Observed changes in oxygen and nutrient concentrations at 50 m to 500 m depth in the eastern North Pacific Subtropical Gyre

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Abstract

As the ocean increases in temperature due to climate change, it is expected to also experience shifts in its chemistry due to increased stratification and decreased solubility. Changes in the subsurface ocean, like decreases in oxygen as well as increases in nutrients like nitrate and phosphate, have been suggested as possible effects of this phenomenon, and could have significant impacts on biogeochemical cycles. For this study, the concentrations of oxygen, nitrate, and phosphate were measured between the depths of 50 m and 500 m depth in the eastern portion of the North Pacific Subtropical Gyre during late December of 2021. These present-day data were then compared to corresponding data from hydrographic cruises conducted in this region in 1985 and 2005, as well as long-term climatological averages. Between 1985 and 2021, oxygen concentrations were shown to decrease by 7.24 μmol/kg (+/- 16.52 μmol/kg), and nitrate and phosphate concentrations were shown to increase by 2.43 μmol/kg (+/- 3.45 μmol/kg) and 0.16 μmol/kg (+/- 0.22 μmol/kg), respectively. The nitrate and phosphate concentrations showed increases of 1.07 μmol/kg (+/- 2.32 μmol/kg) and 0.05 μmol/kg (+/- 0.15 μmol/kg), respectively, when measured against climatological averages. In general, these data were shown to be statistically significant and consistent with the long-term changes predicted by climate models, suggesting that the impact of ocean warming on oxygen and nutrient concentrations will only become more relevant as time passes and the effects of climate change intensify.

Plain Language Summary

It is important to try and understand how molecules like oxygen, nitrate, and phosphate exist in the ocean, as they are central to many of the environmental processes that are critical to the health of marine ecosystems. All kinds of marine life depend on these molecules to grow and develop, and therefore any observed changes in their oceanic concentrations should be recorded, analyzed, and discussed. This study hypothesizes that the decrease in oxygen concentrations and increase in nitrate and phosphate concentrations observed below the surface layer (50-500 m depth) of the North Pacific Ocean are directly related to climate change and ocean warming. It looks at changes in oxygen, nitrate, and phosphate in this region over time, comparing data collected in 2021 to data collected in 1985, 2005, and through the averaging of several decades of similar datasets. The hypothesis was generally proven to be correct by the data, which found a strong correlation between time and decreases in oxygen (-3.96% from 1985 to 2021) as well as increases in nitrate (19.61% from 1985 to 2021; 8.61% when compared to long-term averages) and phosphate (16.5%; 5.45% when compared to long-term averages). Through statistical testing, it was determined that while the uncertainty of specific values was high, the confidence that change had occurred was above 95% for the majority of the dataset. To improve understanding and precision relating to this issue, it is recommended that more data collection and analysis occur in the future.

Introduction

Nutrient availability is one of the most important factors governing the ecology of a given region of the ocean, as it directly correlates with the ability of phytoplankton to grow and produce biomass. Phytoplankton function as the base of the pelagic food web which encompasses all larger marine lifeforms, and elements such as oxygen (O_2), nitrogen (in the form of nitrates; NO_3^-) and phosphorous (in the form of phosphates; PO_4^{3-}) are critical to these organisms' survival. Therefore, fluctuations in these essential nutrients have large implications for the various biogeochemical cycles that dominate the ocean ecosystem and warrant further exploration and documentation in regions where they have been discovered.

Recent studies of the North Pacific Ocean have observed a growth and intensification of the oxygen deficient layer located between the depths of 50 m and 300 m (Stramma et al. 2020). This trend was found to be non-linear in nature, suggesting that it could be the result of several factors, including cycles like the Pacific Decadal Oscillation and North Pacific Gyre Oscillation, as well as the increased role of climate change in the form of ocean warming (Stramma et al. 2020). In recent decades, ocean temperatures have risen at rates equal to or greater than those from previous decades, with record high global mean temperatures being recorded in 2010 (Hansen et al. 2010). This change is occurring alongside fluctuations caused by short-term weather events like La Niña and the unprecedented, large negative temperature anomaly found in North America in 2009, which may appear to contradict this long-term trend of increasing temperatures, but ultimately are shown to be inaccurate models of climate behavior on a decadal scale (Hansen et al. 2010).

Increased ocean temperatures have been linked with decreases in subsurface oxygen through changes in solubility and stratification within the upper waters of the Northern Pacific Ocean (Talley et al. 2016). Solubility is negatively correlated with increased temperature; as water heats, it undergoes stress and therefore experiences a change in its physical equilibrium that is balanced by reducing the amount of dissolved oxygen (Levin 2018). Stratification is positively correlated with increased temperature; warmer surface waters will remain situated above cooler subsurface waters due to their reduced density, decreasing the downward exchange of oxygen facilitated by mixing (Levin 2018). Several other factors related to ocean warming have been suggested to be involved in the reduction of subsurface oxygen levels, but it has been concluded that the phenomenon is primarily due to the combination of these physical processes (Levin 2018). Between the two, the impact of increased stratification has been shown to be greater overall than the impact of decreased solubility, as in addition to slowing downward diffusion, increased stratification also reduces the upwelling of nutrients from waters below the photic zone, an environmental process known as the "biological pump" (Keeling and Garcia 2002). This variation in impact has been documented in the observation that the decrease in dissolved oxygen within the upper ocean is far too large to be solely associated with decreased solubility, suggesting that it must be the less dominant process (Keeling and Garcia 2002).

