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Sea surface temperature trends and the influence of ENSO on the southwest sea of Vietnam using remote sensing data and GIS

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Abstract
In this article, the sea surface temperature trends and the influence of ENSO on the southwest sea of Vietnam were analyzed using the continuous satellite-acquired data sequence of SST in the period of 2002–2018. GIS and average statistical methods were applied to calculate the average monthly and seasonal sea surface temperature, the seasonal sea surface temperature anomalies for each year and for the whole study period. Subsequently, the changing trends of sea surface temperature in the northeast and southwest monsoon seasons were estimated using linear regression analysis. Research results indicated that the sea surface temperature changed significantly throughout the calendar year, in which the maximum and minimum sea surface temperature are 31^{o}C in May and 26^{o}C in January respectively. Sea surface temperature trends range from 0^{o}C/year to 0.05^{o}C/year during the Northeast monsoon season and from 0.025^{o}C/year to 0.055^{o}C/year during the southwest monsoon season. Results based on the Oceanic Niño Index (ONI) analysis also show that the sea surface temperature in the study area and adjacent areas is strongly influenced and significantly fluctuates during El Niño and La Niña episodes.

Keywords: Trend, sea surface temperature, ENSO, remote sensing, GIS, southwest sea of Vietnam.

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INTRODUCTION

Sea surface temperature (SST) is an important indicator when measuring climate change because it describes condition at the boundary between the atmosphere and the ocean, where an important exchange of energy takes place. Changes in the SST can affect atmospheric circulation and the amount of water vapor in the air, thus affecting weather and climate patterns around the world. These changes also affect vital ecosystems in the ocean. SST data have been collected by using in-situ technologies (ships, buoys, autonomous devices, coastal and island stations,...) and monitoring from infrared sensors on satellites, starting with AVHRR/2 sensor on board the NOAA-7 satellite, since 1981. Currently, satellite SST observations contribute to research on global climate change as well as short-term studies on a regional scale for fisheries, ship routing, storm forecasting, upwelling areas, currents and activity of eddies on the ocean.

The results of the Intergovernmental Panel on Climate Change show that average global SST has been increasing. The average SST of the Indian, Atlantic and Pacific oceans increased by 0.65^{o}C, 0.41^{o}C and 0.31^{o}C, respectively between 1950 and 2009 [1]. The global upward trend of SST ranges from 0.09 to 0.14^{o}C/decade (depending on the data set and the average method) [2, 3]. Many studies have used satellite data alone or combined it with re-analysis data to detect global [4, 5] and regional [6–9] SST trends. These include studies in the East Vietnam Sea. Several studies have shown the influence of the El Niño and La Niña phenomena on the average global SST [10, 11], especially during strong El Niño and La Niña episodes. According to NOAA [12], El Niño and La Niña are opposite phases of a natural climate pattern across the tropical Pacific Ocean, which swings back and forth every 3–7 years on average. They are called ENSO (El Niño-Southern Oscillation). The ENSO pattern in the tropical Pacific can be in one of three states: El Niño, neutral, or La Niña. El Niño (the warm phase) and La Niña (the cool phase) lead to significant differences in the average ocean temperatures, wind speeds, surface pressure, and rainfall across parts of the tropical Pacific. A number of studies documenting the effect of ENSO on SST fields [13–15] show that SST in the East Vietnam Sea is warmer (cooler) during El Niño (La Niña) episodes and reaches the maximum (minimum) later than ENSO peak 3 to 6 months.

In Vietnam, SST has also been mentioned in many studies on the structure of water masses in the East Vietnam Sea based on data collected at home and abroad [16–18], among which there are studies using satellite images to calculate SST for Vietnam's waters [19–21]. The SST field in the southwest sea of Vietnam has also been mentioned in several studies based on MODIS satellite image data and field measurement data [22] or calculating seasonal average SST [23]. These studies only mentioned characteristics of spatial SST distribution in the study area without taking into account the trend of fluctuations (increases or decreases) over time and the impact of ENSO on SST fluctuations.

MATERIALS AND METHODS

Data used

The study area is the Vietnam's southwest sea from 102^{o}09'30"E to 105^{o}21'00"E and from 07^{o}40'00"N to 10^{o}40'00"N (figure 1). SST dataset has been made accessible recently via international data sharing protocols. The dataset for our study was the global daily SST at high resolution of 0.01 × 0.01 degree, version 4.1 (MUR-JPL-L4-GLOB-v4.1) for the period of June 2002 to May 2018 [24]. The dataset was considered highly accurate as it was analyzed synthetically using numerous sensor systems of different satellite platforms and groundtruthing data from moored and drifting buoy stations. Correlation coefficient (R) > 0.9 of the dataset for the Vietnam seas has been evaluated previously using the in-situ observation data from Phu Quy island station [25], assuming that the correlation between SST dataset and groundtruth data is considerably high.

