Spatial variations of sea surface pCO_2 in the tropical Western Pacific near Guam

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Abstract

The ocean sequesters carbon through solubility and biological pumps. It serves a critical role in the sequestration of the atmosphere's carbon dioxide (CO_2). Understanding the extent of its sequestration role is an essential tool in tackling climate change policies and protecting the oceans. This study aims to understand the small-scale variabilities with increased levels of anthropogenic CO_2 on the ocean's role as a sink of CO_2. This was done by collecting underway temperature, salinity, sea surface partial pressure of CO_2 (pCO_2), atmospheric pCO_2 and conditions continuously on the 2024-2025 University of Washington Oceanography Senior Thesis Cruise between 4 °N-16 °N, 148 °E-149 °E. Small-scale spatial features of pCO_2 concentrations will be analyzed to find correlations with other parameters (temperature, salinity, bathymetry) to find the driving process of the variations in pCO_2. Highest pCO_2 concentrations were measured around the deepest sections of the Nam-2 Atoll and the furthest south. In contrast, the lowest pCO_2 concentrations were measured around the Namonuito Guyot and directly north of the 4 °N peaks, at 5.5 °N-6.2 °N. It was found that seamounts have a great influence on pCO_2 concentrations. Since pCO2 is relatively consistent in its vertical distribution, local mixing due to currents accelerating against the seamount structures stirs higher concentrations of pCO2 into the mixed layer. This makes these areas with seamounts sources of pCO_2. This will put the atmospheric pCO_2 concentrations into even higher saturation.

Plain Language Summary

Anthropogenic carbon dioxide (CO_2) emissions from fossil fuels have increased the amount of CO_2 in our oceans as the global ocean absorbs the gases to reach equilibrium with the atmosphere. The partial pressure of carbon dioxide (pCO_2) signifies the amount of CO_2 in the ocean. As the oceans absorb more CO_2 through the solubility with water and photosynthesis,

they become increasingly saturated leading to regions becoming sources of CO_2. Therefore, it is essential to collect data regionally to identify and help predict the current and future air-sea fluxes as well as the main drivers of pCO_2 variability. This study aims to increase understanding of the local variability in the sea surface of the western tropical Pacific from 4 °N-16 °N, 148 °E-149 °E. Data was collected from 29 December 2024-9 January 2025 on the R/V *Thomas G. Thompson* using a continuous underway system that collected atmospheric pCO2 data and surface seawater to measure sea surface pCO2 levels. A Thermosalinograph measured temperature and salinity The main causes of anomalies in pCO_2 concentrations were identified as biological processes, proximity to the equator, vertical local mixing, and changes in elevation of the seafloor from underwater mountains (seamounts).

1. Introduction

Carbon dioxide (CO_2) has increased from about 277 parts per million dry air (ppm) to 424.60 ppm in 270 years in the atmosphere due to human activities (Friedlingstein et al., 2022; Lan et al., 2023). The partial pressure of CO_2 (pCO_2) identifies the amount of carbon dioxide in our oceans. Measurements taken in various parts of the world's oceans help to evaluate the global and areal ocean net transport fluxes with the atmosphere, overall change in pCO_2, biological effects on the seawater chemistry, and physical oceanographic processes such as upwelling/downwelling, mixing, and current directions. The oceans are known to be a major sink for CO_2, sequestering about 25% of anthropogenic CO_2 (Jiang et al., 2023). Understanding this balance from a small-scale perspective is essential as different regions react in different ways in response to climate change. The direction of net sea-air CO_2 transfer is determined by the difference in atmospheric and sea surface CO_2, ΔpCO_2, where if the ΔpCO_2 is positive, CO_2 will be absorbed by the ocean, but if ΔpCO_2 is negative, then CO_2 will be released into the atmosphere by the ocean due to oversaturated waters. This was analyzed throughout the region of the cruise to find any area in which the ocean is a source of CO_2 and the outgassing of CO_2 into the atmosphere occurs.

