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Impacts of Seasonal Variations of the Tropical Pacific Ocean Temperatures On Upper Ocean Oxygen Response

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ABSTRACT

The El Niño–Southern Oscillation (ENSO) is the most dominant natural variability in the Earth system, which represents seasonal-to-interannual variations of the surface equatorial Pacific Ocean temperatures and subsurface ocean interior. Impacting the physical upper ocean characteristics, ENSO exerts significant influences on the marine ecosystem, such as oxygen and phytoplankton concentrations via strong quasiperiodic oscillation between El Niño (warm phase) and La Niña (cold phase) events. The present study uses observational reanalysis and satellite data to investigate seasonal variations of ENSO and their impacts on marine biogeochemical processes. The results show that the oxygen and chlorophyll anomalies in the upper ocean exhibit different seasonal responses to ENSO. While both the summer and winter season biological responses significantly lag ENSO, the concentration of oxygen and phytoplankton during summer (winter) has no (large) concurrent covariability with ENSO. Given a strong negative correlation between chlorophyll-based indices and El Niño events, increasing mean ocean temperatures and ocean extreme events may induce lower upper-ocean oxygen levels, leading to possible risks in the ecosystem over the Tropical Pacific Ocean.

Introduction

El Niño and Southern Oscillation (ENSO) is the most significant natural climate mode that provides predictability of the Tropical Pacific SST variability, which is characterized by anomalous warm (El Niño) or cold (La Niña) ocean temperatures in the Equatorial Pacific. Previous literature has reported that ENSO has significant impacts on extreme weather events and ecosystems. [1] The ENSO mechanism is characterized by the interaction between the atmosphere and ocean over the equatorial Pacific, modifying the global atmospheric circulation through the convective excitation of the large-scale stationary atmospheric teleconnections [2]. Also, ENSO is known to regulate the upper ocean structure by modifying an ocean upwelling system associated with changes in the direction and amplitude of the trade winds, affecting nutrient supply [3]. Specifically, the anomalous trade events that are associated with strong El Niño winds and SST anomalies can reduce dissolved oxygen levels in the Pacific Ocean via weakened ocean upwelling over the eastern equatorial Pacific.

The growing evidence has indicated that regional and large-scale atmospheric teleconnection patterns excited by ENSO and upper ocean structure will undergo changes in response to an increasing warming climate, especially to greenhouse gas concentrations [4]. Following the increasing global temperature [5], the Tropical SST has shown significant warming after 1960 (Figure 1). The warming equatorial ocean indicates that changes in ENSO frequency and amplitude may have substantial influences on the regional and large-scale climate and may cause noticeable year-to-year variations in the amount of oxygen, chlorophyll, and net primary production (NPP). Such dynamic changes will affect both the aquamarine environment and the terrestrial ecology. The crucial responsibilities these variables play in supporting regional economic growth for living beings on both land and sea, is dependent on the (frequency and magnitude) of El Niño. The need for oxygen-driven necessities in inaccessible habitats will become increasingly crucial given the expected declines in the worldwide ocean's oxygen content due to global warming. Given the levels of SST increase, ENSO will be directly affected and experience an increase in frequency and intensity, while providing hints and insight into dealing with longer-term future changes, such as disruptions in temperature, rainfall, and winds. The intense changing of ENSO has resulted in large climatic impacts. For example, the 2015 El Niño event led to above-average rainfall, flooding, increased food insecurity, higher malnutrition rates, and devastated livelihoods in the central Pacific that lasted until 2016 [8]. Collectively, it is essential to improve our current understanding of changes in ENSO and its following impacts.

