Effects of El Nino on North Equatorial Current transport in the tropical Pacific

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Keywords: Northern Equatorial Current transport; El Nino; Nino3 index; Least squares filtering; Lead lag coefficient; Ekman transport

Abstract: In the North Pacific Ocean, the North Equatorial Current (NEC) driven by the trade wind flows from the east to the west and bifurcates into the northward Kuroshio Current (KC) and southward Mindanao Current (MC) near the Philippine coast, comprising the NEC-MC-KC (NMK) current system, which is one of the regions with complex circulation system in the world ocean, and plays an important role in the variability of the global and regional ocean and climate. In this paper, the influence of El Nino on the interannual variations of NEC was investigated by utilizing the SLA (Sea Level Anomaly) data, SST (Sea Surface Temperature) data and sea surface wind field data fused by satellite. Firstly, 1.5-layer gravity reduction model can well express that the anomaly of the Northern Equatorial Current was related to the sea surface height anomaly, while the variations of El Nino can be described by nino3 index in first SST mode. The SLA difference value and nino3 index are respectively processed with a least square filter method. By comparing the trend of the two variables above and calculating the lead lag coefficient, it was concluded that there was a significantly positive lead and lag correlation between SLA and Nino3 index: the maximum correlation coefficient for Nino3 index lagging behind SLA difference at (135 ° E, 7° N) and (135 ° E, 10° N) is 0.9083; Lagging behind SLA difference at (170 ° E, 7° N) and (170 ° E, 10° N) is 0.818. This analysis strongly suggests that the transport of the northern equatorial current increases in strong El Nino years. Finally, further analysis found that the sea surface height anomaly, Ekman transport and west wind anomaly are closely related to the mechanism and results of El Nino affecting Northern Equatorial Current through the data of sea surface wind field and temperature.

1. Introduction

The North Equatorial Current (NEC) at 10 to 20 ° N[1], driven by the trade wind and buoyancy flux and across the North Pacific basin, is a steady current from east to west. It reaches the coast of the Philippines where it bifurcates into the northward Kuroshio Current and the southward Mindanao current, thus forming the NEC - MC - KC (NMK) current system [2-3]. The NMK current system has a significant impact on the global thermohaline circulation and the heat budget of the Western Pacific ocean [4-5]. NEC, as a part of the subtropical and tropical circulation in the

North Pacific Ocean, exerts a considerable influence on water exchange. Hence, research in this area has significant theoretical implications on ENSO (El Nino and Southern Oscillation) cycle and global climate change. El Nino phenomenon refers to the abnormal warming of the equatorial Middle East Pacific Ocean over a wide range of temperatures and a long period of time. When the temperature of cold-water in eastern equatorial Pacific is 0.5 ℃ higher than the normal temperature, the El Nino phenomenon happens. There have been at least 30 El Nino events around the world since 1900. Among them, the 1982-1983, 1997-1998 and 2014-2016 El Nino events are considered as the strongest El Nino events ever recorded. La Nina is a coupled ocean-atmosphere phenomenon that is the counterpart of El Nino as part of the broader El Nino–Southern Oscillation climate pattern.

The NEC has been extensively studied before, which mainly focused on the NEC structure features of 137 ° E section [6], NEC bifurcation point [1] and the NEC transport with the variations of the season [4, 11]. The discussion about the relationship between NEC transport and El Nino was limited comparatively. According to previous studies, during El Nino events, the transport of the NEC increased, while during la Nina events, the transport decreased [5]. However, there is still some controversy on the interannual variation of NEC. Furthermore, previous studies have used the P-vector method to calculate geostrophic flow and linear vorticity equation [16-17] to investigate the relationship between El Nino and NEC. However, in the qualitative analysis, the above methods containing solution of linear equation set are too complex, and there is less discussion on how El Nino affects the NEC.