Several previous studies including Guo et al. (2024), Yasunaka et al. (2019), and Feely et al. (2006) reported a negative correlation between sea surface pCO_2 and sea-surface temperatures (SST). Typically, pCO_2 concentrations are found to be driven by SST in subtropical gyres with weak vertical mixing and lower primary productivity (Guo et al. 2024). Primary productivity assimilates CO_2 from the water and converts it into organic matter, causing lower pCO_2 in areas of higher primary productivity. Colder SST aligned with higher pCO_2 levels since colder waters can hold more gases, while high SST, such as the western subtropical Pacific, had

negative values of pCO_2. Primary productivity around Guam is low, SST is high, and thus would be cause for lower pCO_2 concentrations that may be seen.

However, SST is increasing at a much more rapid rate than in the past. In the low-mid latitude North Hemisphere, CO_2 uptake decreases during marine heatwaves by an average of 0.17 mol C (m^2 yr^{-1}) with this region and surrounding central equatorial Pacific experiencing the greatest monthly CO_2 flux anomalies (Li 2024). Marine heatwaves are defined as periods of constant abnormally warm ocean temperatures. As temperatures continue rising, it is essential to have the data to contribute to global assessments. In the region of this study's data collection, there was ~1 °Celsius (C) magnitude of marine heatwave (MHW) with a MHW probability of 30-60% beginning in December 2024 (Jacox et al. 2022).

Yasunaka et al. (2019) found that surface seawater pCO_2 ranged from 370–400 µatm during February along 20 °N–5 °N at the 149 °E track when looking at the long-term mean from 1981-2015 (Fig. 1a). Like the Guo et al. (2024) study, pCO_2 was high when and where SST was

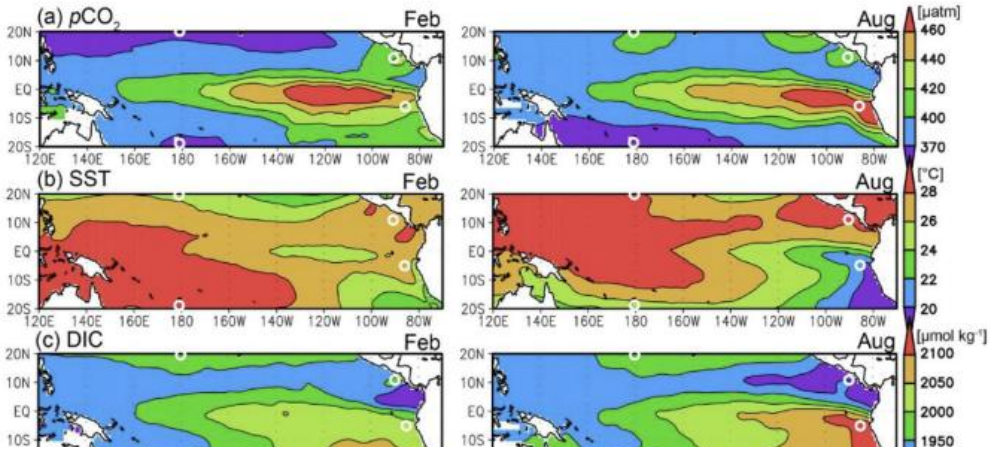

Figure 1. Long-term means from 1981-2015 with February on the left and August on the right (a-c). a) Seawater pCO_2 (µatm), b) SST (°C), c) DIC (µmol kg^{-1}). Area average of seawater pCO_2 was 1.8 ± 0.07 µmol yr^{-1} while atmospheric pCO_2 average for the area was 1.7 ± 0.01 µmol yr^{-1}. (Figure from Yasunaka et al., 2019).

low. Based on these means, this study concluded that pCO_2 seasonal variation is driven by the upwelling of colder, saltier subsurface carbon-rich water at the equator (Yasunaka et al. 2019).