Figure 1. Location of the study area

Methods

Statistical averages

Our study focused on the statistical features of SST fields including monthly, seasonal and annual average values for every grid point in the study area and adjacent areas. By definition, the terms "spring", "summer" (Southwest monsoon season), "autumn", "winter" (Northeast monsoon season) were the periods from March to May, June to August, September to November, and December to February of the following year, respectively. Seasonal SST anomalies were calculated by the difference between the seasonal average value of each year and the seasonal average value of the collective years in the dataset.

Trend analysis

Least squared method in linear regression analysis is used to determine the variation trend of SST seasonal average value of collective years at each grid point. Accordingly, the correlation between SST and time is defined as a linear equation as follows:

$$y = ax + b \quad (1)$$

In the equation (1), y stands for the SST annual average value, x is a corresponding year, a and b are regression constants. If the number of collective years is n, thea and b constants in (1) would be delineated such that the summation of squared odds is the least according to least squared method, which is:

$$S = \sum_{i=1}^{n} \left(y_i - ax_i - b\right)^2 \rightarrow \min \quad (2)$$

Where y_i and x_i are known, thus S depends on a and b. As S is the least, derivative of S should be taken at a and b, and assuming that it is zero, we gain the equations to define a and b as follows:

$$\begin{cases} a\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} y_i x_i \\ a\sum_{i=1}^{n} x_i + nb = \sum_{i=1}^{n} y_i \end{cases} \quad (3)$$

Then the a and b constants would be calculated using the following equations:

$$a = \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i - n\sum_{i=1}^{n} x_i y_i}{\left(\sum_{i=1}^{n} x_i\right)^2 - n\sum_{i=1}^{n} x_i^2} \quad (4)$$

$$b = \frac{\sum_{i=1}^{n} y_i - a\sum_{i=1}^{n} x_i}{n} \quad (5)$$

The a constant as defined in the equation (4) is the slope coefficient of the trend line and represents the rate of SST variation in a given period *x*.

Oceanic Niño Index (ONI)

In order to analyze the SST variations of Vietnam's southwest sea and adjacent areas during El Niño and La Niña events, we compared the alterations of seasonal SST anomaly in the study area and Oceanic Niño Index (ONI). The Oceanic Niño Index is evaluated by the NOAA Climate Prediction Center [26] as an indicator when estimating the occurrence of El Niño and La Niña events. The ONI is calculated using the monthly average value of sea surface temperature in the Niño 3.4 region (covering the area from 5°N to 5°S latitude, 120°W to 170°W longitude on the central tropical Pacific Ocean (figure 2)), then evaluated using the average values from the previous and following months. The running 3-month average was then compared to a 30-year average. According to NOAA, an El Niño event occurs when ONI value reaches +0.5 and beyond, representing a notably warmer east central tropical Pacific region than usual. La Niña is considered present when ONI is –0.5 or lower, revealing an abnormally cooler region.

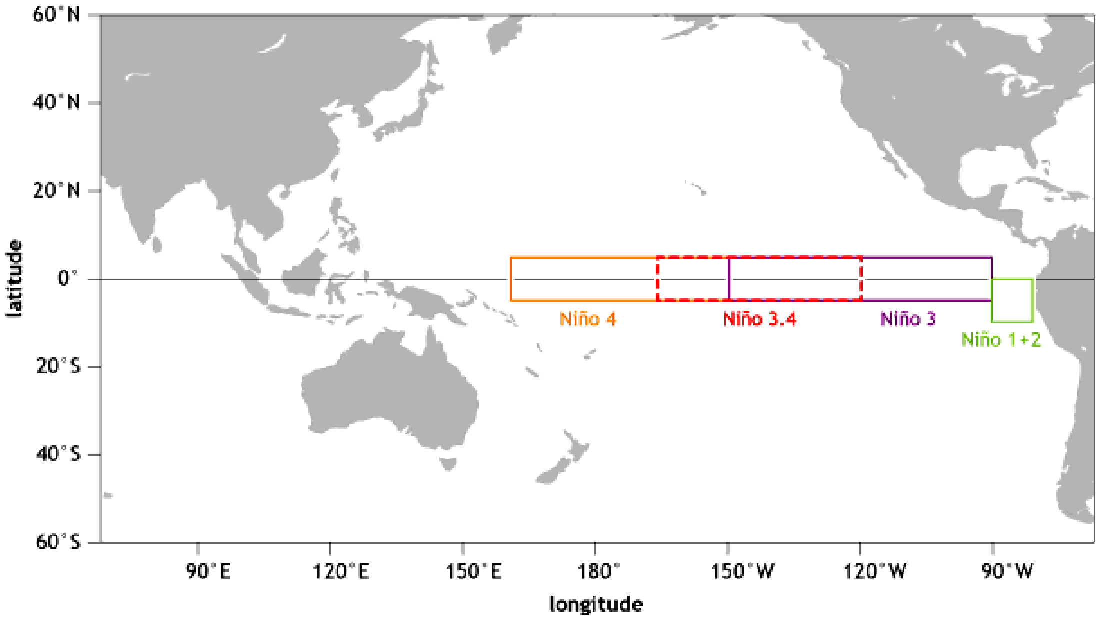

Figure 2. Location of the Niño regions for SST calculation in the eastern and central tropical Pacific Ocean [12]

Geographical Information System (GIS)

SST variation maps are established using GIS techniques, in which two major spatial analysis functions are numerical layered techniques to calculate monthly, seasonal and annual averages of the SST; and neighboring interpolation for grid point values after regression analysis. The map of the study area is also established by GIS applications.