In this study, we closely look at the seasonal impacts of El Niño on the upper ocean phytoplankton variability. The warming climate causes El Niño to negatively impact variables such as oxygen, NPP, and chlorophyll, especially during the winter seasons. Given this relationship between ENSO and certain variables, it is possible to conclude that winter/fall seasons will have a direct negative effect on the levels of oxygen as opposed to summer/spring seasons. In summary, our results indicate El Niño events are more abundant and powerful during winter seasons and have a sharp influence on the availability of ocean oxygen. With a projected large increase in extreme El Niño occurrences during the winter, we should expect more occurrences of devastating weather events, which will have pronounced implications for the amount of oxygen in the water. In a warming climate, observing the ocean–atmosphere system over the past decades is essential for understanding and modeling ENSO. These observations have shown that the effects of ENSO are drastic, impacting the marine life and ecosystem over the Tropical Pacific Ocean.

Methods

Observation Data

The data used in this study are taken from observational reanalysis and satellite biogeochemical hindcast data. The observational SST data are from the Extended Reconstructed SST version 5 (ERSSTv5) available on [2° × 2°horizontal grid] [9]. Mass concentration of Chlorophyll a, Net Primary Production (NPP) of biomass as carbon per unit volume, and mode concentration of dissolved molecular oxygen in sea water (O_2) are obtained from Global Ocean Physics Reanalysis of Copernicus (https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_BGC_001_029/description).
The monthly SST and biogeochemical data are used.

Data Preprocessing

To evaluate temporal and spatial patterns of the variables, we compute anomalies where the annual and seasonal mean were removed from the original variable values. We used a temporal evolution of Tropical Pacific SST that covers the base period 1920 through 2020, to confirm the overall trend of the Tropical Pacific SST. Except for a case in which we show a changing climate SST signal (e.g., warming signal, not detrended), we computed anomalies by removing the mean monthly climatology and linear trend at each grid point. With the seasonal-to-interannual internal variability, the long-term SST trend reveals a positive upward trend indicating a significant increase in Tropical Pacific SST.

Definition of Indices

Following the previous literatures, we define the ENSO index with area-averaged SST over the equatorial

Pacific (the Niño 3.4 region; 120W-170W, 5N-5S) [6]. The selection of the Niño 3.4 region is because the area is known as the "equatorial cold tongue," a band of cool water that runs parallel to the equator from the coast of South America to the center of the Pacific Ocean.

Selection of Analysis

The first analysis is a scatter diagram of ENSO and its correlation on biochemical variables, covering dissolved oxygen, chlorophyll and Net Primary Production (NPP). We use the anomalies of Niño 3.4 and oxygen anomalies in mg m-3. To investigate the trend of ENSO to the variables including oxygen, we compare the results from the scatter diagram to previous results, to find consistent patterns. The second analysis is a histogram for Niño 3.4 anomalies comparing warm and cold seasons. We use the Tropical Ocean SST anomalies and the degree of impact to investigate the intensity of the frequency and magnitude during different seasons. To further respond to the results of the histogram, we categorize the difference of El Niño's developing phases. The third analysis includes the seasonal impacts of El Niño on oxygen and other biological variables. In the third analysis, late winter (JFM/FMA) the correlation coefficient is very low, and rapidly increases by late spring. In each of the three experiments, El Niño's anomalies are most prominent during winter seasons. We compared the impact of external forcing with the uncertainty arising from internal climate variability. Anomalies for the variables and the removal of the warming trend are obtained by removing the seasonal and annual mean of the original values.

Composite Analysis

To present a spatial structure of ENSO phenomena, we used SST composite analysis using Niño3.4 SST index. The El Niño pattern was obtained by the average of the SST anomalies where the ENSO index is above 0.5^{o}C).