Overall, pCO_2 concentrations will have increased since past data collections due to continued anthropogenic emissions but the ocean is believed to remain a sink for atmospheric CO_2. Spikes in pCO_2 concentrations are hypothesized to occur due to increased upwelling at lower latitudes approaching the equator, while a decrease in pCO_2 will be due to higher biological productivity near seamounts through the uptake of CO_2 through photosynthesis. If there are no spikes or decreases in data, then none of these processes are pushing concentrations in a positive or negative direction, and pCO_2 concentrations are in a steady state. This study aims to increase understanding of the main drivers of pCO_2 concentrations, so that, as global concentrations vary, more thorough predictions can be made with knowledge of how similar types of regions will be affected by increasing atmospheric CO_2.

2. Methods

All the data used in this study are the results of direct pCO_2 measurements using the Pacific Marine Environmental Laboratory Underway pCO_2 system during the cruise (Fig. 2). A pump on this underway system continuously took in seawater from about five meters from the bow of the ship and ran it through the SBE45 Thermosalinograph (TSG) TGT 0625 to measure temperature and salinity. This seawater was run through the equilibrator for pCO_2 concentration measurements. The pCO_2 system also has a non-dispersive infrared analyzer built by $LICOR^{®}$ that measures pCO_2 in dry air, including atmospheric pCO_2, air pumped from the bow, and gas in the equilibrator headspace. The analyzer measured four standards every two-and-a-half to three hours, five to ten atmospheric samples at one-minute intervals, then sets of 50-100 seawater

samples at one-to-two-minute intervals (Pierrot et al. 2009). The standards and atmospheric samples caused small gaps in all the data collected. The sea surface and atmospheric CO_2 (ppm)