RESULT AND DISCUSSION

Monthly average SST variability

The results of the monthly average SST statistical analysis in this study area from 2002 to 2018 demonstrated that the monthly average SST begins to increase from March and reaches its peak in May and June (under the influence of the Southwest monsoon), then gradually decreases until December, January and February of the next year (due to the influence of the Northeast monsoon). The monthly average SST reaches the highest value of 31^{o}C in May and falls to its lowest at 26^{o}C in January. In January and February, the temperature rises progressively from the coast to the sea, it remains stable in the west and northwest, ranging between 26.5^{o}C and 27.5^{o}C in the coastal area and stands at the lowest level of 26^{o}C in the southern Ca Mau cape due to the strong influence of the cold tongue from the East Vietnam Sea and the northeast monsoon. In March, the temperature ranges from 27.5^{o}C to 29.5^{o}C, increasing by 1^{o}C or 2^{o}C in comparison with January and February. For the central area of the Gulf of Thailand, the temperature stabilizes at 28.5–29.5^{o}C. It is approximately 29^{o}C in the coastal area but it is lowest (from 27.5 to 28.5^{o}C) in the south of Ca Mau cape because of the slight effects of the cold tongue from the East Vietnam Sea and the northeast monsoon. April is a period of seasonal transition, the Southwest monsoon appears and dominates the distribution of heat in the study area (average temperature is from 29.5^{o}C to 31^{o}C). In May, June and July, the Southwest monsoon gains momentum and the solar radiation is more intense and the influence of the cold tongue from the East Vietnam Sea is no longer a factor. For all those reasons, the SST increases throughout the area and remains stable at around 29^{o}C and 31^{o}C. In August, September and October, the temperature is still high but there is a decrease compared to that in previous months. This is explained by the abatement of southwest wind intensity, increase in rainfall and reduction of solar radiation (temperature fluctuates from 28.5 to 30^{o}C). In November, the Southwest monsoon abates, rainfall decreases and the start of the Northeast monsoon and cold tongue from East Vietnam Sea influences the temperature (the temperature ranges from 28.5 to 29.5^{o}C). In December, the influence of Northeast monsoon and cold tongue from East Vietnam Sea becomes increasingly more obvious (the temperature ranges between 28.5^{o}C and 30^{o}C), the lowest level is at the southeast area of Ca Mau cape and the coastal zone from Ca Mau - Kien Luong. In the west and northwest area, temperature continues to stabilize and holds the highest value of 29.5^{o}C.

The trend of SST variability over the period of 2002–2018

The maps of SST variability trends for two seasons of Northeast monsoon and Southwest monsoon (figures 3, 4) were established based on the calculation results of monthly average SST per year and the application of the least squared method in linear regression analysis in order to identify the variability trend of monthly average SST field for many years at each data grid point. The degree of variability is illustrated by contour lines with contour interval (CI) of 0.005^{o}C/year.

Generally, the rate of SST variability in our study area in the southwest monsoon season is higher compared to that in the northeast monsoon season. The variability rate is widely distributed between 0^{o}C/year and 0.05^{o}C/year in the Northeast monsoon season, whereas in the southwest monsoon season, it has a narrower range of 0.025^{o}C/year to 0.055^{o}C/year. There is a higher variability rate in the waters near the shoreline because of the influence of continental factors. This trend is unique compared to the rest of the data.

In the northeast monsoon season, the rate of variability is greater than 0.02^{o}C/year and mostly in inshore areas. The greatest variability rate (from 0.035^{o}C/year to 0.05^{o}C/year) is in the coastal seas from Ha Tien to Rach Gia. In the Phu Quoc waters and coastal seas in Ca Mau area, the rate of variability fluctuates between 0.025^{o}C/year and 0.035^{o}C/year. With respect to the waters in the west and south of Tho Chu islands, the variability rate has the smallest fluctuation of 0^{o}C/year to 0.015^{o}C/year (figure 3).

During the Southwest monsoon season, a considerable rate of variability is concentrated in shoreline waters. It is notable that the greatest variability rate is concentrated in the sea area from An Bien to Ca Mau cape which is greater than 0.045°C/year, followed by Phu Quoc - Tho Chu waters with 0.035°C/year to 0.04°C/year. Similarly, in the Northeast monsoon season, in the western and southern waters of the Tho Chu islands, the variability rate has the smallest value (only in the range of 0.025°C/year to 0.035°C/year) (figure 4).