Results

Sea Surface Temperature

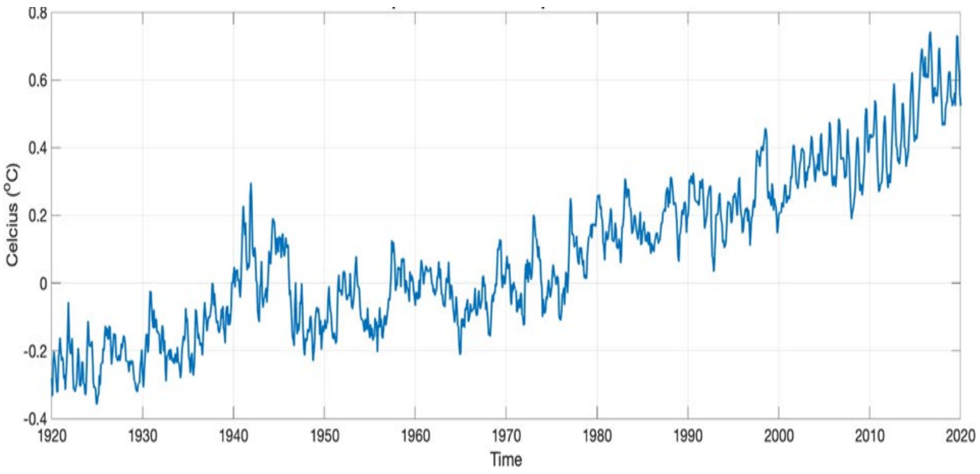

Figure 1. Temporal evolution of Tropical Pacific SST. Temporal evolution of Tropical Pacific sea surface temperature (SST) between the time period 1920 through 2020, where the long-term trend indicates an increase in Tropical ocean temperature.

To investigate changes in the temporal evolution of equatorial Pacific SST, we first show the time series of area-averaged Tropical Pacific SST anomalies. Responding to a robust increase of global SST since the late 1900s, the linear trends of Tropical Pacific SST over the period 1920–2020 is measured as 0.08°C per decade. Compared to the previous periods (i.e., 1920-1960), the recent period (i.e., 1980-2020) shows a more significant upward trend, indicating an increase in ocean temperature anomalies. The more frequent and large fluctuations after 2000 indicate stronger interannual sea surface temperature variations during the recent 10 years, implying increasing uncertainties in Tropical SST predictability.

Tropical Pacific Climate

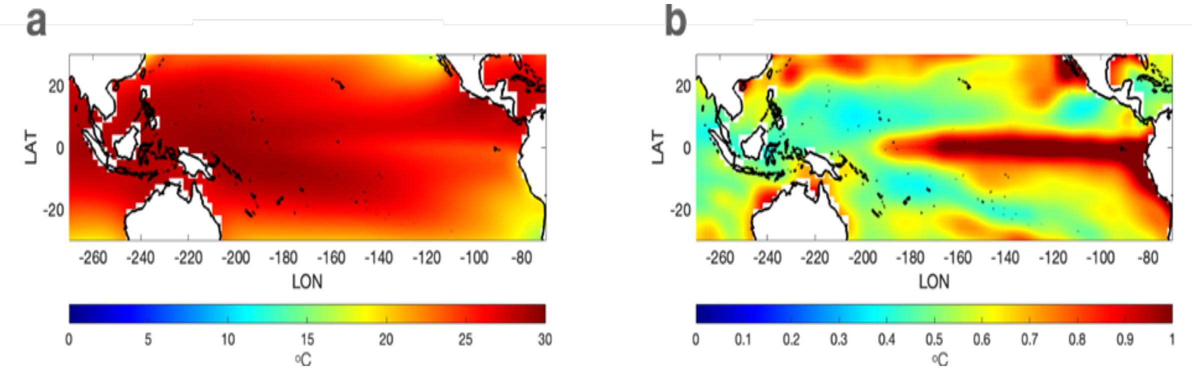

Figure 2. Spatial distribution of Tropical Pacific ocean temperature. **a** Annual mean Tropical Pacific SST: The Tropical Pacific SST climatology calculated by temporally averaged SST between 1920 through 2020. **b** Monthly standard deviation of Tropical Pacific SST: A standard deviation map of the Tropical Pacific SST time series at each grid point.