Therefore, the current study aimed to simplify the mathematical derivation process in order to obtained relationship between the NEC and El Nino through in-depth analysis. Specifically, we build on previous research by analyzing the SLA data, the interannual changes of geostrophic transport of NEC can be indirectly reflected, thus verifying the conclusion that the NEC strengthens during El Nino. Taking the strong El Nino in 1997 as an example, the mechanism of the influence of sea surface wind and temperature on the transport of the northern equator during El Nino was explored. The NEC transport variations were strongly associated with variations of the gyre and wind forcing in the tropical North Pacific Ocean. During EP-El Nino, the strong westerly wind anomalies and positive wind stress curl anomalies in the tropical North Pacific Ocean caused upward Ekman pumping velocity anomalies, which induced negative sea surface height anomalies and westward propagating upwelling Rossby waves. In the western tropical Pacific Ocean, local upward Ekman pumping and the upwelling Rossby waves which spread from central and eastern Pacific decreased the sea surface height and generated a cyclonic flow anomaly enhancing the NEC transport. The influence of sea surface wind on NEC transport ascribed to the distribution of SST on western Pacific Ocean.

2. Data and Method

2.1 Data sources

Sea surface height anomaly (SLA) data from Copernicus - sea environmental monitoring sites (CMEMS), resolution of 0.25 ° x 0.25 °, time range from January 1993 to now, was gathered through Jason-3、Sentinel-3A、Jason-2、ENVISAT satellite altimeters. The Nino3 data were retrieved from the National Oceanic and Atmospheric Administration's Climate Prediction Center, which combines the ERSSTv5 high-frequency filter to provide Nino3 data from January 1950 to 2018, so as to use thresholds from the ocean Nino index to determine warm and cold periods. Sea surface temperature anomaly was derived from Hadley Centre SST data set (HadSST3). From January 2018, additional data were obtained from drifting buoy observations on ERDDAP. The data of sea surface height anomaly were attained from TOPEX satellite. According to the satellite's precise ephemeris and reference surface model (geoid or mean sea level), the instantaneous sea surface height relative to the reference surface was calculated.

2.2 1.5-layer gravity reduction model

According to the geostrophic balance equation, the relation between the variations of sea surface height and geostrophic velocity was derived indirectly (formula 1) to reflect the change of ocean current transport.

Geostrophic flows along the intersection of the equipotential surface and the isobaric surface, so the velocity of the current is proportional to the tangent value of two planes.

$$v=\frac{1}{2\rho\omega sin\varphi}\frac{\partial p}{\partial x}=\frac{1}{\rho f}\frac{\partial p}{\partial x}=\frac{g}{f}\tan\beta \quad (1)$$

$$T_{reg}=-\int_{y_1}^{y_2} uhdy \quad (2)$$

Wunsch[8] previously stipulated that the vertical stratification structure of the ocean determines the ocean is mostly dominated by the first baroclinic mode, so the change of ocean transport can be reflected by the upper layer transport in the 1.5-layer reduced gravity model. In addition, for the transport of the northern equatorial flow in the 1.5-layer reduced gravity model, the correlation coefficient between it and the depth integral water transport is more than 0.8 (the confidence level is greater than 95%). Therefore, from the upper water transport expression (formula 2), the transport anomaly in the 1.5-layer reduced gravity model is expressed as:

$$T'_{reg} = -\int_{y_1}^{y_2}\left(u'\bar{h} + \bar{u}h'\right) dy = \int_{y_1}^{y_2} \frac{g}{fg'}[g\eta'\frac{\partial\bar{\eta}}{\partial y} + g\bar{\eta}\frac{\partial\eta'}{\partial y} - C\frac{\partial\eta'}{\partial y}]dy \quad (3)$$

$$T'_{reg} \approx C_0\Delta\eta'\Big|_{y_1}^{y_2} \quad (4)$$

The above equation proves that NEC transport is associated with sea surface height anomalies. Therefore, the North Pacific tropical circulation circle center and the interannual variability of sea surface height anomaly at 20 ° N was arguably a very good baseline to reflect the interannual change of NEC transport over the same longitude.

