A Comparison of Net Primary Production Calculations using Remote Sensing and Oxygen Balance Method in the Equatorial Pacific

Max Daley

University of Washington, Seattle, WA

School of Oceanography

Email: mdaley20@uw.edu

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Abstract

Primary Production is a fundamental concept in oceanography and represents the rate at which photosynthetic organisms use chemical energy to synthesize organic compounds. Net Primary Production (NPP), or photosynthesis minus respiration, serves as a critical measure of ecosystem health and carbon cycling in marine environments. This study investigated the dynamics of marine NPP in the Equatorial Pacific from 5 N to 5 S at a 167 W transect from January 1st, 2024, to January 6th, 2024. It is a region characterized by significant biological productivity due to upwelling. Satellite data, including chlorophyll measurements, provide invaluable insights into phytoplankton and primary production across oceanic regions. Through both field research and analysis using two different equations, the effect of an El Niño and La Niña periods on NPP were observed. The data collection was done using temperature, nutrient data, upwelling patterns, wind data and oxygen concentrations. Satellite-derived chlorophyll data, along with in situ measurements, were used to assess primary production levels across different latitudes in the Equatorial Pacific. The findings of this paper demonstrate that while satellite derived NPP estimates generally align with in situ measurements, variations do exist. On average in situ measurements recorded higher values of NPP than remote sensing. NPP levels are influenced by multiple physical, chemical, and biological variables. This study contributes to advancing our understanding of primary production dynamics in the Equatorial Pacific and hopes to test the accuracy of satellite-based observations for ecosystem management and climate research. By using real-time data from remote sensing along with field observations, we can improve our ability to monitor and act upon changes in marine environments and better protect our oceans.

Plain Language Summary

Primary production is the process of converting sunlight, CO_2 and nutrients into organic matter by phytoplankton. Net Primary Production (NPP) was determined to understand this process. This study looked at the equatorial Pacific ocean because of the presence of upwelling, a process where nutrients come up from deeper colder waters and enhance NPP. NPP cannot be measured directly and for this study, two equations were used to calculate NPP from satellite data and in person observations with oxygen samples. Satellites track chlorophyll levels in the ocean, which indicate the presence of phytoplankton. Large recurring climatic events of El Niño and La Niña where examined to see how they affect NPP in the Equatorial Pacific. It was found that while satellite data can provide valuable information, factors like mixing in the ocean and potential errors in the satellite measurements need to be taken into consideration. Overall, the research done looked at the differences in satellite data and field observations to understand primary production. Both methods allow us to see how changes in the environment impact the ocean which and how we can effectively measure NPP.

Introduction

Primary Production is a term that refers to the process when photosynthetic organisms capture radiant chemical energy to produce organic compounds. Global Primary production is extremely important for both the planets food cycle and biological pump. Currently the ocean provides $\sim 50 \times 10^{15}$ g C yr^{-1}, which is about half of global NPP (Field et al., 1998). Primary production is also the base of the complex food chain of the ocean. Net Primary Production (NPP) is a measure of photosynthesis minus respiration. Marine NPP (mg C m^{-2}) is a reliable method of measuring ecosystem health and carbon cycling (Behrenfeld et al., 2005). Different locations also affect the amount of NPP that is present. The equatorial Pacific is a region of high biological productivity due to it being an area of upwelling that supplies an abundance of nutrients (Chavez & Barber, 1987). The factors governing NPP in the environment encompass sunlight, nutrients, carbon dioxide levels, and temperature. These elements are subject to the influence of both oceanic and atmospheric events. Marine NPP cannot be measured directly but can be calculated using the oxygen balance method(Emerson, 1987) and an equation converting satellite chlorophyll to NPP (Behrenfeld & Falkowski, 1997).

Satellite data holds a prominent and accepted position in today's scientific literature. These orbiting instruments, such as those deployed by NOAA, make important observations of the surface ocean, and of particular significance, chlorophyll, a pigment primarily associated with photosynthetic organisms(phytoplankton), and serves as a key metric for estimating phytoplankton abundance across various oceanic regions. Previous laboratory investigations have established that phytoplankton dynamically controls their chlorophyll levels in response to changes in light, nutrient availability, and temperature conditions. This dynamic adjustment in cellular pigmentation optimizes the rate of photosynthesis (Behrenfeld et al., 2005). Phytoplankton's essential role in sustaining life on Earth cannot be overstated, as they contribute significantly to approximately one-fifth of global photosynthetic activity (Benoiston et al., 2017).

In the Equatorial Pacific, a variety of factors influence phytoplankton growth. These factors include biological, physical, and chemical processes. The most important factors in phytoplankton growth are nutrient availability and light availability. Other important factors to consider are seasonal variability, and significant climatic events like El Niño and La Niña or also known as the ENSO cycle. The purpose of the research conducted in this paper was to look at how primary production changed in the Equatorial Pacific during an El Niño event and how it differed from La Niña chlorophyll levels. These two climatic patterns represent opposing climate conditions: La Niña happens when intensified trade winds displace warm water toward

Asia, resulting in the upwelling of cold, nutrient-rich deeper waters from the western Americas and results in enhanced primary production. In contrast, El Niño transpires when weakened trade winds direct warmer waters toward the western coast of the Americas, creating a period of unusually warm equatorial Pacific waters.