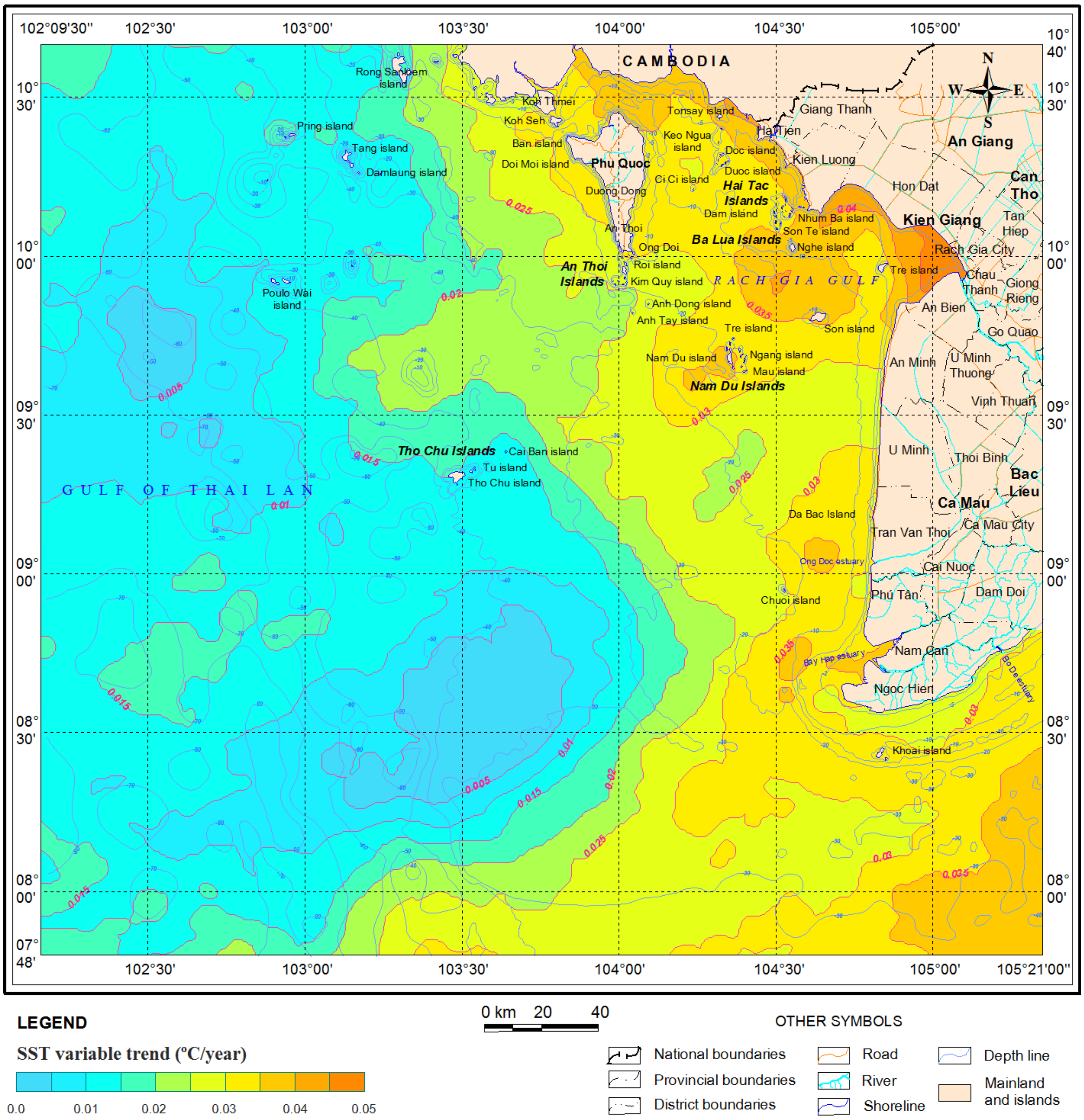

Figure 3. Map of SST variability trend in Northeast monsoon season

The graphs illustrating trends in SST variability of the three regions in figures 5–7 indicate noticeable extrema. In Northeast monsoon season, the average temperature reached the maximum in 2015, at 28.7°C, 28.88°C and 27.69°C in Rach Gia - Phu Quoc, Tho Chu islands and Ca Mau respectively, whereas it reached the minimum in 2013, at

27.14°C, 27.52°C and 26.14°C in Rach Gia - Phu Quoc, Tho Chu islands and Ca Mau respectively. In the two years of 2008 and 2013, the sea surface temperature field was 0.5–1°C smaller, than the annual average due to La Niña phenomenon.