We next show the spatial distributions of Tropical ocean temperature in Figure 2. The annual mean climatology of Tropical Pacific SST (Figure 2a) exhibits the Tropical Warm Pool, which is a mass of the warmest surface ocean water (>28°C) over the western Tropical Pacific. In contrast, the SST standard deviation map (Figure 2b) is characterized by a tongue-shape SST pattern stretching from the eastern Pacific to the western equatorial Pacific, where indicating the most variant SST fluctuations on different time scales (seasonal-to-decadal), implying the ENSO.

Time Series of El Niño

The temporal and spatial patterns of ENSO are shown in Figure 3. The time series of the ENSO index presented in Figure 3a clearly shows that the ENSO variability has been increasing over the last decades. In particular, the huge amplitude of El Niño events exceeding 2°C has started occurring since 1970, implying the increase in both general mean temperature as well as interannual variability. Consistently, Figure 2b exhibits the ENSO pattern (Figures 3b and 3c) characterized by the strongest SST variation along the equator from the eastern to the western equatorial Pacific. The ENSO pattern indicates that the anomalous Tropical Pacific SST is accompanied by other regions' warming and cooling through ENSO teleconnection impacts [2]

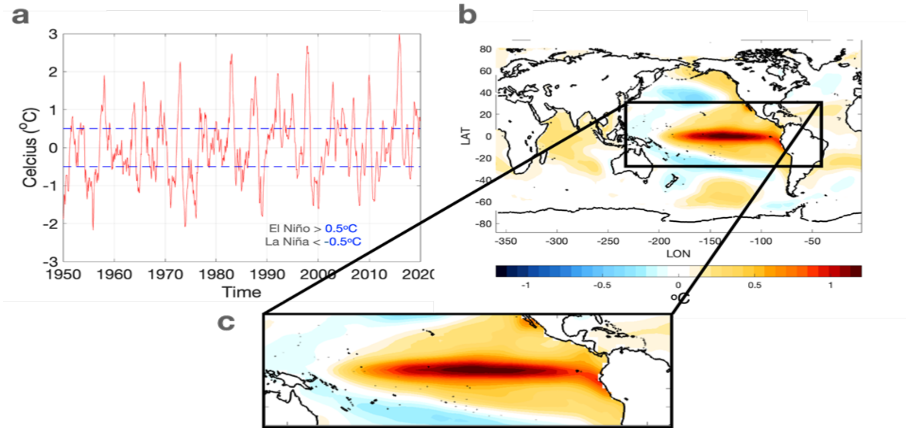

Figure 3. Time series of El Niño. a Temporal Evolution of El Niño: El Niño index; positive anomalies represent El Niño years and negative anomalies represent La Niña years. b El Niño SST distribution: Related SST pattern called El Niño spatial pattern. The pattern was obtained by composite analysis of SST where the Niño3.4 region SST anomalies above the 0.5 °C threshold. **c** Zoomed in version of panel b illustrates clear visualization of spatial distribution.

ENSO and Biological Indices

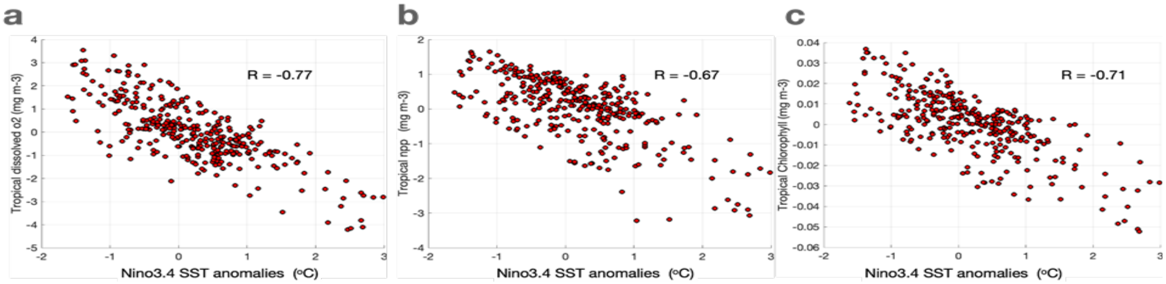

Figure 4. Scatter plots of between ENSO and biological indices (monthly), including a Upper-ocean Oxygen variability in the Tropical Pacific b Upper-ocean NPP variability in the Tropical Pacific and c Upper-ocean Chlorophyll variability in the Tropical Pacific; over the Tropical Pacific. The R indicates a negative correlation coefficient between ENSO and upper ocean biological variables.