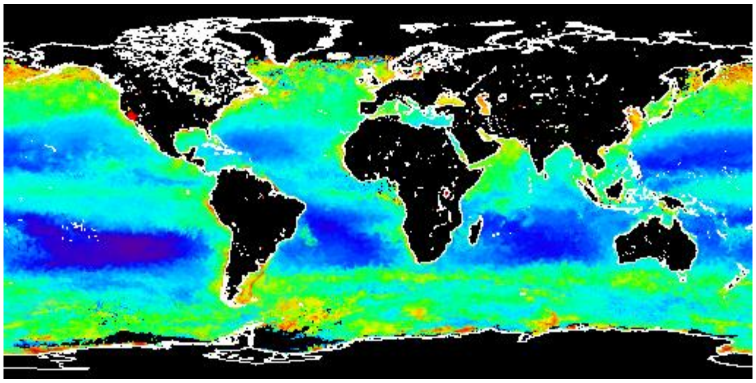

Figure 1 A: Satellite global chlorophyll surface concentration for January 2021 during a La Niña period. (NASA MODIS database)

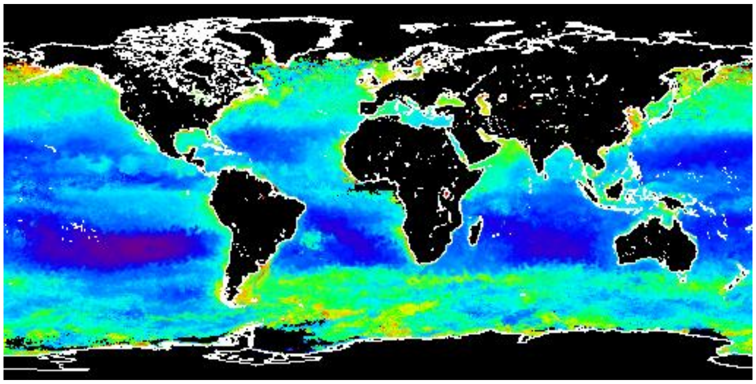

Figure 1 B: Satellite global chlorophyll surface concentration for January 2016 during an El Niño period. (NASA MODIS database)

Chlorophyll levels in the surface waters of the Equatorial Pacific during the La Niña period (Figure 1 A) are higher than the respective factors during El Niño period (Figure 1 B). Research done in the Equatorial Pacific during 1997 to 1998, in a generally moderate productive region, showed very low phytoplankton biomass and production during an unusually strong El Niño period. The authors concluded that the primary cause of less production was an absences of nitrate throughout the entire photic zone (Strutton & Chavez, 2000). The low concentration levels lasted until May of 1998 when stronger, more normal, trade winds returned and caused upwelling (Strutton & Chavez, 2000). Studies have also concluded that the amount of NPP present varies on the ENSO cycle with higher values occurring during a La Niña period. Global NPP is strongly anti-correlated to El Nino Southern Oscillation (Bastos et al., 2013). For this experiment, a hypothesis was concluded that satellite data would be higher than measurements made in the field (Engel 2012) and satellite data using the chlorophyll to photosynthetic rates method would be very close but higher than production collected on board the Thompson due to it being an El Niño period. During El Niño there is a deeper mixed layer with warmer water that results in less nutrients. (Strutton & Chavez, 2000). In recent years, using Nasa, La Niña characteristics observed have resulted in a shallower mixed layer and colder surface waters due to upwelling and an increase in nutrients for phytoplankton growth. The chlorophyll data observed from both field experiments and satellite data was compared against each other to see the correlation between the two and was helpful in determining the validity of satellite information. The objective of this research was to place real-time primary production data with data acquired via remote sensing, a resource widely accessible to everyday users. Satellite-derived information is frequently employed and may be inadvertently presumed as accurate. Finding the NPP from both methods helps support how an El Niño period changes it. Should the satellite-derived information align effectively with actual conditions during the complex El Niño phase, this paper determined the credibility of satellite chlorophyll measurements when applied to the understanding of primary production in the Equatorial Pacific.