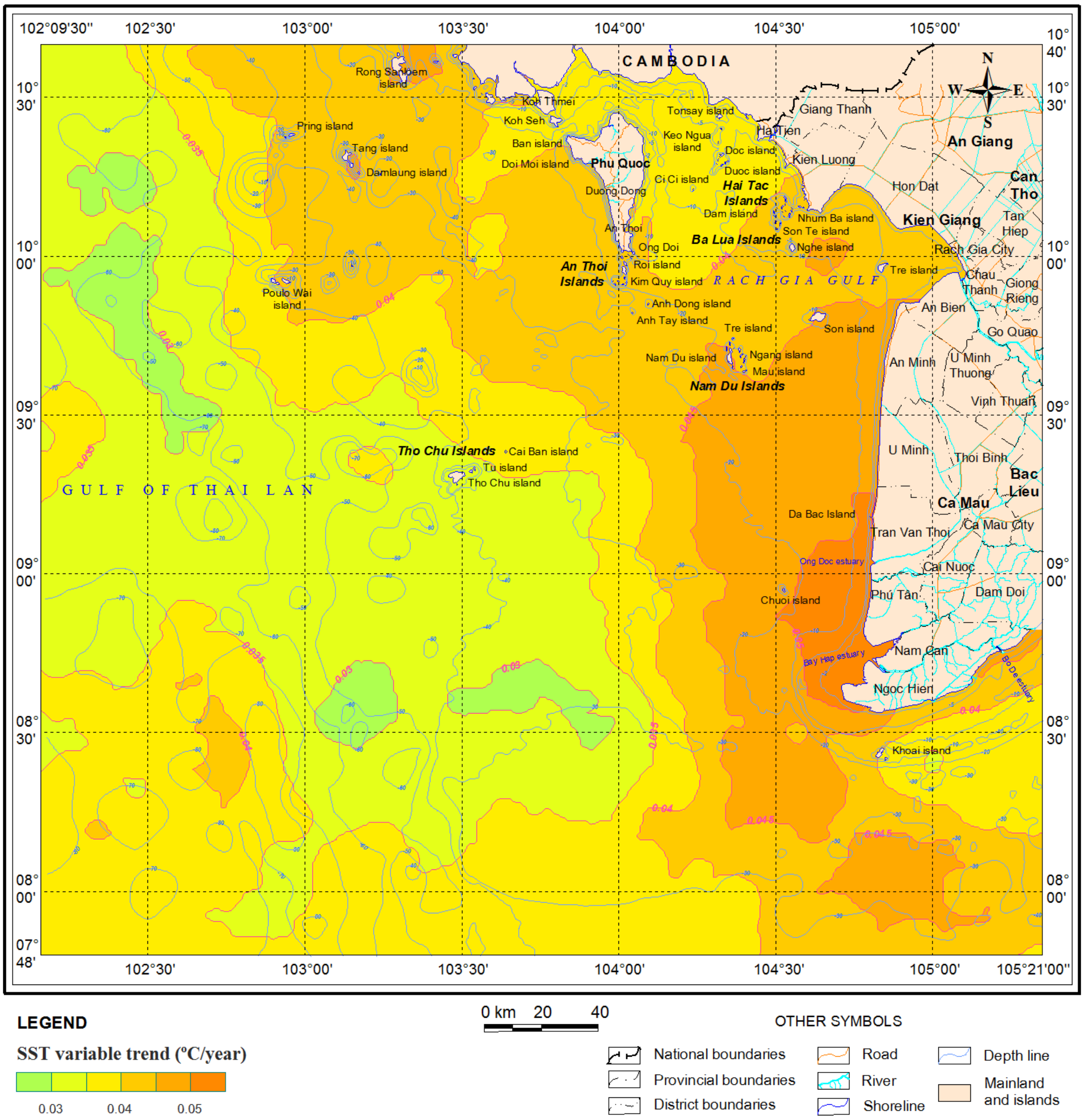

Figure 4. Map of SST variability trend in Southwest monsoon season

During the Southwest monsoon season, there were also notable extrema in 2010 and 2016, temperature rose over the region because there were the two times when the El Niño phenomenon occurred intensively. The greatest average SST in 2010 was 30.21°C, 30.38°C and 30.22°C in Rach Gia - Phu Quoc, Tho Chu and Ca Mau, respectively. The average of SST in 2016 was the second highest, at 30°C, 30.14°C and 30.06°C in Rach Gia - Phu Quoc, Tho Chu and Ca Mau, respectively.

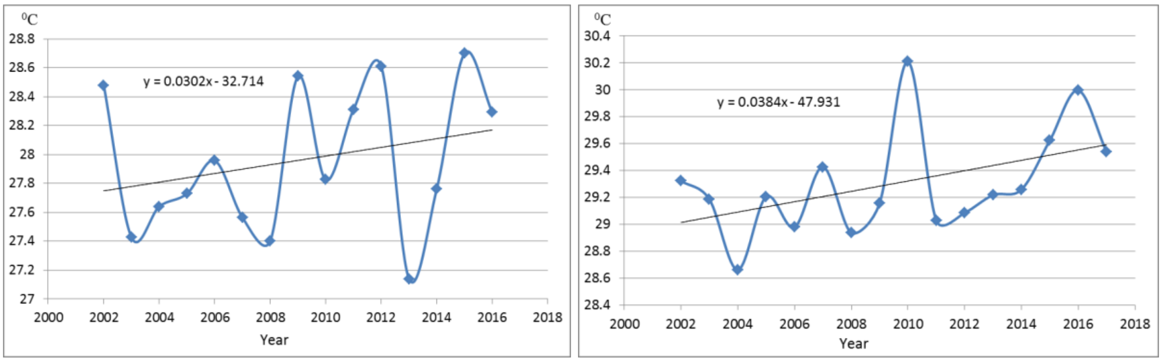

Figure 5. The trend of SST variability in Rach Gia - Phu Quoc waters in the Northwest monsoon season (left) and the Southwest monsoon season (right)