In response to these physical changes, a 2% global decrease in oceanic oxygen has occurred since 1960, with the biggest changes being visible in the North and equatorial Pacific (Schmidtko et al. 2017). Ocean climate models suggest that global oxygen levels may decrease an additional 1-7% from current values by 2100 (Schmidtko et al. 2017). In addition to these observed shifts in oxygen concentrations, changes in nutrient concentrations have also been reported, with significant enrichment of nitrate and phosphate recently being identified in the subsurface layer of the subarctic Pacific (Whitney et al. 2013). Ocean warming has been suggested as an explanation for these changes by the claim that a large vertical redistribution of nutrients has taken place in response to increased bacterial remineralization rates at shallower depths (Whitney et al. 2013). This correlation is made possible through a series of biogeochemical cycles (ocean warming results in lower oxygen concentrations; lower oxygen concentrations increase carbon dioxide saturation; carbon dioxide saturation is associated with increased acidity; increased acidity produces slower sinking rates of organic matter; slower sinking rates result in a longer duration of time where remineralization can occur) which further emphasize the diverse impact that ocean warming has on ocean ecosystems (Whitney et al. 2013).

Decreases in subsurface oxygen levels can lead to large regions of low oxygen concentration (referred to as oxygen minimum zones) which have been shown to have experienced horizontal and vertical expansion in the equatorial Pacific over the last 50 years (Stramma et al. 2008; Stramma et al. 2010). Despite most marine organisms not exhibiting evidence of being highly sensitive to small variations in oxygen concentration, hypoxic conditions (where the supply of oxygen falls below the demand from organisms for a given area) can create high stress environments which can lead to significant increases in mortality if sustained for long periods of time (Keeling et al. 2010). Hypoxic conditions have been shown to affect many species differently, with fish and crustaceans, two of the most economically relevant groups of marine life, being some of the most affected (Vaquer-Sunyer and Duarte 2008). It has been suggested that in response to these expanding oxygen minimum zones, intolerant organisms will experience habitat compression, eventually leading to a decrease in regional biodiversity (Stramma et al. 2010).

It is clear from the results of previous studies that climate change and ocean warming play a significant role in the subsurface concentrations of oxygen and nutrients. There have been attempts to model this relationship accurately and precisely, but there is not currently sufficient enough data to do so, and more development is required before models can be produced with confidence (Long et al. 2016). Therefore, this research seeks to explore this topic by testing the following hypothesis: ocean warming caused by climate change has decreased oxygen concentrations and increased nitrate and phosphate concentrations in the subsurface layer of the eastern North Pacific Subtropical Gyre over the past several decades. The null hypothesis predicts no change in oxygen, nitrate, and phosphate concentrations. In order to test this hypothesis, oxygen and nutrient samples will be collected from the eastern North Pacific

Subtropical Gyre and compared against data from previous hydrographic cruises for significant change.

Methods

Sampling occurred during transit from Oahu, Hawaii (21.4° N, 155.6° W) to San Diego, California (37.8° N, 117.2° W) for two weeks in late December of 2021 (TN398, US, *RV Thomas G. Thompson*, 2021-12-18/2021-12-30). Casts using a Sea-Bird Model SBE 9 CTD were conducted along the cruise track at intervals of 2° of longitude (Fig. 1). These casts alternated between approximately 1000 m and 500 m depth, until the vessel exited the North Pacific Subtropical Gyre (31.2° N, 128.5° W), after which casts were consistently deployed at 500 m. The exception to this pattern was Station 10, where a 4000 m cast was conducted in between a 500 m cast at Station 9 and a 1000 m cast at Station 11. There were 23 total stations (see