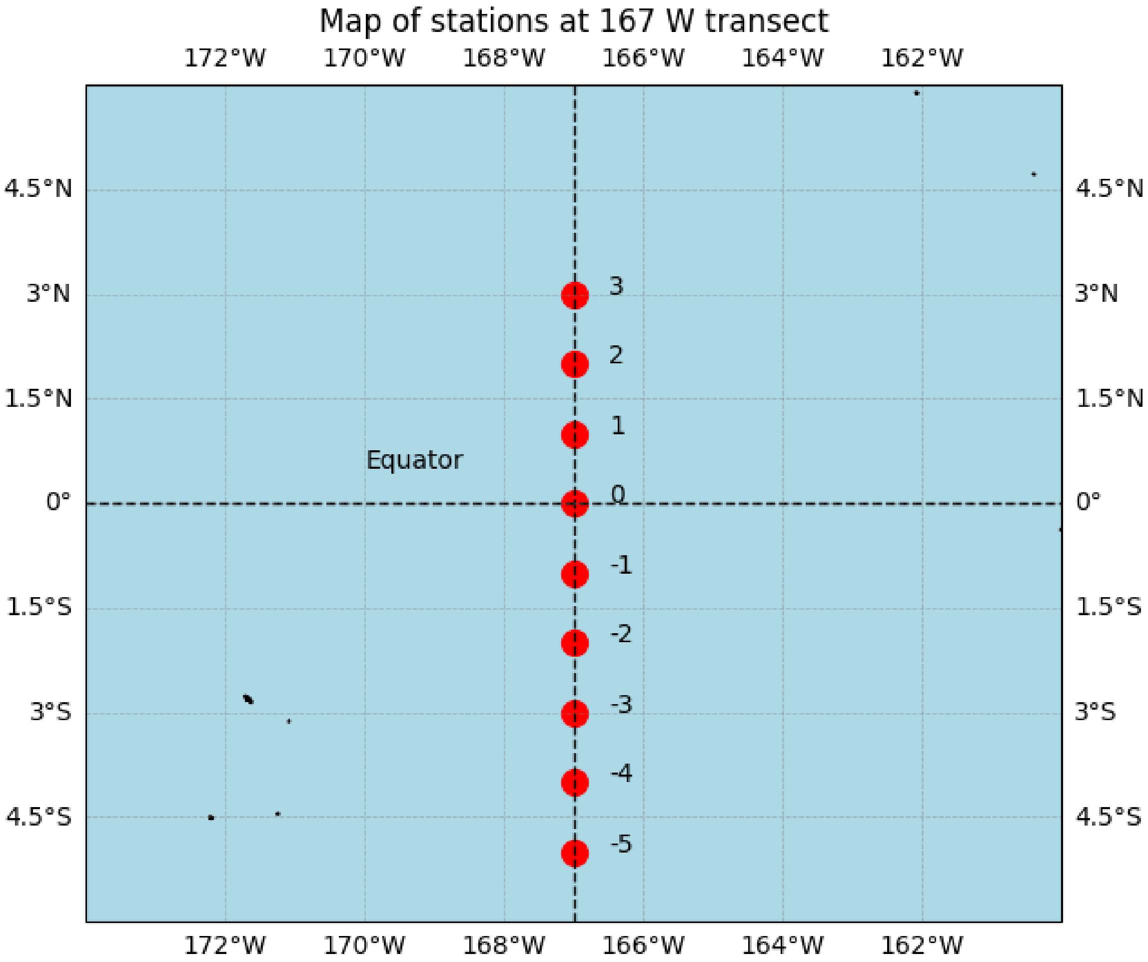

Figure 2: A map of the equatorial Pacific region at 167 W at the equator. The nine stations labeled are regions where the oxygen concentrations were measured as well as chlorophyll data.

The in-field studies were focused on the Equatorial Pacific at 167° W (Figure 2) These respective stations were where oxygen concentration was measured. The Equatorial Pacific is a region where upwelling during El Niño affects primary production (Strutton & Chavez, 2000). Chlorophyll global models during December proved the low primary production in the region. From this information it was concluded that the data collection occurred during an El Niño period. Other sources to track and monitor the progress of the current El Niño period can be found such as (https://www.pmel.noaa.gov/elnino/status, accessed on Feb, 2024).

To compare respective primary production levels, data from satellite data was converted into a measurement of primary production. For comparison, marine net primary production (NPP) was calculated to measure the health of the marine ecosystem and how well it cycles carbon. The equation (Equation 1) can be used to convert the chlorophyll(chl) concentration found in the MODIS global model.

$$\text{NPP} = \text{chl} * \text{pb\_opt} * \text{day length} * \text{z\_eu} * f(\text{par}) \quad (1)$$

Where Chl is measured in mg m^{-3}. The unit pb_opt is the maximum daily net primary production found within a given water column (Behrenfeld & Falkowski, 1997). The pb_opt, or the daily integrated production measurement can be found as a function of sea surface temperature, pb_opt = sum(i=0,7) a_i * (sst/10)**i. The day length was recorded in hours. The z_eu, or euphotic depth is measured in meters which was determined by the surface chlorophyll levels, and the f(par) is a function of par that was calculated using ship PAR data at each station and was determined using f(par) = 0.66125 * par / (par + 4.1) (Ocean Productivity: NPP Productivity Models (oregonstate.edu), accessed on Feb, 2024).

To measure the NPP for using in field experiments, the Emerson Oxygen balance method (Figure 3), also known as the oxygen mass balance approach, was used. This method involves measuring the concentration of oxygen over time to gauge the rate of oxygen production. The focus of the oxygen mass balance method determining NPP lies in monitoring the equilibrium between oxygen generation through photosynthesis and oxygen consumption through respiration, while also considering a balance of physical processes including horizontal advection, vertical mixing, and gas oxygen exchange with the atmosphere(Emerson, 1987).