A strong link between ENSO and the dissolved oxygen (Figure 4a), net primary production (NPP, Figure 4b) and chlorophyll (Figure 4c) is presented. Consistent with previous findings, the scatter diagram shows that the upper-ocean oxygen variability in the Tropical Pacific is largely correlated and driven by ENSO. The vertical shifts in thermocline depth during ENSO events appears to cause the reduced negative O_2 variations. Depending on ENSO magnitude and location, these shifts alternately elevate and depress cold, hypoxic waters from the ocean interior. Figure 4 supports a known mechanism that during ENSO a reduced equatorial upwelling driven by weakened trade winds can suppress phytoplankton nutrient supply, causing chlorophyll concentrations and biological heating to decrease. All three graphs have a relationship close to one, indicating a strong negative correlation

Seasonal Differences in ENSO

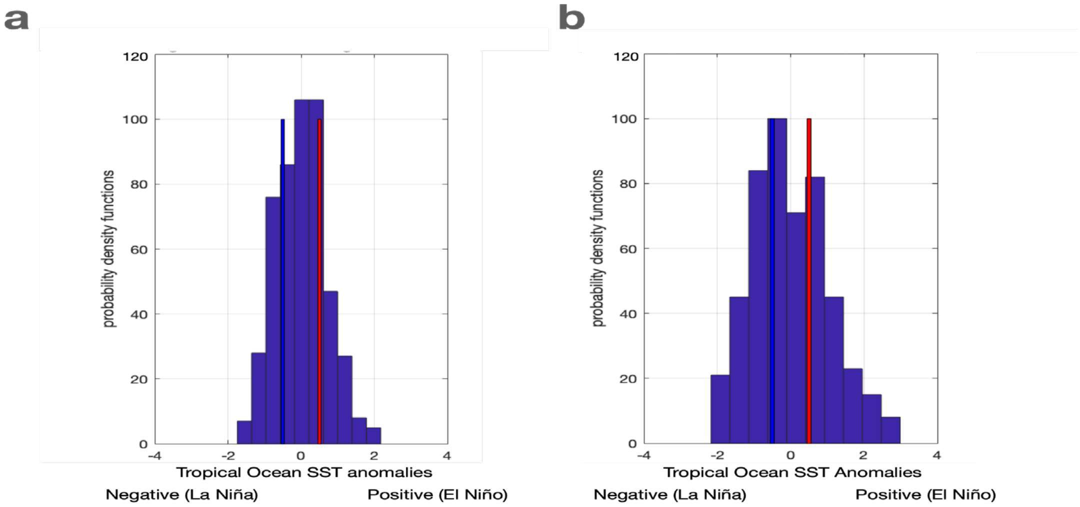

Figure 5. Histogram of Niño3.4 SST anomalies during warm (left) and cold (right) season. Y-axis represents the frequency and X-axis represents the ENSO phase (negative for La Nina and positive for El Niño) with its magnitude. **a** Histogram Niño3.4 SST anomalies during warm season **b** Histogram Niño3.4 SST anomalies during cold season.

Figure 5 shows a seasonal difference in ENSO intensity between the warm (April-to-September) and cold (October-to-March) seasons. Tropical Pacific SST anomalies histograms indicate a normalized probability density function on the y-axis and the phase and magnitude of Niño3.4 region SST anomalies representing ENSO on the x-axis. A comparison of two histograms (Figure 5a and 5b) reveals that the number of ENSO episodes where the Tropical SST anomalies are above and below 0.5^{o}C and -0.5^{o}C (e.g., right of the red line and left of the blue line in Figure 5, respectively) and larger amplitude of ENSO extreme events reaching ~2^{o}C SST anomaly are more frequent during the cold season.