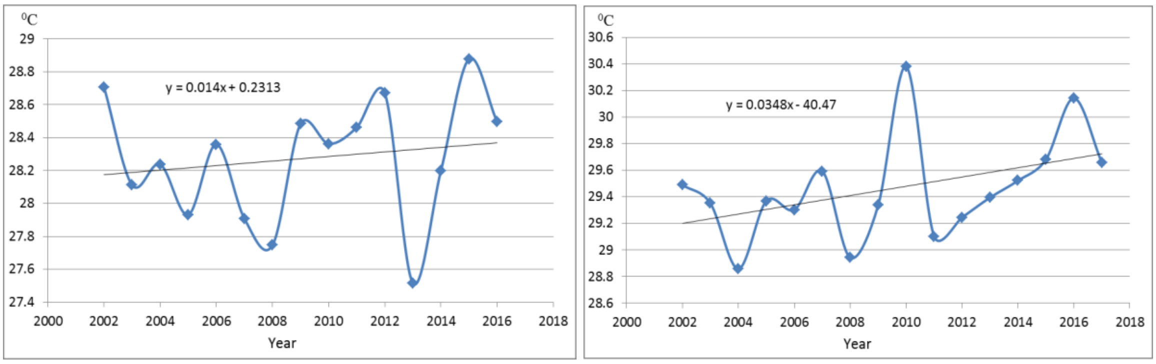

Figure 6. The trend of SST variability in Tho Chu water in the Northwest monsoon season (left) and the Southwest monsoon season (right)

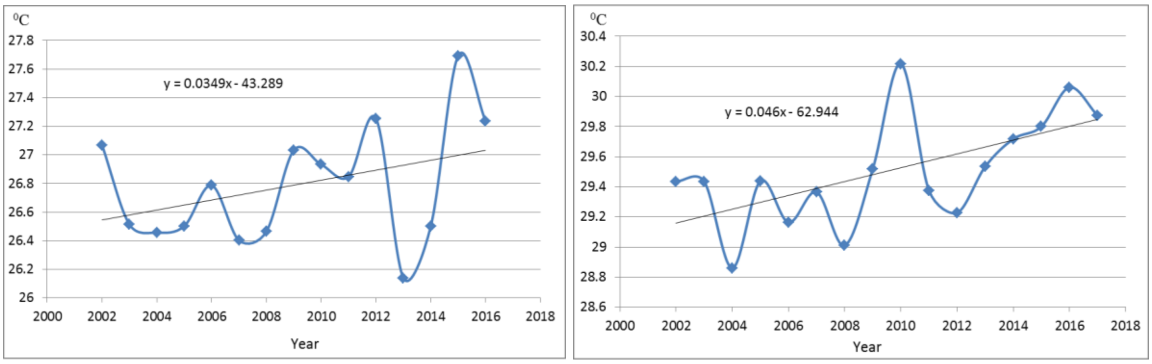

Figure 7. The trend of SST variability in Ca Mau water in the Northwest monsoon season (left) and the Southwest monsoon season (right)

SST fluctuations during El Niño and La Niña events

The Oceanic Niño Index (ONI) has become the standard that NOAA uses for identifying El Niño and La Niña events in the tropical Pacific Ocean. The intensity of each period of El Niño and La Niña is classified into weak (with ONI from 0.5 to 0.9), moderate (1.0 to 1.4), strong (1.5 to 1.9) and very strong (≥ 2.0). However, in order to determine the intensity of an El Niño or La Niña event, the ONI must be equal to or exceed the threshold for at least 3 consecutive overlapping 3-month periods. According to statistics from 1951 to 2018, there were 25 events of El Niño (10 weak, 7 moderate, 5 strong and 3 very strong) and 22 La Niña events (11 weak, 4 moderate and 7 strong). From 2002 to 2018, there were 6 events of El Niño (3 weak, 2 moderate and 1 very strong) and 7 events of La Niña (4 weak, 1 moderate and 2 strong) (tables 1, 2).

Table 1. Statistics of El Niño events from 2002 to 2018

Number	El Niño events	Start time	End time	Total time	Maximum of ONI (^{o}C) and occurrence time	
1	2002–2003	6/2002	2/2003	9 months	1.3	11/2002
2	2004–2005	7/2004	2/2005	8 months	0.7	9–12/2004
3	2006–2007	9/2006	1/2007	5 months	0.9	11–12/2006
4	2009–2010	7/2009	3/2010	9 months	1.6	12/2009
5	2014–2015	11/2014	3/2015	5 months	0.7	12/2014
6	2015–2016	4/2015	5/2016	14 months	2.6	12/2015