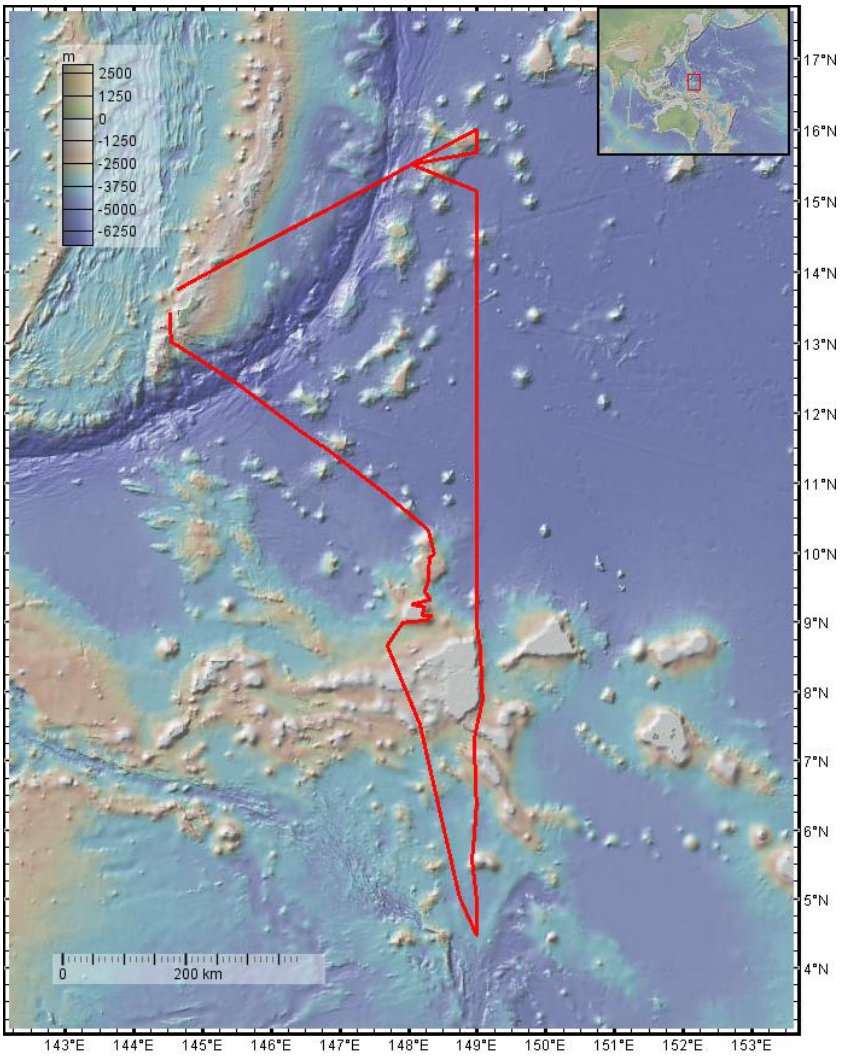

Figure 2. Map of cruise transect from December 29, 2024, to January 9, 2025. Made using GeoMapApp.

levels and oxygen were measured. The same control software contains GPS information from the navigation system, and data from the meteorological sensors of the ship.

Measurements from the entire cruise track were analyzed to identify the peaks and troughs in pCO_2 concentrations and identify a correlation among pCO_2 variations, temperature,

and salinity. Atmospheric pCO_2 was averaged across the cruise dates since CO_2 has a long lifetime and becomes well-mixed in the atmosphere (Hakkarainen et al. 2016). The average of 424.7 ppm was used for ΔpCO_2 calculations.

3. Results

Throughout the two weeks, the highest pCO_2 concentrations up to 424.5 ppm was measured on 1 January 2025, adjacent to Nam-2 Atoll, while the lowest pCO_2 concentrations of 391 ppm along with the highest temperatures of 30.5 °C was measured on 3 January 2025 near 5 °N along the 149 °E (Fig. 3). The pCO_2 concentration, temperature and salinity all increased on 3 January 2025, after this low in pCO_2 (Fig. 3). From 3 January 2025 through 5 January 2025, the greatest range of pCO_2 concentrations were measured at 391-418 ppm. 6 January 2025 through 9 January 2025 had the smallest variability with a range of 413-403 ppm. Other low pCO_2 concentrations were measured around 5.8 °N-6.1 °N of 392 and another at 9.8 °N of 392 ppm.