The stronger and more frequent ENSO variability is also supported by Figure 6. In Figure 6, the seasonal development of ENSO across the different calendar months indicates that El Niño has a larger amplitude in winter/fall compared to summer/spring. To be specific, Figure 6 presents the seasonal evolution of ENSO variability from the initial to developing and mature phases. The standard deviation of monthly Tropical Pacific SST anomalies indicates that the ENSO barely develops over the equatorial Pacific before May but gradually initiates and grows warm SST anomalies from summer. Where the tongue shape SST anomalies are most prominently developed during the winter season (e.g., November and December), consistent with a clear ENSO seasonal phase-locking behavior where the ENSO variability increases in the fall and winter and decreases in the spring and early summer. Given that the seasonality of the Tropical Pacific Ocean is relatively weaker than mid-latitude and the ENSO development is largely driven by seasonal atmospheric forcing (e.g., sea level pressure, winds), the enhanced surface wind variability during winter can help the ENSO development. Specifically, a larger difference between sea and air temperatures during the cold season can help the ocean to experience a large fluctuation. These results support the known previous finding that compared to other seasons, ENSO is most significant during winter.

Seasonal Development of ENSO

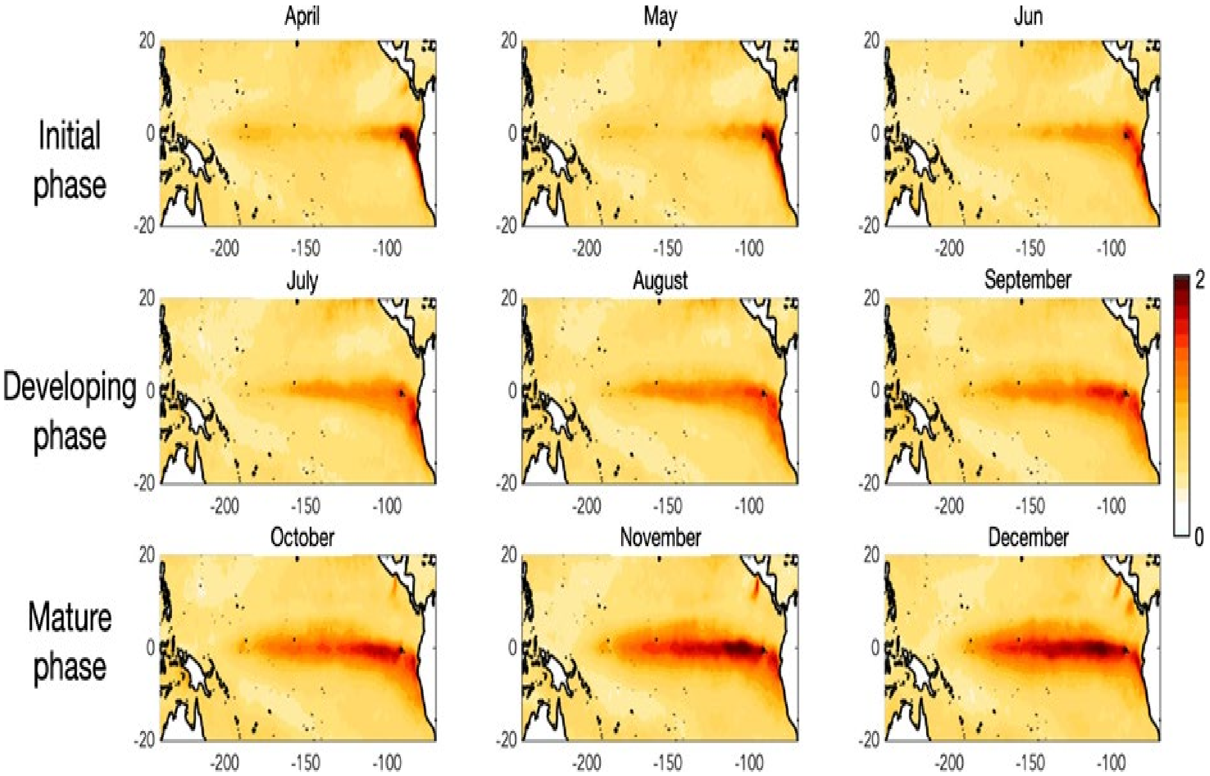

Figure 6. Seasonal development of ENSO. Standard deviation of seasonal tropical Pacific SST anomalies, where the magnitude of standard deviation implies the initial (top row), developing (middle row), and mature (bottom row) phase of ENSO variability from the warm to cold season.

Seasonal ENSO Impacts

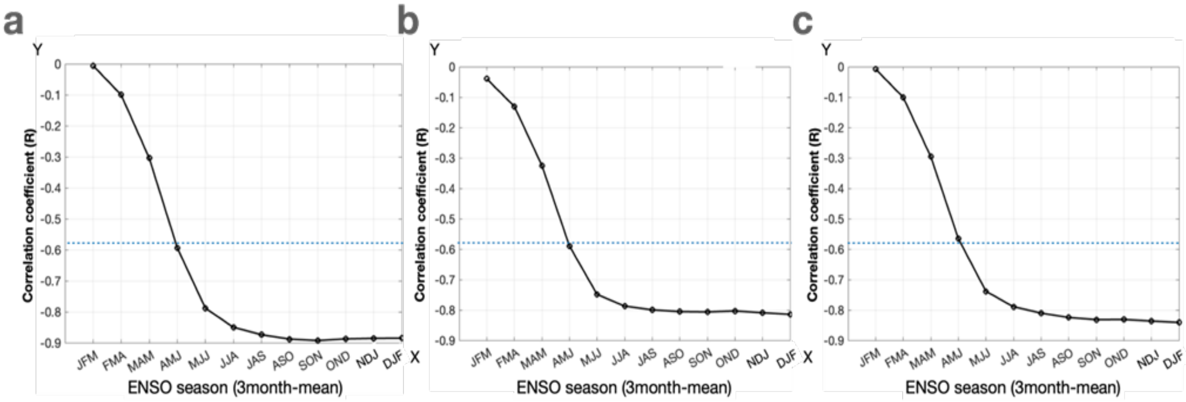