Within the mixed layer, the concentration of oxygen represents the combination of both physical and biological processes. Once the physical processes were estimated, the Net Primary Production (NPP) was calculated. NPP is measured in mg C m^{-2} d^{-1}. Our sampling encompassed stations located across the equator at 167° W. The equation used for determining NPP was (Equation 2)

$$\Delta[O2]/\ \Delta t = \text{Advection} + M([O2_{DEEP}]-[O2]M) + KGE([O2]_{SAT} - [O_2]) + J. \quad (2)$$

Where advection accounts for the lateral mixing of oxygen, which is negligible and thus was not factored into the NPP calculations for this experiment. The advection is minimal because currents at the equator move east-west and the east-west gradient of dissolved oxygen is small. It's worth noting that in this context, Emerson assumes a steady state, so the focus was solely on measuring oxygen concentrations. Previous studies have shown that during the El Niño period of 1998 was reported at 410 mg C m^{-2} d^{-1} (Strutton & Chavez, 2000).

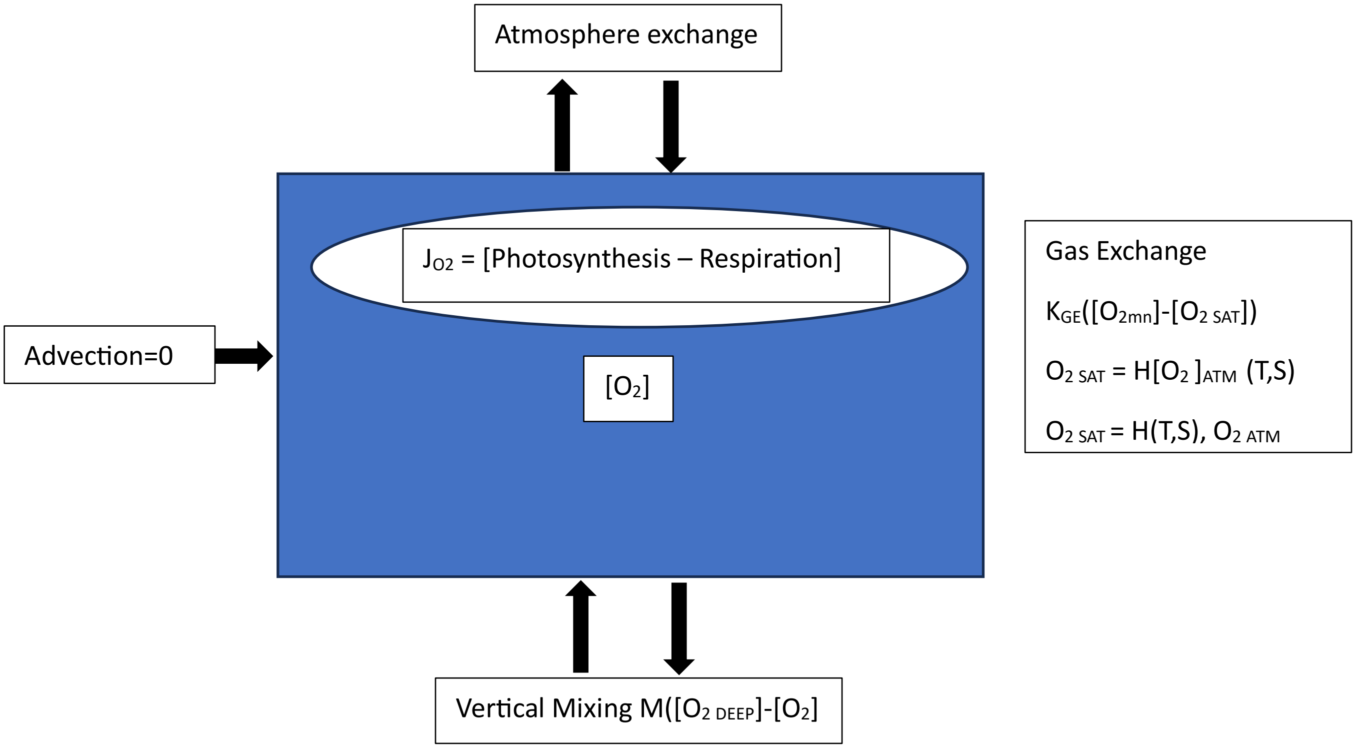

Figure 3: A Schematic Model showing the processes that control the concentration of O_2 using an Ocean Box model. (Emerson 1987)