When calculating the NEC transport, the latitude range selected by previous research [16] was 7°N - 21°N and 135 ° E - 170 ° E. Previous research has revealed that NEC transport and sea surface height anomaly were highly correlated [7]. Therefore, this paper selects both 135 ° E and 170 ° E meridional sections, calculating SLA difference between (135°E,21°N) and (135°E,7°N); (170°E,21°N) and(170°E,7°N).

2.3 SST variation modes

Recent studies have shown that there are two different types of independent SST modes in the tropical Pacific [14]. The first mode is the traditional ENSO event, which is manifested as the zonal "dipole" SST distribution in the tropical Pacific. During the traditional ENSO event, a large-scale sustained abnormal warming (cooling) appears on the sea surface of the central and eastern tropical Pacific, while the opposite sign of SST anomaly appears in the western tropical Pacific. The second mode is a wide range of abnormal SST warming (cooling) in the central equatorial Pacific. One of the characteristics of traditional El Nino is that the strongest warm SST anomaly appears in the nino-3 region (5 ° S-5 ° N, 150 ° W-90 ° W). This region has large variability on El Nino time scales, and is close to the region where changes in local sea-surface temperature are important for shifting the large region of rainfall typically located in the far western Pacific. Therefore, the nino3 index is one of several ENSO indicators based on sea surface temperatures. The Centre Pacific (CP) El Nino, also known as the warm pool El Nino in other studies, is characterized by the strongest warm SST anomaly near the International Date Line (5 ° S-5 ° N, 160 ° E-150 ° W)[15]. This paper aimed to study the traditional ENSO events by accounting for the strongest warm SST anomaly, SST index and southern oscillation index (nino3 index) in the nino-3 region. It can be seen from figure 1 that nino-3 index fluctuates from 1993 to 2013, and there is no specific time or cycle pattern.

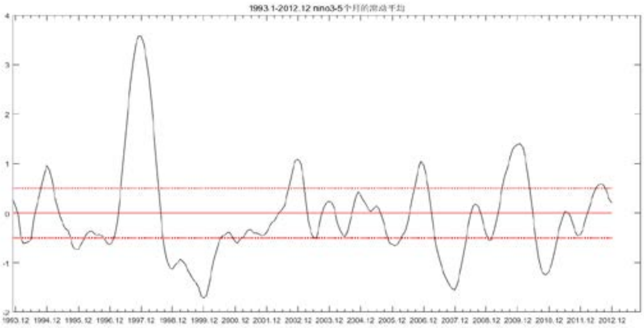

Figure.1 The variations of Nino3 from 1993 to 2013 (Nino3 indexes are moving averaged)

In terms of the standard of El Nino defined by ENI: An El Nino or La Nina event is identified if the 5-month running-average of the nino3 index exceeds +0.4°C for El Nino or -0.4°C for La Nina for at least 6 consecutive months. A strong El Nino event is when the ENI is greater than 1.0 for 3 months or more. Conversely, a weak El Nino process occurs when the number of months with ENI ≥0.5 lasts less than 7 months [9]. Figure 2 shows that the nino3 index in 1997 was 0.5 and lasted for more than 6 months. Meanwhile the nino3 index slipped for 5 consecutive months, the value of which exceeded 1.0 for more than 3 months as well. Consequently, 1997 is the strong El Nino year. In the following part, this paper will discuss the strong El Nino phenomenon in 1997. The influence of El Nino on NEC transport is transformed into an exploration of the relationship between the difference value of SLA and nino3 index. The following time series diagrams of the two are made to intuitively describe the relationship between them.

2.4 Least squares filtering and lead lag correlation analysis

Least squares filtering is a method of determining the optimal estimation of random parameters from observational data (non-random parameters are not included in its functional model).