Figure 7. Seasonal ENSO impacts on DJF through oxygen, NPP, and chlorophyll, where seasons are computed as 3-month mean. The blue dashed line indicates statistical significance at the 95% level according to a 2 sided Student's t-test. **a** Seasonal impacts of El Niño on Winter Oxygen **b** Seasonal impacts of El Niño on Winter NPP **c** Seasonal impacts of El Niño on Winter Chlorophyll

To examine the seasonal impacts of El Niño on the upper ocean nutrition supply, we plot the correlations of seasonal El Niño with winter (DJF) oxygen, NPP, and chlorophyll. During the late winter (JFM/FMA) and early spring (MAM), ENSO has little influence on the biological variables. However, once ENSO starts initiating from the late spring (AMJ), the biological variables immediately show significant linkages with ENSO, indicating that there is a strong sensitivity between phytoplankton and ENSO. During late spring to winter, El Niño is matured, and during this state, it influences oxygen levels to decrease from summer to winter. Implying as the ocean temperature increases, the amount of oxygen will decline. Supporting that ENSO is most significant during winter seasons, with the highest impact. The level of oxygen appears to decrease more readily during the winter.

Discussion

The present study uses a statistical approach to conduct the analysis of biological disturbances during the ENSO cycle. To investigate the Tropical phytoplankton concentration variations and predictability, we chose to examine the ocean chlorophyll and oxygen concentration, which are largely modulated by natural ocean dynamics such as ENSO. In the Tropical Pacific Ocean, increasing ocean temperatures and ocean extreme events could lead to significant changes in those upper-ocean chlorophyll dynamics by reducing the oxygen level and thus posing a threat to marine life and ecosystems. The results especially demonstrate that the degree of linkages of equatorial biological response to El Niño may increase during the cold season due to the strong seasonality of ENSO, where the ENSO is fully matured from fall to early winter.