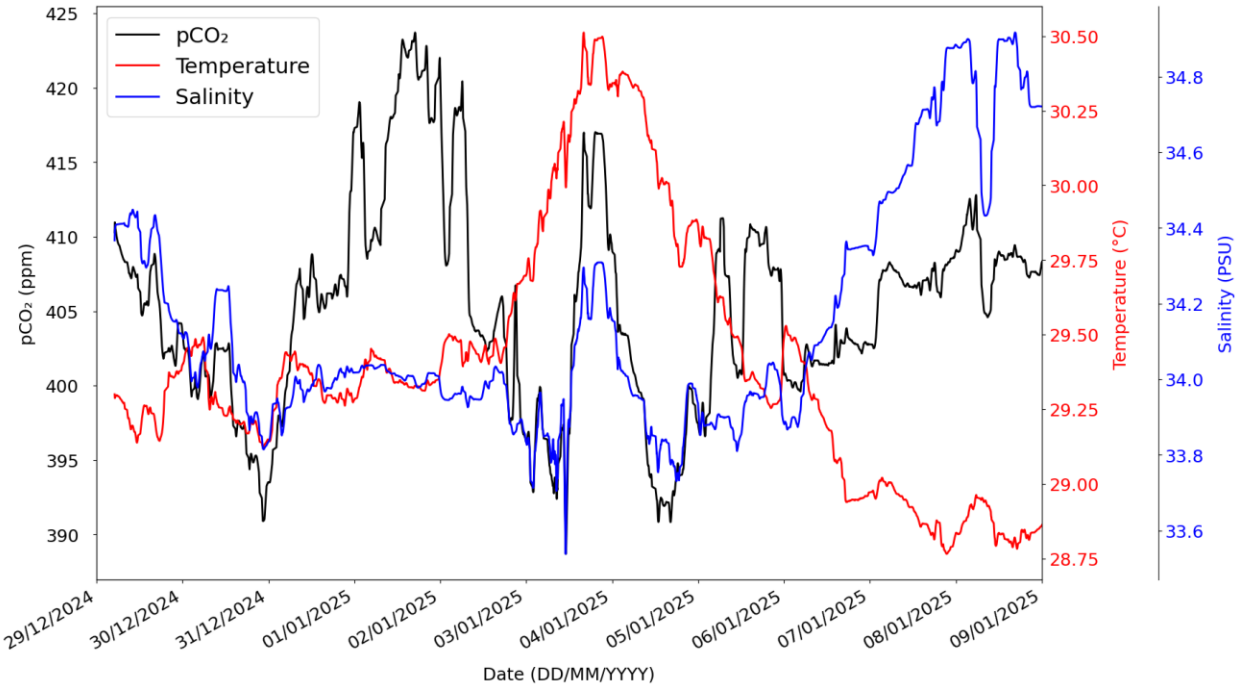

Figure 3. Values of pCO_2 in ppm, temperature in °C, and salinity in PSU throughout the cruise dates (DD/MM/YYYY).

Overall, temperature had little correlation to pCO_2. The temperature only varied by 1.75 °C throughout the whole cruise. On 4 January 2025, there was a pCO_2 concentration of 416 ppm but a temperature of about 30.5 °C. Salinity followed a similar pattern of peaks and troughs as the pCO_2 concentrations, ranging from 33.25-35 PSU. However, on 1 January 2025, salinity stayed steadily around 33.9 PSU despite the largest pCO_2 increase at the Nam-2 Atoll (Fig. 3). High pCO_2 concentrations up to ~418 ppm was measured on 3 January 2025 and 5 January 2025 which were when the ship was the closest to the equator, southwards to 4 °N. Temperature was highest with the 3 January 2025 pCO_2 peak then it decreased slightly after this day (Fig. 3). There is a peak in pCO_2 concentrations at 4 °N before it drops down steeply to 393 ppm. With these latitudinal changes, temperatures show an increase southwards while there is a decrease in salinity with only a small peak at 4 °N (Fig. 4).