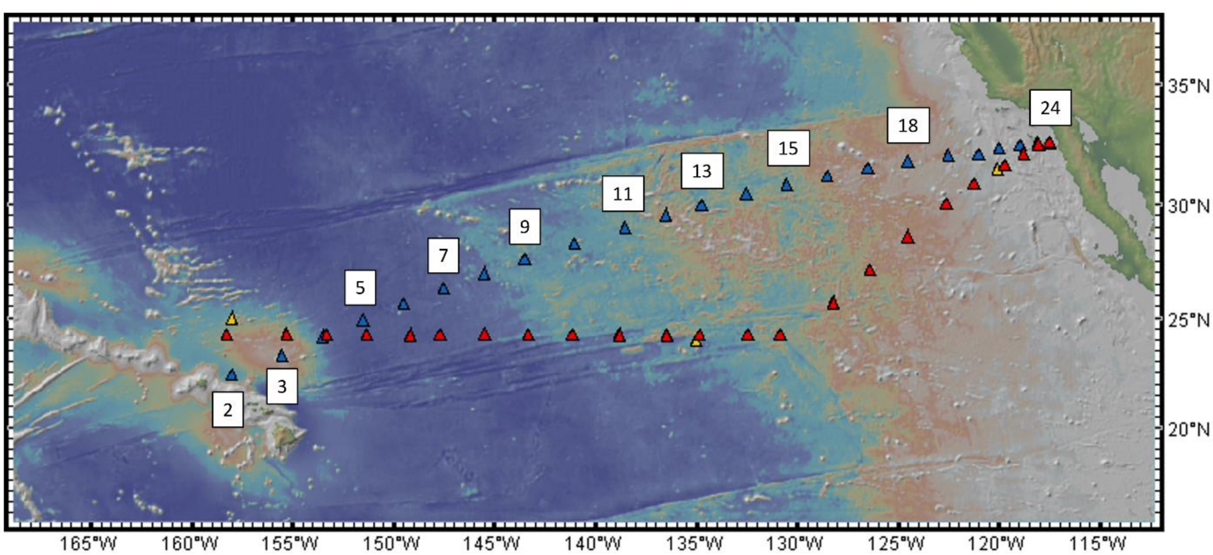

Figure 1. Map of the region of study. *A portion of the North Pacific subtropical gyre located in between Oahu, Hawaii and San Diego, California. Displays sampling stations for the 1985 RV Thomas G. Thompson, 2005 RV Mirai, and 2021 RV Thomas G. Thompson cruises, marked by red, yellow, and blue triangles, respectively. The station numbers of the first (2), last (24), and featured (3, 5, 7, 9, 11, 13, 15, 18, as represented in Fig. 2, 3, and 4) stations from the 2021 RV Thomas G. Thompson cruise are displayed either above or below their corresponding marker. Where stations are located closely enough together that their markers visually overlap, the marker for the oldest data overlays the markers for the newer data.*

Appendix 1) at which data collection occurred, where a rosette containing 24 10-L Niskin bottles was used to sample water from a selection of 10 to 17 depths located between 5 m and 4000 m. Dissolved oxygen concentrations were determined from these samples while aboard the *RV Thomas G. Thompson* by way of modified Winkler titrations (Carpenter, 1965) and making use of a Dosimat - Model 665 Titration Unit. These calculated dissolved oxygen concentrations were used to calibrate the Sea-Bird SBE 43 Dissolved Oxygen Sensor from which oxygen (O_2) concentration data were determined.

Samples of water intended for nutrient analysis were collected from a selection of 10-L Niskin bottles (ideally the ones corresponding to 5 m, 25 m, 50 m, 75 m, 100 m, 150 m, 200 m, 300 m, 400 m, and 500 m, as well as 750 m, 1000 m, 2000 m, 3000 m, and 4000 m when applicable), following each cast, and were placed into 75 ml plastic sample bottles. For water collected at depths of 50 m and above, a 0.45 micron filter was utilized in order to preserve the chemical state of the sample. These sample bottles were then labeled and numerically sequenced before being frozen to await analysis. They were analyzed in the School of Oceanography Marine Chemistry Laboratory at the University of Washington, which used a Seal Analytical AA3 to calculate nitrate and phosphate concentrations for each sample (Becker *et al*., 2020).

Analysis of the data primarily consisted of a comparison between the nutrient data collected on the 2021 *RV Thomas G. Thompson* cruise and that which was collected on two previous cruises from 1985 (31TTTPS24_1, US, *RV Thomas G. Thompson*, 1985-03-30/1985-04-30, https://cchdo.ucsd.edu/cruise/31TTTPS24_1, last accessed 2022-03-10) and 2005 (49NZ20051031, JP, *RV Mirai*, 2005-10-31/2005-11-24, https://cchdo.ucsd.edu/cruise/49NZ20051031, last accessed 2022-03-10), both of which ran along PO3E lines (Fig. 1). The data from these cruises were not analyzed in their entirety, as the locations and depths selected from them were chosen in the manner that would make for the most direct comparison possible between the older data and the data collected on the 2021 *RV Thomas G. Thompson* cruise. The stations in the older dataset that possessed longitudes closest to each given station in the present-day dataset were selected for use, and all others were discarded. The individual depths at each station were selected in a similar manner, with only measurements of up to 1000 m being extracted for analysis.

In addition to these cruises, long-term climatological average data from this region were gathered as a part of the World Ocean Atlas 2018 (https://www.ncei.noaa.gov/products/world-ocean-atlas, last accessed 2022-03-10) oxygen (Garcia et al. 2018*a*) and nutrient (Garcia et al. 2018*b*) datasets and were selected using the visualization tool available through the Simons CMAP data cataloguing project (https://simonscmap.com/visualization/charts, last accessed 2022-03-10). These datasets represent data averaged from six, decade long periods, those being 1955-1964, 1965-1974, 1975-1984, 1985-1994, 1995-2004, and 2005-2017, as well as a "climate normal" period from 1981-2010. Plots of average seawater nitrate and phosphate concentrations were generated using the region parameters of 22.4° N to 32.7° N and 158.5° W to 117.5° W, measured from January to December at 1000 m depth, from which corresponding data files were extracted. The method of selecting data comparable to that of the 2021 *RV Thomas G. Thompson* cruise from these files was identical to that which was employed for the selection of data from the 1985 *RV Thomas G. Thompson* and 2005 *RV Mirai* cruises.

The first method of data analysis examined the relationship between oxygen, nitrate, and phosphate concentrations and depth at a given station, compared across the three previously mentioned cruises. The climatological averages of nitrate and phosphate concentrations were also compared with their respective cruise data. In response to the results from this method, the region of study was refined for the second method of analysis (see Results below). This approach calculated the long-term changes in oxygen, nitrate, and phosphate concentrations between the 1985 *RV Thomas G. Thompson* cruise data, the long-term climatological data, and the present-day data.