The known mechanisms of chlorophyll response to ENSO have been described via changes in equatorial Pacific upwelling and thermocline depth and zonal oceanic advection, which are strongly linked to air-sea coupling [3]. A strong inverse relationship between the chlorophyll and Tropical Pacific SST (e.g., ENSO) can be explained by suppressed (enhanced) equatorial upwelling of nutrient-rich deep water mass with zonal advection of nutrient-poor (rich) waters from the west (east) to east (west). Given the strong connection between the ENSO and anomalous westerly winds, the equatorial chlorophyll concentration might be an effective indicator for the development of the Tropical SST anomalies and the ENSO progression and phase. It is notable that the correlation between winter biological indices with ENSO becomes dramatically increasing from the late spring (e.g., April-May-June, AMJ as seen in Figure 7. The significant correlation reaching -0.6 indicates that the changes in upper ocean nutrients are an immediate response to changes in equatorial Pacific SST anomalies. Although the Tropical SST is barely distinguished during AMJ (Figure 6), the strong correlation between winter chlorophyll and seasonal ENSO from the late spring to winter reveals the robust and sensitive linkages between the two.

The results contrast the claim of previous findings which focused on the understanding of the evolution and impacts of El Niño Southern Oscillation frequencies on marine ecology [10]. Moreover the data indicates a correlation coefficient between ENSO and biological indices. Which suggests that the decline in oxygen levels are closely linked with the increased frequency and magnitude of El Niño. Additional graphs support evidence that while ENSO is the main driver of deoxygenation, different seasons have distinct impacts. In line with the hypothesis, the results met the expectations of the research question.

This study strove to find the impacts of seasonal variations of the Tropical Pacific ocean temperatures on upper ocean oxygen. The graphs narrowed down to show which season of El Niño would have the most impact on biological indices. However, due to the rising climate temperature, ENSO has experienced apparent changes in its impacts. And many features associated with ENSO including its climate impacts have changed. These changes occur not only in temperature and precipitation, affecting the daily life of human beings, but also in the level of oxygen, chlorophyll and net primary production available. Causing problems and imbalances in both aquatic and terrestrial ecosystems. While the present study provides a clear relationship between ENSO and oxygen on the seasonal time scale, due to the lack of data on previous El Niño occurrences, the results cannot confirm definite evidence of oxygen declines during winter seasons. This constraint limited this project to experiment with only a maximum number of previous El Niño occurrences, ranging from 1950 - 2020. While we believe these limitations have not impacted the primary outcome of the study, future work could seek to include additional controls.

Conclusion

Global warming is increasing the frequency of El Niño Southern Oscillation. Evidence from previous studies indicates that there is a fourfold increase in the frequency from one event in 60 years in the control to one event in 15 years in the climate change period. This study conducted a systematic literature review, observing seasonal Tropical Pacific sea surface temperature anomalies and seasonal El Niño impacts on winter compared to summer seasons. Most importantly focusing on how ocean temperature would cause fluctuations in oxygen levels. However, there have been limitations throughout this study. For example, this study was exposed to only a limited amount of data which kept us from making our results more empirically meaningful. The process of finding which season of El Niño in the Tropical Pacific Ocean has the most impact on oxygen is based on previous El Niño events. Hence, the short period, the data provided may be a coincidence that El Niño is more frequent during winter months. However, our study uses additional variables to strongly support the evidence that oxygen declines more readily during winter El Niño months. This study is the first step, and several future studies will be carried out. These include a precise measurement of decreasing oxygen levels in the Tropical Pacific Ocean to validate the proposed claim of El Niño’s impact. These findings should be used to better predict the occurrence of El Niño.

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