Methods

The research part of the cruise took place from January 1st, 2024, to January 6th, 2024. The stations were strategically placed at every degree of latitude, starting at 5° S and ending at 3° N Oxygen concentrations were measured using a SEA-Bird SBE-43 dissolved oxygen sensor that was mounted on the rosette and lowered at each station (Figure 2). The sensor was calibrated using Winkler titrations of discrete samples collected from Niskin bottles. The purpose of the Winkler titrations was to measure how much dissolved oxygen was in water and give the sensor a standard scale (Figure 4). Also on the rosette, the shipboard conductivity temperature and depth (CTD) apparatus were deployed at each station (Figure 2) to measure temperature and salinity of the mixed layer. The CTD electronics included probes measuring oxygen concentration, temperature, and salinity. $M([O2_{DEEP}]-[O2])$ represents the mixing occurring between the deep ocean and the mixed layer. This was measured using the Nitrate nutrient data at the mixed layer and just below the mixed layer at 100 meters depth. The change in nitrate was then converted to oxygen using the Redfield nitrate to oxygen ratio of 16:138 (Lenton & Watson, 2000). An important point to consider is that approximately 80% of primary production takes place within the Mixed Layer (Emerson, 1987), which is why the concentration within this layer was measured. Wind speed was also tracked, denoted as KGE, and the difference between $([O2]_{SAT}-[O_2])$, which relates to oxygen, temperature, and salinity. The $[O_2]_{SAT}$ was found using the Henry's Law coefficient(H) for gas solubility. Since the atmospheric concentration of oxygen is constant, oxygen solubility measured in seawater is a function of temperature and salinity.(Garcia & Gordon, 1992) Temperature and salinity was measured aboard the ship. J accounts for the Net Primary Production value, calculated as the production minus respiration. Onboard the RV Thompson, instrumentation that measured daily wind speed was also included.

The wind data (u) in m/s was used to find the KGE(figure 3). KGE =0.31 * $u^2(Sc/660)^{(-1/2)}$ where Sc is Schmidt number was set equal to what oxygen in seawater, or 365 (Wanninkhof, 1992). Once the KGE at each station was found, it was multiplied by the change in oxygen at 100 meters and at the mixed layer depth using the corrected calibrated oxygen values. The estimation of mixing that occurred at depth was observed using nutrient data and using the Redfield ratio as well as nutrients with depth and the mixed layer to the vertical mixing at the same stations. Once the oxygen values were measured, the oxygen balance method was used to measure NPP. The surface chlorophyll, and sea surface temperature data were taken from MODIS which is laid out on (https://simonscmap.com/). MODIS satellite data was taken during the sampling time of the research cruise in January 2024. The surface chlorophyll was converted to NPP using the chlorophyll and the NPP = chl * pb_opt * day length * z_eu * f(par) formula (Equation 1) (Behrenfeld & Falkowski, 1997).

Results

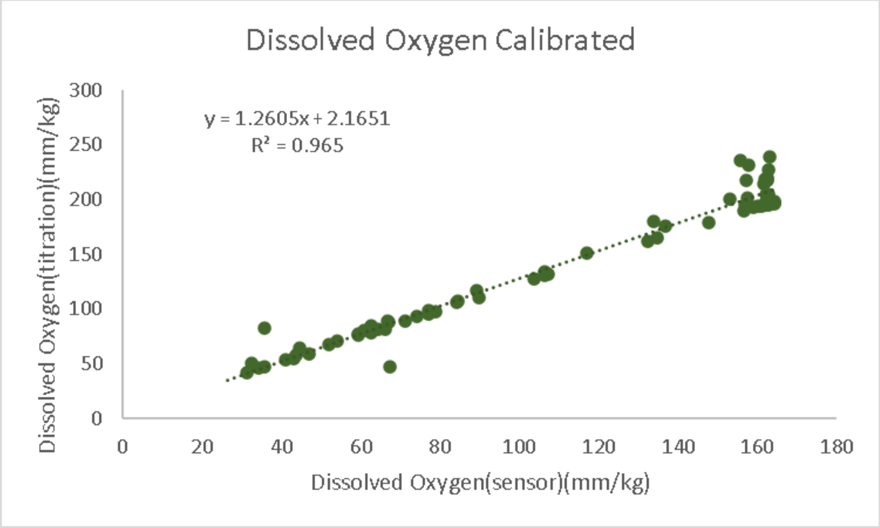

Figure 4: The calibration curve of dissolved oxygen from sensor and Winkler Titration method at every station from 5S to 3N

Using Equation 1 the Net Primary Production was calculated at each station from 5° S to 3° N along a 167° W transect. (Figure 2) NPP for remote satellite data was calculated using equation 2. The two NPP values (Table 1) are compared in Figure 4. The NPP(In-situ) is data using equation 1 while NPP(Remote) is data calculated using equation 2.

Table 1: Variables used in Equation 2 that affected the NPP level for in-situ measurements

(LATITUDE)	**KGE (CM/HR)**	**([O2]-[O2]$_{SAT}$) (µMOL/KG)**	**([NO$_{4\ DEEP}$]-[NO$_4$] (µMOL/KG)**	**MIXING (m/d)**
-5	5.3	10.6	0.7	2.2
-4	21.3	9.8	1.1	11.2
-3	21.3	9.5	1.3	9.5
-2	21.3	7.0	0.5	4.8
-1	21.3	7.9	0.4	2.7
0	21.3	7.1	0.1	3.3
1	29.2	4.0	-0.1	1.8
2	29.2	4.8	-0.2	1.1
3	14.8	4.7	0.8	1.2

Table 2: The NPP values recorded for each station(Figure 2). The NPP(in-situ) is calculated using equation 2 while NPP(remote) is calculated using equation 1. The calculations are observed in figure 5.

