.csr.2004.06.005

[22] Wang, G., Chen, D., and Su, J., 2006. Generation and life cycle of the dipole in the South China Sea summer circulation. *Journal of Geophysical Research: Oceans*, *111*(C6). https://doi.org/10.1029/2005JC003314

[23] Cai, S., Long, X., and Wang, S., 2007. A model study of the summer Southeast Vietnam Offshore Current in the southern South China Sea. *Continental Shelf Research*, *27*(18), 2357–2372. https://doi.org/10.1016/j.csr.2007.06.002

[24] Lanh, V. V., 1995. Thermohaline structure and water masses of South China Sea. *Collection of Marine Research Works*, *6*, 25–35.

[25] Bui, H. L., Nguyen, N. L., Polhmann, T., Voss, M., and Wiesner, M., 2008. The Vietnamese–German protocol cooperation programme in marine sciences during 2003–2006: archives from the study on upwelling in South Central Coast of Vietnam. *Proceedings of National Conference 'Bien Dong - 2007', Sept. 12–14, 2007, Nha Trang*. pp. 3–14. (in Vietnamese).

[26] Long, B. H., 2009. The phenomenon of rising water in Vietnamese waters. *Publishing House for Science and Technology*. (in Vietnamese).

[27] Long, B. H., 2009. Upwelling phenomenon in the marine region of Southern Vietnam. *Publishing House for Science and Technology*. 210 p. (in Vietnamese).

[28] Zheng, Q., Fang, G., & Song, Y. T. (2006). Introduction to special section: dynamics and circulation of the Yellow, East, and South China Seas. *Journal of Geophysical Research: Oceans*, *111*(C11). doi: 10.1029/2005JC003261

[29] Zheng, Q., Xie, L., Xiong, X., Hu, X., and Chen, L., 2020. Progress in research of submesoscale processes in the South China Sea. *Acta Oceanologica Sinica*, *39*(1), 1–13. https://doi.org/10.1007/s13131-019-1521-4

[30] Bolton, A., Goodkin, N. F., Druffel, E. R., Griffin, S., and Murty, S. A., 2016. Upwelling of Pacific intermediate water in the South China Sea revealed by coral radiocarbon record. *Radiocarbon*, *58*(1), 37–53. doi: 10.1017/RDC.2015.4

[31] Wu, C. R., Wang, L. C., Wang, Y. L., Lin, Y. F., Chiang, T. L., and Hsin, Y. C., 2019. Coherent response of Vietnam and Sumatra-Java upwellings to cross-equatorial winds. *Scientific reports*, *9*(1), 1–7. doi: 10.1038/s41598-019-40246-w

[32] Xiao, F., Wu, Z., Lyu, Y., and Zhang, Y., 2020. Abnormal strong upwelling off the coast of southeast vietnam in the late summer of 2016: a comparison with the case in 1998. *Atmosphere*, *11*(9), 940. https://doi.org/10.3390/atmos11090940

[33] Xu, D., Qiu, C., and Yan, Y., 2019. Role of the south china sea summer upwelling in tropical cyclone intensity. *American Journal of Climate Change*, *8*(01), 90170. doi: 10.4236/ajcc.2019.81001

[34] Zheng, Z. W., Zheng, Q., Kuo, Y. C., Gopalakrishnan, G., Lee, C. Y., Ho, C. R., Kuo, N. J., and Huang, S. J., 2016. Impacts of coastal upwelling off east Vietnam on the regional winds system: An air-sea-land interaction. *Dynamics of Atmospheres and Oceans*, *76*, 105–115. doi: 10.1016/j.dynatmoce.2016.10.002