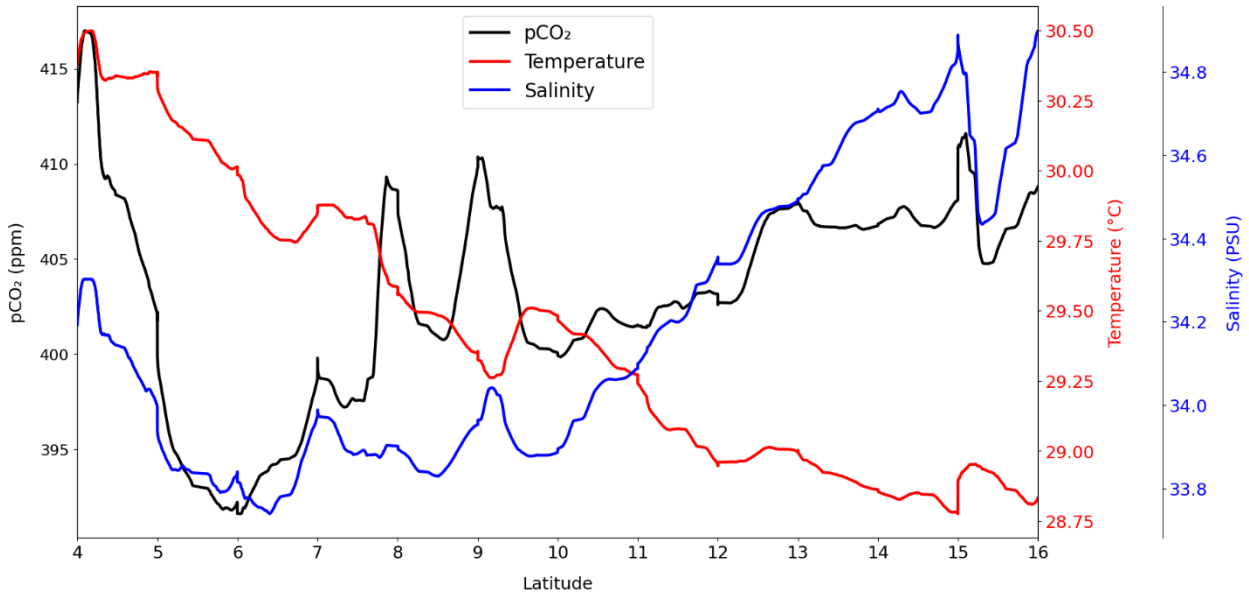

Figure 4. Concentrations of pCO_2 across latitude for the entire cruise track.

Latitudinally, pCO_2 decreases after concentrations of ~418 ppm at 4.1 °N but then increases starting at 5 °N. A slight increase up to ~408 ppm was measured at 8°N before decreasing sharply until a large peak at the Nam-2 Atoll location at 9°N (Fig. 5). Northwards

from 9.8 °N, pCO_2 concentrations increase up to 10 ppm. More decreases in concentration to 392 ppm were measured between 5.8 °N-6.1 °N (Fig. 3).

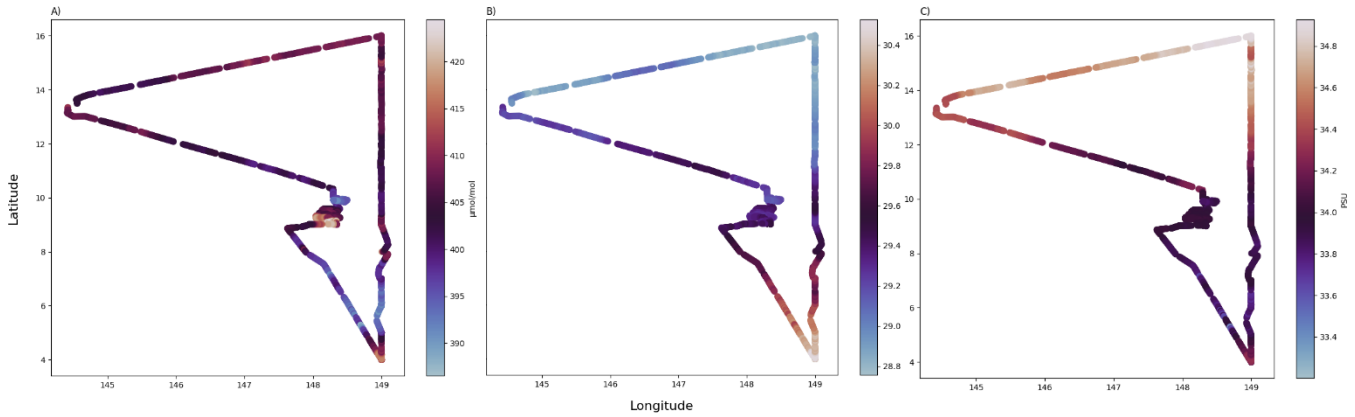

Figure 5. Measurements of a) pCO_2 in ppm, b) temperature in °C, and c) salinity in PSU throughout the cruise across longitude vs. latitude.

Based on an average atmospheric pCO_2 concentration of 424.68 ppm, this region remains undersaturated in pCO_2 concentrations up to -38 ppm (Fig. 6). The atoll area does go up to over 424 ppm and can be a source of outgassing throughout a longer-time frame.