LATITUDE	NPP(IN-SITU) MG C M^{-2} D^{-1}	NPP(REMOTE) MG C M^{-2} D^{-1}
-5	238.4	503.2
-4	1179.1	455.3
-3	1142.4	461.1
-2	721.0	533.2
-1	785.1	685.7
0	946.5	701.5
1	558.5	618.8
2	323.5	576.6
3	335.2	528.7

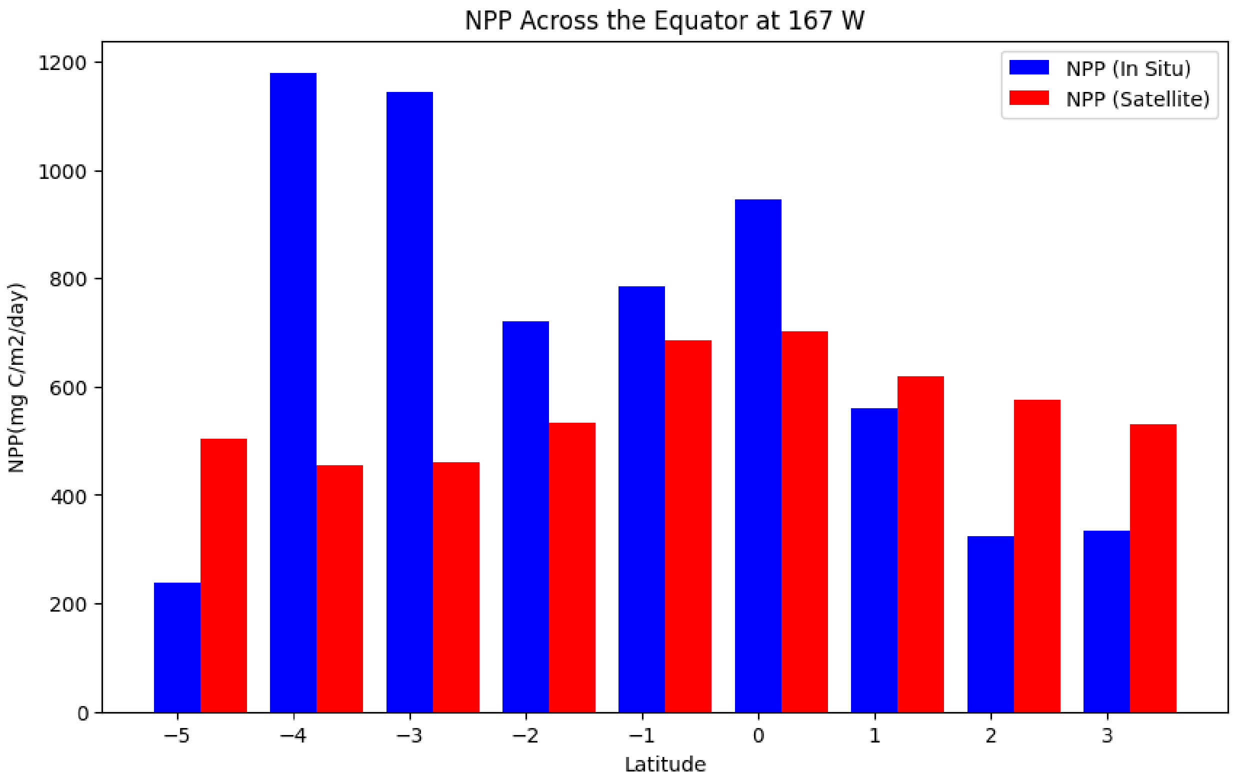

Figure 5: The NPP levels measured in mgC/m^2 day from stations in figure 2. The values can be seen in Table 2. The negative values represent southern latitudes while positive represent northern latitudes.

After satellite and in situ calculations were graphed, chlorophyll data from 2023 was collected using the same MODIS platform as the data above. The chlorophyll was also converted to NPP using equation 2. The 2023 data is during a La Niña period and is compared against the NPP of the El Niño period in 2024 using a bar graph.