<u>Results</u>

Visually assessing the series of depth profile plots produced through the first method of analysis (selections of these plots can be viewed in Fig. 2, Fig. 3, and Fig. 4) revealed clear evidence of several trends. Oxygen concentrations (Fig. 2) appeared to be generally lower in the subsurface layer in 2021 than they were in 1985. Conversely, the concentrations of nitrate (Fig. 3) and phosphate (Fig. 4) appeared to be generally higher in 2021 than those reported from 1985.

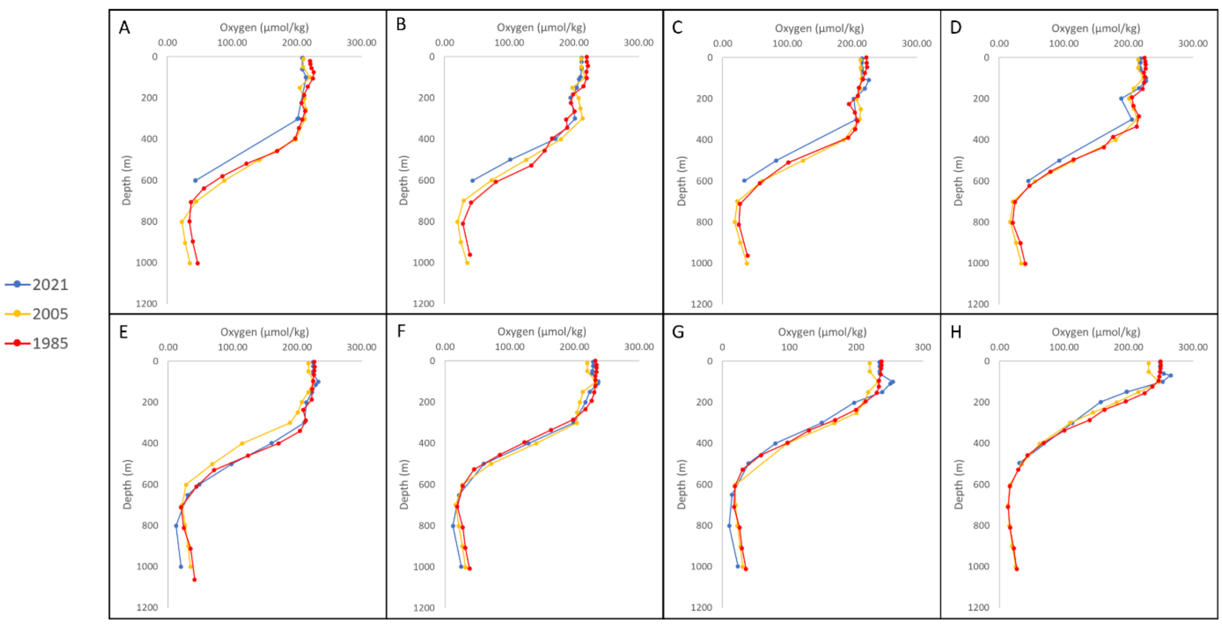

Figure 2. Decadal comparisons of oxygen profiles sampled across the eastern North Pacific Subtropical Gyre. *The x-axis denotes the concentration of oxygen (O_2) in in µmol/kg for a given depth in m along the y-axis. The three lines on each graph each correspond to a different year of data: blue represents the 2021* RV Thompson G. Thompson *cruise data, yellow represents the 2005* RV Mirai *cruise data, and red represents the 1985* RV Thompson G. Thompson *cruise data. Each panel corresponds to a different 2021* RV Thompson G. Thompson *cruise station and its longitude; the data from 2005 and 1985 represented in these panels are taken from stations similar in longitude to the* RV Thompson G. Thompson *cruise stations. (A) corresponds to 155.5 °W, (B) corresponds to 151.5 °W, (C) corresponds to 147.5 °W, (D) corresponds to 143.5 °W, (E) corresponds to 138.5 °W, (F) corresponds to 134.7 °W, (G) corresponds to 130.5 °W, (H) corresponds to 124.5 °W.*