A lead–lag effect, describes the situation where one (leading) variable is cross-correlated with the values of another (lagging) variable at later times. In nature and climate, bigger systems often display more pronounced lag effects. For two time series A(t) and B(t), the lead lag correlation coefficient C(t) is defined as the correlation coefficient between A(t) and B(t + Δt), if Δt is positive, it means A is leading B; if Δt is negative, it means A is lagging B. In order to demonstrate that the change of nino3 lags behind the SLA during El Nino period (take 1997 as an example) quantitatively, the correlation between the two curves was analyzed.

3. Result

Utilizing least squares filtering method on SLA and nino3 data, the SLA difference and nino3 time sequence comparison chart were made. Green represents the SLA at 170 ° E, and blue represents the SLA at 135 ° E. The figure shows that the SLA difference with nino3 time sequence has an obvious lead lag correlation, and 135 ° E SLA difference seems more hysteretic compared with the 170 ° E SLA difference. This conclusion is verified in the following calculation results. It can be qualitatively described as follows: during the El Nino period, especially from 1996 to 1998, the change of nino3 lags behind the change of SLA difference.

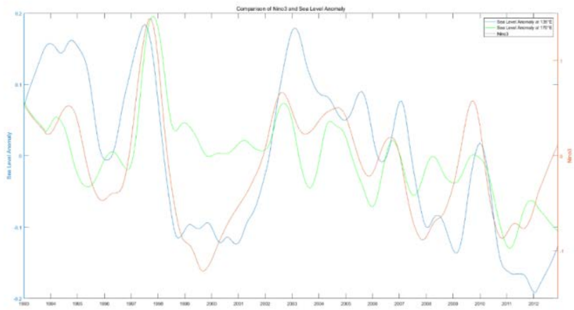

Figure.2 Comparison between nino3 and Sea Level Anomaly from 1993 to 2013

Through the analysis of the lead lag coefficient under the condition of confidence interval greater than 95% (figure 3), nino3 and SLA at 135 ° E maximum correlation coefficient was 0.9083 (the time lag for five months), while nino3 and SLA at 170 ° E maximum correlation coefficient was 0.818 (the time lag for a month). As for SLA at 170 ° E, stemming from the fact that nino3 region is close to 170 ° E, it is sound that the correlation coefficient is larger, and the lagging time is shorter. Therefore, when El Nino occurs, the nino3 coefficient increases subsequently. When it comes to the highly correlated relationship between SLA and nino3 index, it can be inferred that the transport of NEC also augment.

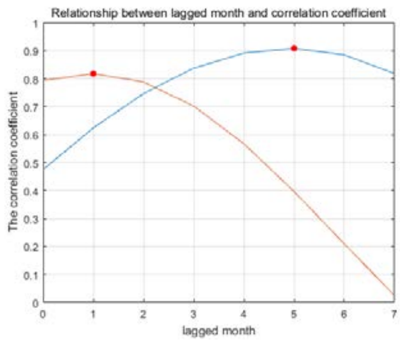

Figure.3 Relationship between lagged months and correlation coefficient

4. Dynamic mechanism of transport in the northern equatorial region affected by El Nino

4.1 Sea surface wind field

Sea surface wind field is one of the rudimentary elements of marine environment and pivotal research objects in oceanography. In the tropical northwest Pacific Ocean, the low-frequency variation of ocean circulation is mainly caused by surface wind forcing [5,10-12].

To put it from another angle, the figure below shows the composite diagram of wind stress and Ekman transport in the winter of 1997, and the red area signifies the positive Ekman transport. In the light of the graph, in the north of the equator, south of 20 ° N in the Midwest of the tropical north Pacific emerged a stronger westerly anomaly and the Ekman transport is abnormal during the winter. A positive Ekman transport anomaly will lead to a rising Rossby wave propagating westward, resulting in a negative sea surface height anomaly and cyclonic circulation anomaly in the tropical northwest Pacific Ocean. The data of sea surface height anomaly obtained from TOPEX satellite can validate the above views.