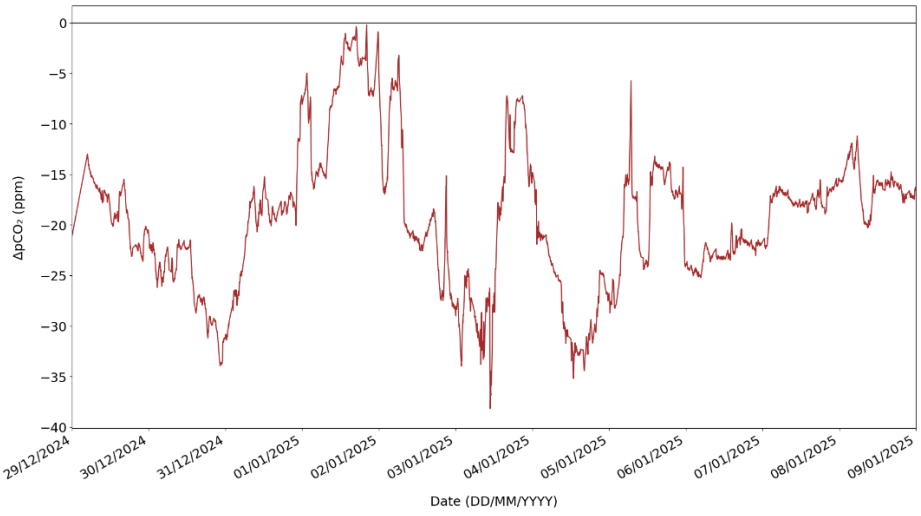

Figure 6. Measurements of ΔpCO_2 for the duration of the cruise. Difference in sea surface pCO_2 and averaged (across the cruise dates) atmospheric pCO_2 to get ΔpCO_2. Line at 0 indicates where the ocean would become a source of pCO_2.

Around Namonuito Guyot, pCO_2 concentrations range from 392-402 ppm. There is a steep drop in concentrations starting at 1300 on 30/12/2024 when the R/V *Thompson* nears the guyot (Fig. 7).

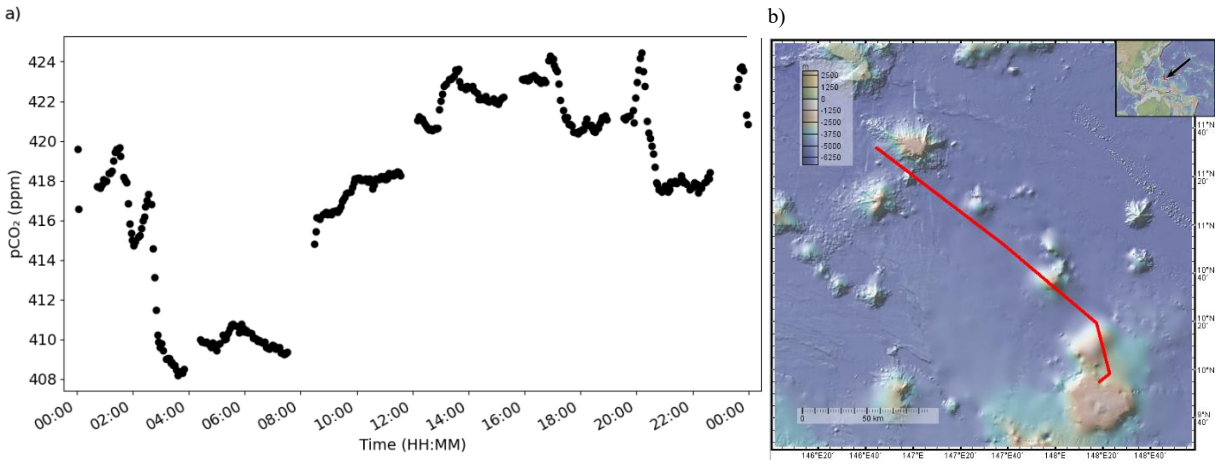

Figure 7. a) Concentrations of pCO_2 throughout 30 December 2024 from 11.5 °N, 147 °E to 9.91 °N, 148 °E approaching Namonuito Guyot (depth of 1500 m). Gaps in data are from the underway pCO_2 system taking standards and atmospheric samples. b) Map of 30/12/2024 transect. Made using GeoMapApp.