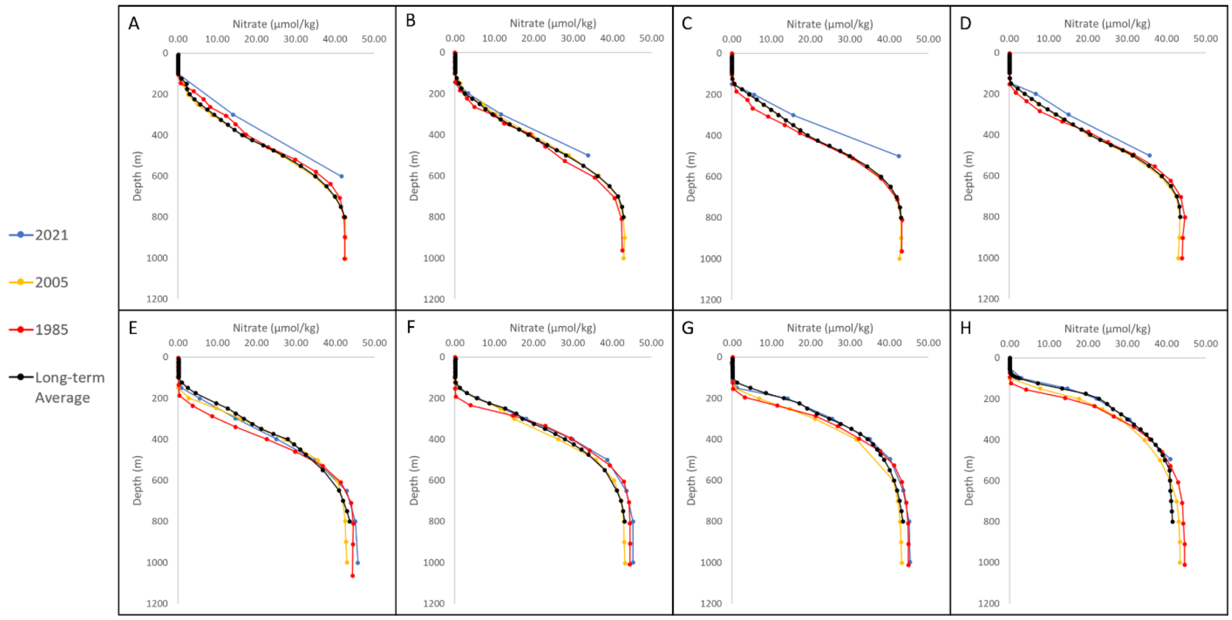

Figure 3. Decadal comparisons of nitrate profiles sampled across the eastern North Pacific Subtropical Gyre. *The x-axis denotes the concentration of nitrate (NO_3^-) in in µmol/kg for a given depth in m along the y-axis. The four lines on each graph each correspond to a different source of data: blue represents the 2021* RV Thompson G. Thompson *cruise data, yellow represents the 2005* RV Mirai *cruise data, red represents the 1985* RV Thompson G. Thompson *cruise data, and black represents the long-term climatological averages from the World Ocean Atlas 2018 dataset. Each panel corresponds to a different 2021* RV Thompson G. Thompson *cruise station and its longitude; the data from 2005 and 1985, as well as the long-term averages represented in these panels are taken from stations similar in longitude to the 2021* RV Thompson G. Thompson *cruise stations. (A) corresponds to 155.5 °W, (B) corresponds to 151.5 °W, (C) corresponds to 147.5 °W, (D) corresponds to 143.5 °W, (E) corresponds to 138.5 °W, (F) corresponds to 134.7 °W, (G) corresponds to 130.5 °W, (H) corresponds to 124.5 °W.*

The latter of these trends appeared to persist with the comparison of present-day nitrate and phosphate concentrations to long-term climatological averages, albeit possessing a slightly weaker correlation than the comparisons between 2021 *RV Thomas G. Thompson* cruise data and the 1985 *RV Thomas G. Thompson* cruise data.

This first set of results also revealed that the region of study likely needed to be reduced if the following analyses were to most effectively display how the collected data related to the central hypothesis. It became clear that the data from Station 17 contained evidence of malpractice which made them inaccurate and unusable. Additionally, Stations 20, 21, 22, 23, and 24 were all determined to be more representative of the environment of the western North