Table 2. Statistics of La Niña events from 2002 to 2018

Number	La Niña events	Start time	End time	Total time	Minimum of ONI (^{o}C) and occurrence time	
1	2005–2006	11/2005	3/2006	12 months	–0.8	12/2005–1/2006
2	2007–2008	6/2007	5/2008	5 months	–1.6	12/2007–1/2008
3	2008–2009	11/2008	3/2009	12 months	–0.8	1/2009
4	2010–2011	6/2010	5/2011	9 months	–1.7	10–11/2010
5	2011–2012	7/2011	3/2012	5 months	–1.1	10–11/2011
6	2016	8/2016	12/2016	6 months	–0.7	9–11/2016
7	2017–2018	10/2017	3/2018	5 months	–1.0	12/2017

In general, almost all El Niño and La Niña events impact the SST field in the southwest sea of Vietnam and adjacent waters, especially strong El Niño and La Niña events. The following is an analysis of the variation of the average seasonal SST field anomalies in the southwest sea of Vietnam during typical El Niño and La Niña events according to strong and very strong ONI.

The 2009–2010 El Niño event: This was an El Niño event with moderate intensity lasting 9 months from July 2009 to March 2010. The maximum ONI value of 1.6^{o}C was recorded in December 2009. The consequences of this El Niño event can be seen clearly in the variation of SST anomalies in the study area. After only 6 months, the whole area had a positive anomaly which continued to increase in the next 9 months and then decreased. The maximum positive anomalies reached up to 1.2^{o}C in the summer of 2010.

The 2015–2016 El Niño event: This was an El Niño period with a very strong intensity lasting 14 months from April 2015 to May 2016. The maximum ONI value of 2.6^{o}C was recorded in December 2015. Due to the extension of the two El Niño events (previously the 2014–2015 El Niño event), this was a very strong El Niño event with a long operating time, so the impact on SST field is very clear (figure 8). During this period, the whole region had a positive anomaly, the maximum SST anomaly reached more than 1.5^{o}C in the winter of 2015.

The 2007–2008 La Niña event: This La Niña event had a strong intensity lasting 12 months from June 2007 to May 2008. The minimum ONI value of –1.6^{o}C was recorded in December 2007 and January 2008. We can clearly see its impact on the SST field in the study area, only 3 months after this La Niña event, the entire study area had negative anomalies and after 9 months the negative anomalous field reached the minimum value. The minimum negative anomaly was recorded as –1.2^{o}C in the spring of 2008.

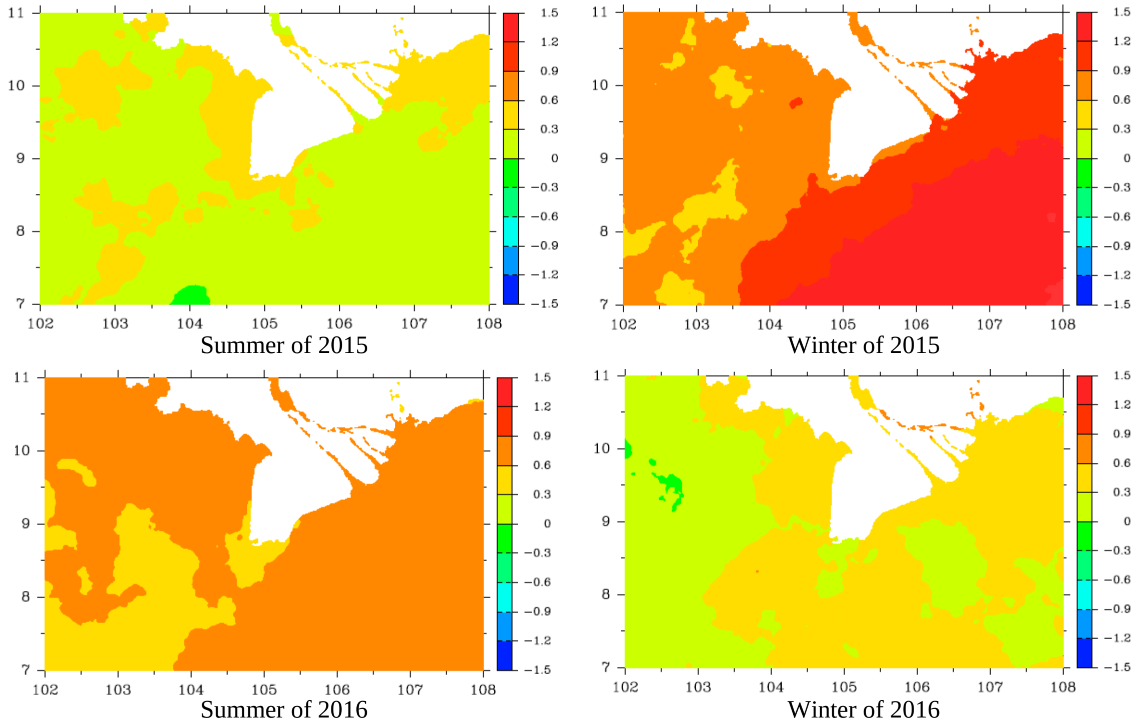

Figure 8. Variation of seasonal SST anomalies before and after the 2015–2016 El Niño event in the southwest sea of Vietnam and adjacent waters (^{o}C)