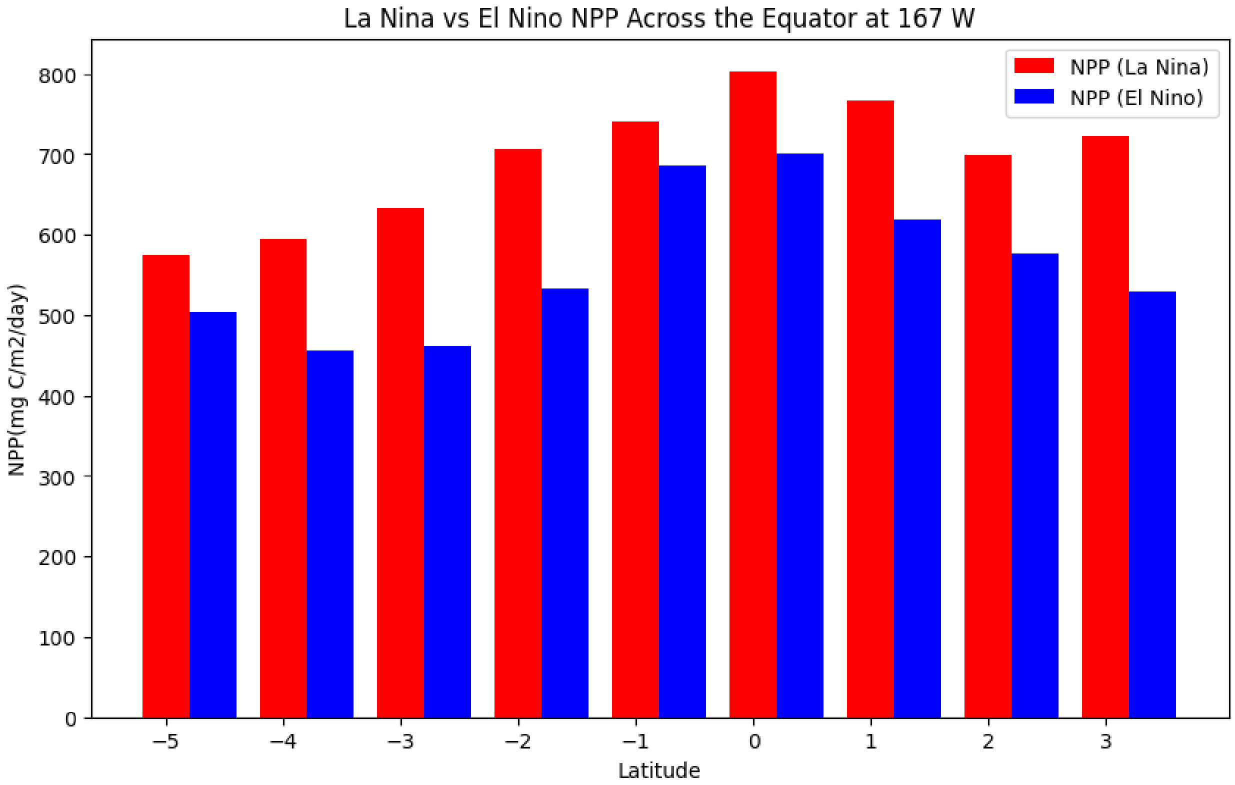

Figure 6: NPP levels from the 2024 El Nino period represented in blue at every station. In red the 2023 La Nina period is represented.

Discussion

Before discussing the results found, it is important to note that to measure NPP, steady state was assumed (Emerson, 1987). Regarding in-situ measurements, it's notable that latitudes -4° and -3° exhibit particularly high levels of NPP, with values of 1179.1 and 1142.4 mg C m^{-2} d^{-1}, respectively (Table 2). This exceptionally high productivity in these regions is intriguing and could potentially be attributed to the unusually high mixing coefficients observed at these latitudes, recorded at 11.2 and 9.5, respectively (Table 1). These high mixing coefficients suggest intense vertical mixing is happening at these stations, which can increase nutrient availability and stimulate biological productivity in surface waters. Consequently, the pronounced peaks in NPP at latitudes -4° and -3° likely reflect the effects of both mixing and favorable environmental conditions for photosynthesis. This phenomenon finds its logical explanation in the presence of upwelling in the equatorial region (Strutton & Chavez, 2000). The upwelling process can be attributed to the significantly high mixing coefficient observed in this area (Table 1). For in situ measurements across the nine different stations the average NPP was equal to 693.3 mg C m^{-2} d^{-1} and for remote satellite calculations, 562.7 mg C m^{-2} d^{-1}. In a previous study conducted during the El Niño of 1997-1998 recorded relatively low values for NPP at 410 mg C m^{-2} d^{-1} (Strutton & Chavez, 2000). Initially, it was hypothesized that satellite data would exhibit higher NPP values compared to in situ observations. While this holds true for stations situated at latitudes 1°, 2°, and 3° (Figure 5), this pattern doesn't consistently apply for negative latitudes. Satellite data algorithms, being empirical, provide a snapshot that is considered more reliable when data is collected over a month or longer period. Consequently, satellite data is typically aggregated over a week or month to limit the errors of factors like cloud cover, which can corrupt the resolution of the samples. In this context, especially in the northern hemisphere, it's possible that cloud coverage may have compromised the overall accuracy of the data collection (Chavez et al., 2011). A previous study looking at average global NPP levels from 2003-2012, the average NPP was equivalent to around 821.9 mg C m^{-2} d^{-1} which is a 19% increase from in situ measurements and a 46% increase from satellite measurements (Boyd, et al., n.d.). This supports the statement that NPP values during an El Niño period report relatively low values. This also shows to be true for Figure 6 where satellite measurements from an El Niño and a La Niña period were compared. At all nine stations, NPP values during the 2023 La Niña were on average 24% greater than those reported during the 2024 El Niño period (Figure 6). While NPP is higher during the La Niña period (Figure 6) this is not due to the absence of nitrate (Table 1) in the entire photic zone (Strutton & Chavez, 2000) This observation supports the hypothesis suggesting higher NPP during La Nina periods, but not attributed to increased upwelling and intensified trade winds (Strutton & Chavez, 2000).