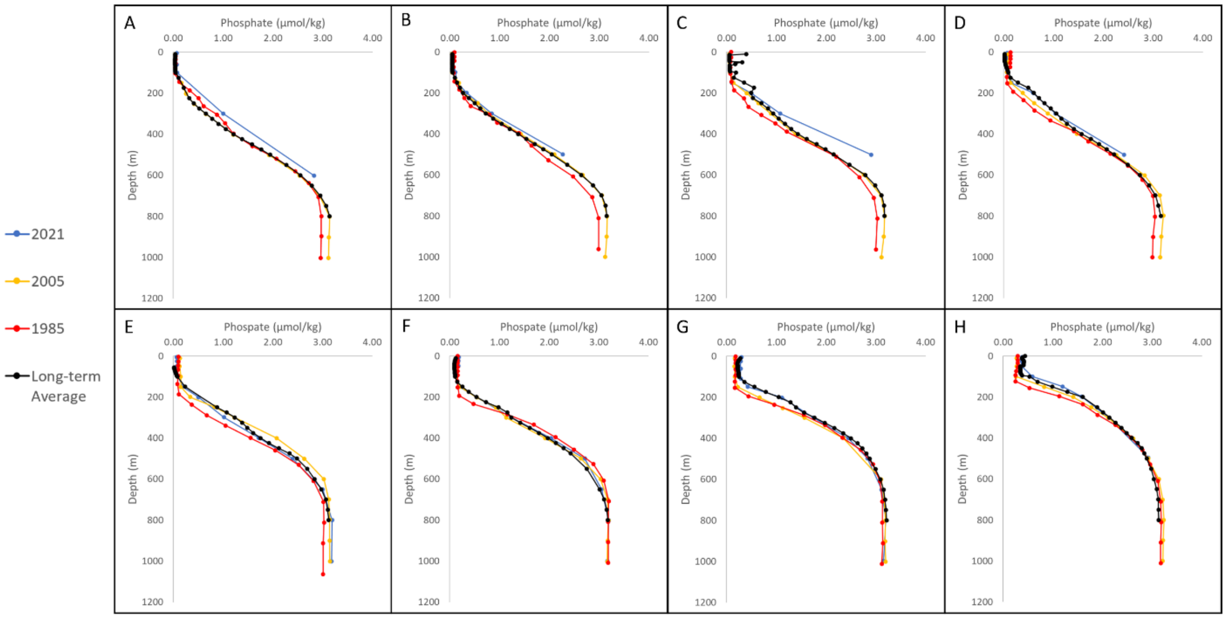

Figure 4. Decadal comparisons of phosphate profiles sampled across the eastern North Pacific Subtropical Gyre. *The x-axis denotes the concentration of nitrate (*PO_4^{3-}*) in in µmol/kg for a given depth in m along the y-axis. The four lines on each graph each correspond to a different source of data: blue represents the 2021* RV Thompson G. Thompson *cruise data, yellow represents the 2005* RV Mirai *cruise data, red represents the 1985* RV Thompson G. Thompson *cruise data, and black represents the long-term climatological averages from the World Ocean Atlas 2018 dataset. Each panel corresponds to a different 2021* RV Thompson G. Thompson *cruise station and its longitude; the data from 2005 and 1985, as well as the long-term averages represented in these panels are taken from stations similar in longitude to the 2021* RV Thompson G. Thompson *cruise stations. (A) corresponds to 155.5 °W, (B) corresponds to 151.5 °W, (C) corresponds to 147.5 °W, (D) corresponds to 143.5 °W, (E) corresponds to 138.5 °W, (F) corresponds to 134.7 °W, (G) corresponds to 130.5 °W, (H) corresponds to 124.5 °W.*

American coastal region than that of the eastern North Pacific Subtropical Gyre. The plots from these stations displayed minimal changes between datasets and were likely representative of an area dominated by upwelling and other biogeochemical cycles unrelated to the primary region of study. Thus, the data from these six stations were excluded from further analysis. The average mixed layer depth at this new selection of stations was reported to be 89.03 m, with a low of 59.58 m and a high of 103.32 m. In tandem with this fact, the available data below 500 m of depth at these stations were significantly less abundant than the available data above 500 m. Thus, in an effort to greater emphasize the distinct qualities of this region, the data range for this portion of the analysis was reduced to only contain values lying between 50 m and 500 m.

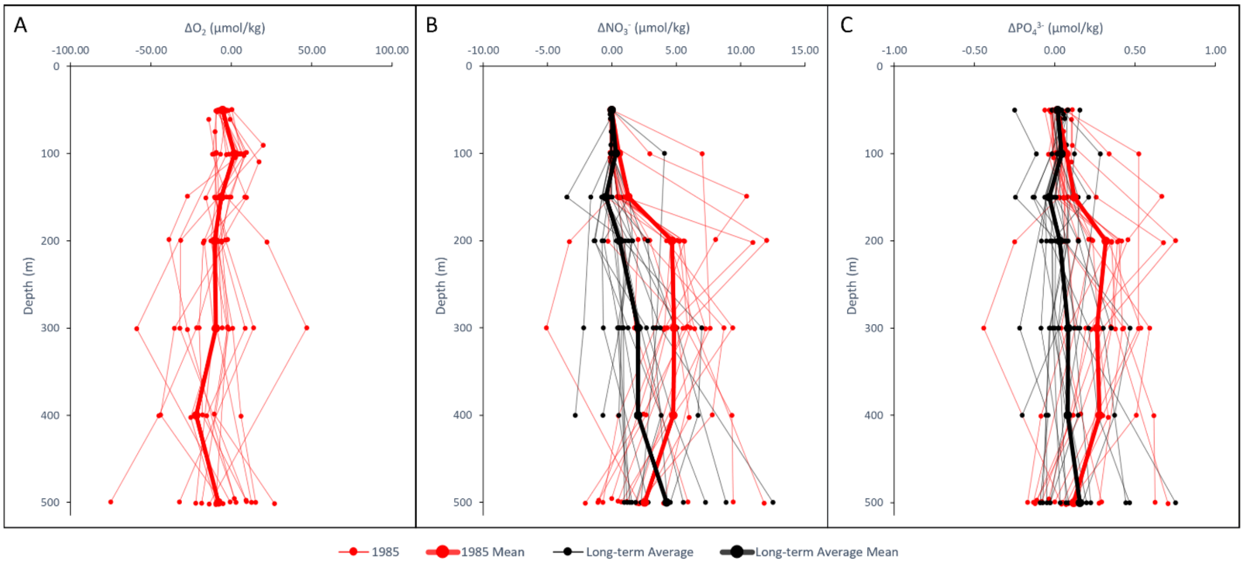

Figure 5. Decadal change in oxygen and nutrient concentrations across the eastern North Pacific Subtropical Gyre. *Changes measured between the 1985* RV Thompson G. Thompson *cruise data and the 2021* RV Thomas G. Thompson *data are shown in red. Changes measured between the World Ocean Atlas 2018 dataset and the 2021* RV Thomas G. Thompson *data are shown in black. Thin lines denote profiles of change at individual stations, thick lines represent average values of change from across the entire dataset. (A) displays the change in oxygen (O_2) concentration between data in µmol/kg on the x-axis with depth in meters on the y-axis. (B) displays the change in nitrate (NO_3^-) concentration between data in µmol/kg on the x-axis with depth in meters on the y-axis. (C) displays the change in phosphate (PO_4^{3-}) concentration between data in µmol/kg on the x-axis with depth in meters on the y-axis.*