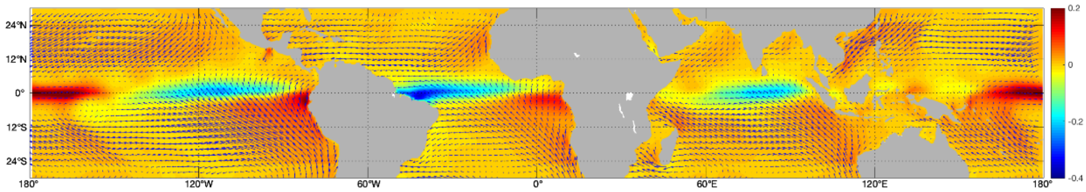

Figure.4 Variations of Ekman transport and wind stress in winter, 1997

The figure below illustrates the trend of sea surface height shift in the period of El Nino in 1997, namely November and December in 1997. All the reliable evidence justifies a view that sea surface height anomaly strengthens and northern equatorial current transport increases when El Nino intensification. In addition, the northwest Pacific Ocean experiences negative sea level anomalies during El Nino. As can be seen from the figure below, the maximum of El Nino and the sea surface height anomaly reached the maximum in the same period (December).

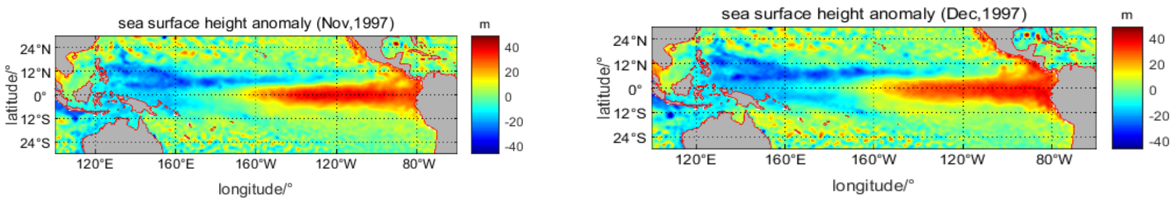

Figure.5-6 sea surface height anomaly from January to December,1997

The northern equatorial flow also reacts on the sea surface flow field inversely. The following figure is the surface (5 meters thick) flow velocity distribution at the tropical Pacific in December 1997, the data was retrieved from the APDR website (http://apdrc.soest.hawaii.edu). Given the figure, during the mature stage of El Nino in 1997, the directions of flows in the north-central equatorial region (shown in the blue box below) were chaotic, and the easterly current was not the dominant wind direction. By contrast, in the immature stage of El Nino, there was a strong easterly flow with a consistent direction and strong intensity. Based on the analysis of the wind field in January, the western sea surface height anomaly appeared negative. As time goes on, the negative sea surface height anomaly and cyclonic circulation anomalies reinforced uninterruptedly, then spurred and peaked in December. The anomaly of westerly flow gradually strengthened and moved to the north until December. Specifically, the core of anomaly of westerly flow moved to 18 ° N. These findings indicate that negative sea level anomaly promotes the movement of sea current from east to west.

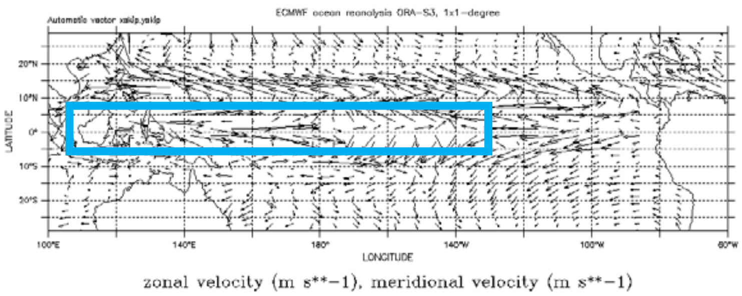

Figure.7 Surface current velocity and directions in Pacific region

4.2 Sea surface temperature

In the tropical north Pacific, sea surface wind field and Ekman suction are related to the distribution of sea surface temperature. Hence, the analysis of sea surface temperature was also a momentous factor for investigating the internal connections between wind field and north equatorial current. Figure 10-11 shows the sea surface temperature anomaly distribution in November and December 1997.