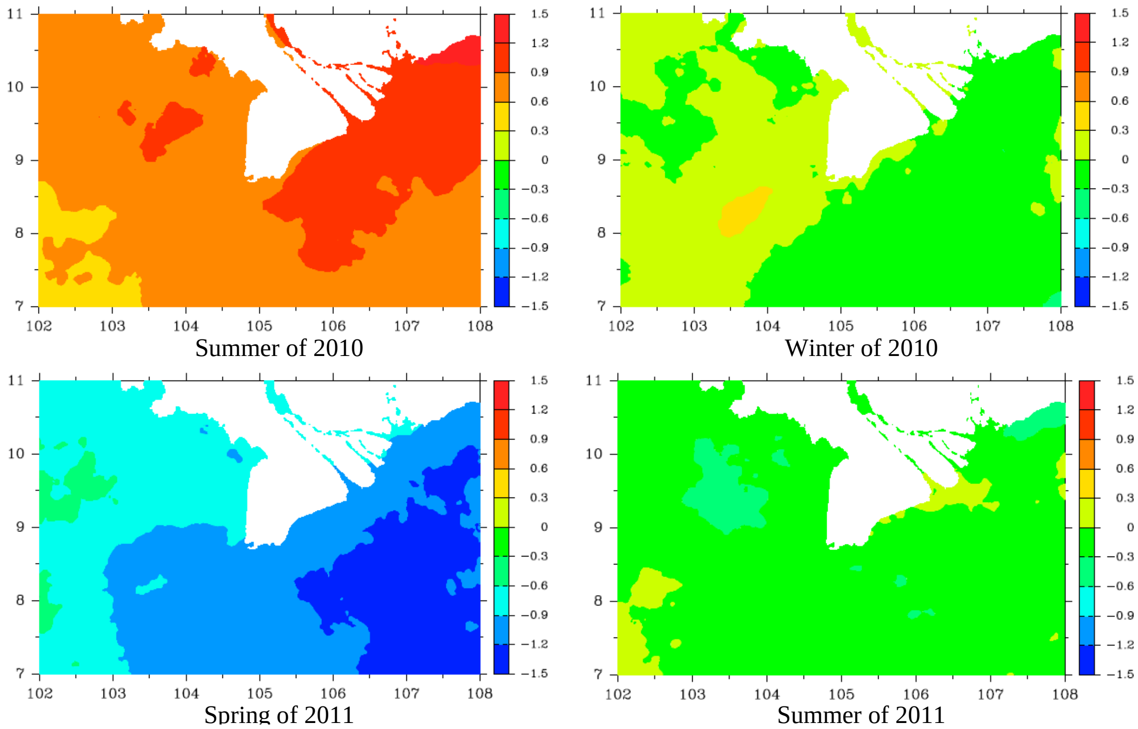

Figure 9. Variation of seasonal SST anomalies before and after the 2010–2011 La Niña event in the southwest sea of Vietnam and adjacent waters (^{o}C)

The 2010–2011 La Niña event: This was a La Niña event with a strong intensity lasting 12 months from June 2010 to May 2011. The minimum ONI value of –1.7°C was recorded in October and November 2010. Due to the effects of the previous 2009–2010 El Niño event, the entire study area had a high positive anomaly, however, this La Niña event had a stronger intensity, causing the temperature of the entire area to decrease sharply. 9 months after the beginning of this La Niña event, the minimum negative anomaly was recorded as under –1.5°C in spring 2011 (figure 9).

CONCLUSIONS

Variation of monthly SST average in the southwest sea of Vietnam was considerable over vast areas and throughout many months of the year, in which temperature distribution showed seasonal characteristics. In the northeast monsoon, SST was stable in the winter months, the temperature distribution graph shows the intrusion of a cold water flux from the East Vietnam Sea passing Ca Mau Cape, along the shore of Ca Mau province and Kien Giang province to the Gulf of Thailand. This resulted in the lowest temperature of 26°C in January. During the Southwest monsoon, temperature distribution was moderately uniform in the whole study area, reaching its maximum of 31°C in May.

SST variation trend analysis and mapping at the scale of 1:250.000 were implemented using the monsoon seasonal dataset for the period of 2002–2018. Variation trends show general temperature rise in both the northeast and the Southwest monsoons at the calculated differences of 0°C to 0.05°C and 0.025°C to 0.055°C, respectively.

El Niño and La Niña phenomena strongly determined the SST of the Vietnam's the southwest sea of Vietnam and adjacent areas, especially during intense events. For the period between 2002 and 2017, there were 6 El Niño events recorded (3 weak, 2 moderate and 1 very strong) and 7 La Niña events (3 weak, 1 moderate and 2 strong). The maximum positive SST anomaly of over 1.5°C was recorded in the winter of 2015 because of the influence of intense El Niño events throughout the two years of 2015 and 2016. Meanwhile, intense La Niña event in 2010–2011 caused the maximum negative SST anomaly of –1.5°C in the spring of 2011.

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