As a result of these alterations, the corresponding data from the second method of analysis (Fig. 5) showed a strong general trend of decreasing oxygen concentrations and increasing nitrate and phosphate concentrations since 1985 in the subsurface layer. The change in nitrate and phosphate concentrations between climatological averages and present-day values was also positive, but to a lesser extent than the change observed from 1985 to 2021. The average change in oxygen concentrations from 1985 to 2021 was -7.24 µmol/kg (+/- 16.52 µmol/kg), a negative change of 3.96%. The average change in nitrate concentrations for the same period was 2.43 µmol/kg (+/- 3.45 µmol/kg), a positive change of 19.61%. The average change in phosphate concentrations for the same period was 0.16 µmol/kg (+/- 0.22 µmol/kg), a positive change of 16.5%. The average changes in nitrate and phosphate concentrations when comparing long-term climatological averages to present-day values were 1.07 μmol/kg (+/- 2.32 μmol/kg, 8.61% change) and 0.05 μmol/kg (+/- 0.15 μmol/kg, 5.45% change), respectively.

A one-tailed, t-test was conducted comparing the dataset against the null hypothesis of 0 μmol/kg change between past and present-day values for each of the average changes in concentration. The t-scores for the average changes in oxygen, nitrate, and phosphate between 1985 and 2021 were -1.806, 2.902, and 2.880, respectively. The t-scores for the average changes in nitrate and phosphate from long-term averages to present-day values were 1.891 and 1.426, respectively. Assuming an α of 0.05, the critical t-value for a sample size of 17 stations would be 1.746.

Discussion

Analysis of the data generally supports the hypothesis that climate change has caused decreases in oxygen as well as increases in both nitrate and phosphate within the subsurface eastern North Pacific Subtropical Gyre over the past several decades. As is consistent with previous, widely observed trends in North Pacific Ocean subsurface oxygen concentrations (Stramma et al. 2020; Talley et al. 2016; Leven 2018), oxygen has experienced significant decreases in average concentration in the region of study since 1985. Change in nutrient concentrations with time displayed an inverse relationship to change in oxygen concentrations with time, corroborating previous observations on the subject (Talley et al. 2016; Whitney et al. 2013) as well as suggesting that these processes possess a strong relationship with one another. The concentrations measured on the 2021 *RV Thomas G. Thompson* cruise were shown to be generally consistent with Redfield ratios, with the average ratio of nitrate to phosphate being approximately 13:1 and the average ratio of oxygen to phosphate being approximately 194:1, which implies that the values collected are likely consistently accurate.

The validity of this data was determined using a one-tailed t-test that compared the measured results to the null hypothesis. For an α of 0.05, the critical t-value for a sample size of 17 stations would be 1.746. Therefore, it can be assumed with 95% confidence that oxygen, nitrate, and phosphate experienced a change in concentration from 1985 to 2021, and that nitrate experienced an increase in concentration when compared to long-term climatological averages. Based on these results, it can be assumed that the null hypothesis is incorrect, and that significant change has occurred within this region in the last several decades. The t-scores for the change in nitrate and phosphate from 1985 to 2021 actually corresponded to a critical t-value with an α of 0.01, meaning that those results reflect a 99% confidence in a reported increase in concentration over time. These results imply that nutrient availability in the subsurface ocean has experienced a generally positive increase over time, possibly reducing the limiting role that nitrate and phosphate have been observed to play in the oligotrophic environment of the North Pacific Subtropical Gyre. However, the data representing the change in phosphate when compared to climatological averages did not possess an absolute t-score greater than the critical t-value, and thus could not be assumed to have experienced positive change with a confidence of 95% or higher. This is curious considering the consistency between nitrate and phosphate concentrations with Redfield ratios found in the data from the 2021 *RV Thomas G. Thompson* cruise. This could be due to the fact that the climatology values given by the World Ocean Atlas 2018 dataset are averaged based on numerous individual datasets which may possess slight inconsistencies between nitrate and phosphate records.

There are some discrepancies between the compared datasets that could result in more significant uncertainty, but they were accounted for during data selection in an attempt to minimize their impact. For one example, the 2021 *RV Thomas G. Thompson* and 2005 *RV Mirai* cruises were conducted in the winter, during December and November, respectively, while the 1985 *RV Thomas G. Thompson* cruise was conducted in the spring, during March. Therefore, it might be suggested that seasonal cycles play a significant role in the results of this study, but the eastern North Pacific Subtropical Gyre is a region where seasonal cycles have minimal impact when compared to the greater Pacific Ocean (Yasunaka et al. 2014). For another, the stations used to compare concentrations across decades were selected in reference to the longitudinal component of their location exclusively, leading to latitudinal differences of more than 8° at some locations. Therefore, it might be suggested that large-scale nutrient gradients play a significant role in the results of this study, but the sampling sites were all located at points where the contour lines of the large-scale nutrient gradients ran parallel to the meridians (Stramma et al. 2020).