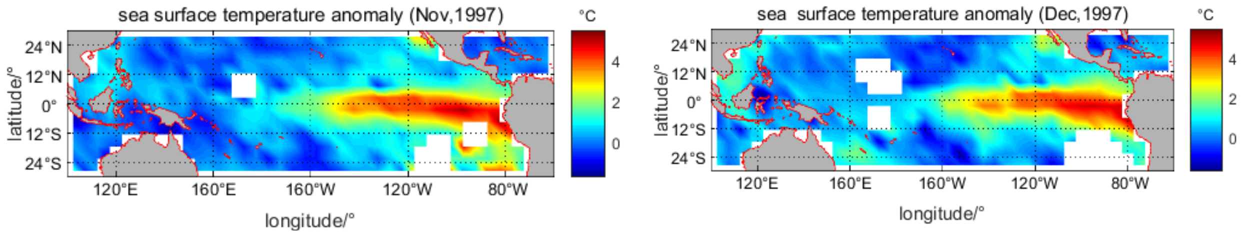

Figure.8-9 Sea surface temperature anomaly at North Equatorial Current

From the above figure, when the sea surface experiences the mature stage of the El Nino period, there are strong positive anomalies of sea surface temperature in the central and western equatorial regions. Li lijuan et al. [12] have elucidated that the velocity of the northern equatorial current varied with the seasons, and its annual average velocity was approximately 0.292m/s. The surface velocity in winter was the largest, while the velocity in summer was the smallest, and there is only tiny difference of velocity in spring and autumn to some extent. Given the velocity distribution from 1989 to 1998 (Table 3), the four seasons of flow velocity in 1998 was greater than its adjacent months'. This is because in autumn and winter at the beginning of the El Nino, the subtropical northwestern Pacific SST appeared negative anomaly. Through the tropical ocean-atmosphere interaction in western Pacific, the zonal wind of western Pacific becomes negative anomaly, which renders Hadley circulation stronger and subtropical high-pressure belt strengthened and extensive westward in equatorial regions (10 ° N - 20 ° N). Under the effect of subtropical high-pressure belt, the NEC enhanced, and the Kuroshio flux mounted steadily [13]. The relationship between the transport of the NEC and the sea surface temperature is proved indirectly.

5. Summary

According to the 1.5 layer gravity reduction model and the SST variation mode, nino3 can reflect the strength and weakness of El Nino. Additionally, the difference of SLA longitude can mirror the magnitude of geostrophic current velocity, thus reflecting the strength and weakness of the NEC transport. As a consequence, the correlation between SLA difference and nino3 coefficient can qualitatively analyze the relationship between NEC transport and El Nino. The results have showed that there was a high positive correlation between the nino3 index and SLA difference, and the delay time was positive proportional to the distance away from the nino3 region. Overall, the findings indicate that the intensity of NEC transport increases during El Nino.

There are two primary ways in which El Nino affects the transport of NEC – sea surface wind field and sea surface temperature. For the sea surface wind field, the main mechanism is that the strong westerly wind anomaly and the positive Ekman transport anomaly induce the rising Rossby wave in the westward propagation, resulting in the negative sea surface height anomaly and cyclonic circulation anomaly in the tropical northwest Pacific Ocean. When it comes to the sea surface temperature, it exerts influence on the sea surface wind field and Ekman transport, thus indirectly affecting the NEC. The negative anomaly of SST in the northwestern subtropical Pacific made subtropical high-pressure belt strengthen and spread westward, which finally reinforce the transport of the NEC.

In a nutshell, the northern equatorial current not only plays an indispensable role in ocean circulation dynamics by influencing other equatorial flow systems in the low-latitude boundary region but also regulates global climatic system in a profound and far-reaching way.

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