Surprisingly, NPP values in the northern hemisphere surpass those observed through in situ measurements (with exception to station 5S) and in the southern hemisphere, the in-situ values are higher than remote satellite NPP. A possible explanation for this is the January period when the data was collected. January is a summer month for southern latitudes and winter for northern latitudes. Factors like temperature and sunlight do affect NPP levels and these are higher in summer months. A more intensified study would need to be done to prove this.

Lastly, besides stations at -4 south and -3 south, NPP does increase as you reach towards the equator with the third highest NPP value being located at 0° for in situ measurements. When looking at satellite data, the increase in NPP as you get to the equator supports the original hypothesis. Since satellite data is just surface chlorophyll levels, it is possible that mixing occurred below the surface since at -4° and -3° the mixing is very high.

The greater NPP levels at the equator and La Nina are crucial for carbon sequestration. Understanding the dynamics of NPP fluctuations during such climatic events is helpful for comprehending the carbon cycle and the broader weather patterns that significantly influence various aspects of daily life. Elevated NPP values contribute significantly to mitigating the effects of climate change by decreasing the atmospheric carbon concentration and influencing the global carbon cycle and impacting global climate patterns. Recognizing this increase in NPP during La Niña years can enable us to leverage this additional carbon sequestration potential effectively.

Conclusion

In conclusion, this study has provided insights into the dynamics of marine Net Primary Production (NPP) in the Equatorial Pacific, a region where there is significant biological productivity due to upwelling. By using a combination of satellite data and in situ measurements, the impact of El Niño and La Niña events on NPP levels were investigated. Findings indicate that while satellite NPP estimates generally align with in situ measurements, variations do exist. More specifically in regions with high mixing coefficients and gas exchange processes. It is also important to consider factors such as temporal resolution and cloud cover when interpreting satellite data. NPP levels tend to be higher near the equator, attributed to the presence of upwelling processes that supply abundant nutrients to phytoplankton, but the other factor of mixing listed above resulted in stations away from the equator having higher NPP values. Historical satellite data shows that NPP values during La Niña periods are higher compared to El Niño periods and highlight changes climatic events have on NPP. It is essential that continued research in this field will improve our understanding of primary production dynamics and their broader implications for marine ecosystems and global climate patterns. A specific study could look at the seasonality across the equator in the equatorial Pacific to see if there is any effect on NPP values in northern and southern latitudes. Efforts to enhance the accuracy and reliability of satellite-based observations will further advance our ability to monitor and protect our oceans in the face of ongoing environmental issues.

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References

Bastos, A., Running, S. W., Gouveia, C., & Trigo, R. M. (2013). The global NPP dependence on ENSO: La Niña and the extraordinary year of 2011. *Journal of Geophysical Research: Biogeosciences*, *118*(3), 1247–1255. https://doi.org/10.1002/jgrg.20100

Behrenfeld, M. J., & Falkowski, P. G. (1997). Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnology and Oceanography*, *42*(1), 1–20. https://doi.org/10.4319/lo.1997.42.1.0001

Behrenfeld, M. J., Boss, E., Siegel, D. A., & Shea, D. M. (2005). Carbon-based ocean productivity and phytoplankton physiology from space. *Global Biogeochemical Cycles*, *19*(1), 2004GB002299. https://doi.org/10.1029/2004GB002299

Boyd, P. W. (n.d.). Net Primary Production in the Ocean.

Chavez, F. P., & Barber, R. T. (1987). An estimate of new production in the equatorial Pacific. *Deep Sea Research Part A. Oceanographic Research Papers*, *34*(7), 1229–1243. https://doi.org/10.1016/0198-0149(87)90073-2

Emerson, S. (1987). Seasonal oxygen cycles and biological new production in surface waters of the subarctic Pacific Ocean. *Journal of Geophysical Research: Oceans*, *92*(C6), 6535–6544. https://doi.org/10.1029/JC092iC06p06535

Garcia, H. E., & Gordon, L. I. (1992). Oxygen solubility in seawater: Better fitting equations. *Limnology and Oceanography*, *37*(6), 1307–1312. https://doi.org/10.4319/lo.1992.37.6.1307

Lenton, T. M., & Watson, A. J. (2000). Redfield revisited: 1. Regulation of nitrate, phosphate, and oxygen in the ocean. *Global Biogeochemical Cycles*, *14*(1), 225–248. https://doi.org/10.1029/1999GB900065

Strutton, P. G., & Chavez, F. P. (2000). Primary productivity in the equatorial Pacific during the 1997–1998 El Niño. *Journal of Geophysical Research: Oceans*, *105*(C11), 26089–26101. https://doi.org/10.1029/1999JC000056

Wanninkhof, R. (1992). Relationship between wind speed and gas exchange over the ocean. *Journal of Geophysical Research: Oceans*, *97*(C5), 7373–7382. https://doi.org/10.1029/92JC00188