The data reflecting the negative change in oxygen from 1985 to 2021 suggest that an oxygen minimum zone is present in the subsurface eastern North Pacific Subtropical Gyre, which would be an expansion of the previously observed oxygen minimum zones in the tropical Pacific (Stramma et al. 2008; Stramma et al. 2010). As a result of this possible expansion, there could be a shift observed in the ecological make-up of the subsurface ocean within this region, with an expected increase in protozoan and metazoan concentrations (groups that thrive in low oxygen environments due to specialized adaptations) and an expected decrease in macrofauna and megafauna (groups that struggle in low-oxygen environments due to their biological demands) (Levin 2003). However, this study did not include an analysis of average climatological oxygen values to compare against the data from 1985, and thus this result is inconclusive. In general, the greatest uncertainty within these results lies in the lack of data, as the comparisons between years only measure changes between specific points in time, and do not necessarily provide a complete picture of climate from the year that they correspond to. Therefore, future studies could seek to collect more data from each sampling station (Appendix 1) or sample at more locations within the region. Additionally, comparing the collected data to more cruises, such as the 2005 *RV Mirai* cruise and others, as well as utilizing climatological averages for oxygen, could result in a more complete and confident results section.

Conclusion

It is important to seek to understand the possible impacts of climate change on oxygen and nutrient availability within the interior of the ocean because these factors can ultimately impact highly significant aspects of the ocean's greater ecosystem, such as biological composition and diversity. Previous studies had suggested that areas of low oxygen in the subsurface ocean could be increasing in size and intensity with time in response to ocean warming, and that nutrient profiles would experience inverse changes as a result. This was shown to be highly accurate in comparisons between present-day day concentrations of oxygen, nitrate, and phosphate in the subsurface North Pacific Subtropical Gyre and concentrations taken from older data. The data comparing two specific points in time (1985 and 2021) showed a stronger trend than the data comparing the present-day to long-term climatological averages, which makes logical sense, as these climatological averages are calculated using data that both precede and succeed 1985. It was unexpected that the comparison of phosphate concentrations between long-term averages and the present-day was less statistically significant than a similar comparison of nitrate concentrations. This was determined to likely be related to the variability between different individual datasets used to develop the World Ocean Atlas 2018 climatological averages for different nutrients. Despite a significant degree of uncertainty regarding the specificity of the data, the results of this study indicate that oxygen minimum zones will continue to expand and intensify, becoming more of a dominant force in the subsurface ocean as time progresses and the impacts of climate change continue to increase in severity. Thus, it is recommended that more extensive data be collected in these regions in order to achieve more conclusive results surrounding these issues. That process could begin by analyzing this dataset in the context of alternative pre-existing datasets and could eventually include further sampling over a larger portion of the North Pacific Subtropical Gyre and beyond.

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372 # Appendices

Appendix 1. Table of sampling locations. This table contains complete latitudinal (positive values denote Northern coordinates) and longitudinal (negative values denote Western coordinates) data for the 23 stations associated with the 2021 *RV Thomas G. Thompson* research cruise in the North Pacific subtropical gyre. Alongside these stations, there are also 23 stations listed with their coordinates for each of the research cruises conducted within the same region in 2005 and 1985. These stations most closely correspond to the longitudes of the stations in the 2021 dataset. The blue columns are associated with the 2021 *RV Thomas G. Thompson* cruise stations, the yellow with the 2005 *RV Mirai* cruise stations, and the red with the 1985 *RV Thomas G. Thompson* cruise stations.

2021 Station	Latitude	Longitude	2005 Station	Latitude	Longitude	1985 Station	Latitude	Longitude
2	22.45034	-158.001	120	25.0053	-158.003	120	24.2617	-158.27
3	23.31982	-155.507	112	24.3017	-155.285	112	24.2833	-155.277
4	24.15	-153.5	106	24.2723	-153.308	106	24.255	-153.302
5	24.90875	-151.502	100	24.268	-151.32	100	24.2583	-151.315
6	25.65948	-149.5	94	24.2515	-149.158	94	24.24	-149.153
7	26.32928	-147.501	90	24.2763	-147.698	90	24.2583	-147.697
8	26.986	-145.498	84	24.3025	-145.476	84	24.285	-145.468
9	27.60836	-143.501	79	24.2653	-143.315	79	24.255	-143.318
10	28.3157	-141.018	74	24.2823	-141.149	74	24.2717	-141.142
11	29.00974	-138.5	69	24.249	-138.803	69	24.2433	-138.8
12	29.52022	-136.5	64	24.2457	-136.456	64	24.2333	-136.443
13	29.95275	-134.716	X17	23.9967	-135.011	60	24.255	-134.828
14	30.4471	-132.505	55	24.2452	-132.435	55	24.245	-132.432
15	30.83742	-130.504	51	24.2592	-130.847	51	24.26	-130.833
16	31.19966	-128.5	44	25.6872	-128.208	44	25.6817	-128.198
17	31.53008	-126.499	38	27.148	-126.382	38	27.1517	-126.378
18	31.83889	-124.498	33	28.5845	-124.522	33	28.5867	-124.507
19	32.09794	-122.5	28	30.0147	-122.589	28	30.0217	-122.585
20	32.11038	-120.999	24	30.8785	-121.235	24	30.8867	-121.237
21	32.36924	-119.989	20	31.4987	-120.046	18	31.6733	-119.715
22	32.5098	-118.938	10	32.1495	-118.761	10	32.1583	-118.753
23	32.60922	-118.07	6	32.5222	-118.027	6	32.5317	-118.028
24	32.64036	-117.521	3	32.6133	-117.505	3	32.6467	-117.498