For the atoll location, pCO_2 concentrations range from 410-424 ppm with a steep increase measured at 0830 and concentrations remain around 424 ppm for the rest of this day (Fig. 8).

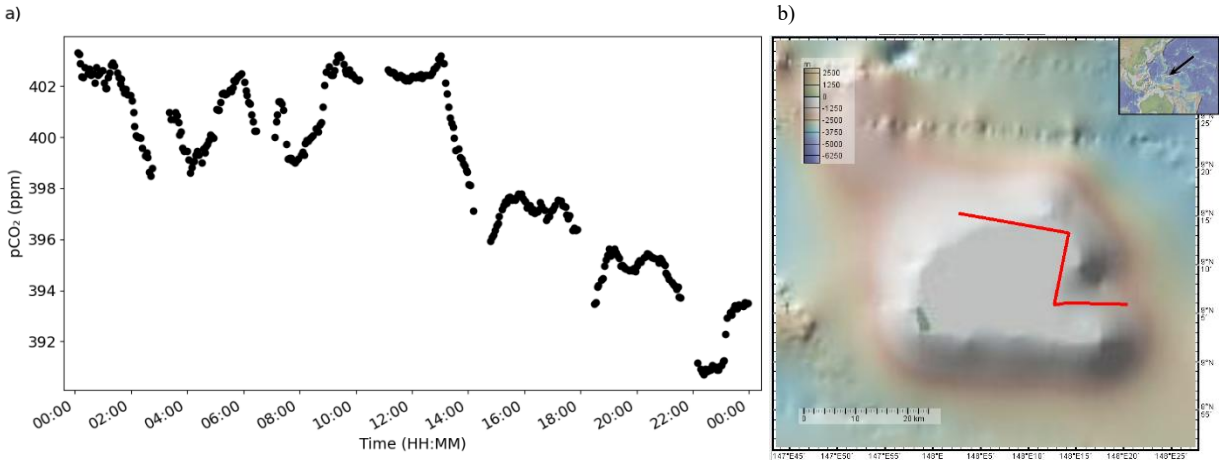

Figure 8. a) Concentrations of pCO_2 throughout 1 January 2025 from 9.26 °N, 148 °E to 9.10°N, 148 °E, at Nam-2 Atoll. Gaps in data are from the underway pCO_2 system taking standards and atmospheric samples. Bb) Map of the cruise track on 1 January 2025 over Nam-2 Atoll. Made using GeoMapApp.

4. Discussion

4.1. Temperature and salinity correlations with pCO_2 vary

The surface seawater pCO_2 ranged from 390-420 ppm, only about 10-20 ppm difference in concentration levels compared to Yasunaka et al. (2019) findings. This cruise only went to 4 °N but there is a signal of increased pCO_2 concentrations from equatorial upwelling. Temperature was lower while salinity was measured to be higher at 4 °N (Fig. 3).

The weak correlation between pCO_2 and temperature is due to the region being an area where temperatures hardly fluctuate. The monthly average of Apra Harbor, Guam, the ship's port, spans from 26.4 °C-29.7 °C (NCEI 1994-2022). For this study's cruise, the temperature ranged from 28.8 °C-30.4 °C. This is an increase from 1981-2015 long-term means that gave SST of about 25 °C-28 °C, though the increase is only from two weeks, even with 1 °C of SST anomaly in the region. Based on these ranges, it is expected that pCO_2 would be low (Yasunaka et al. 2019). It is difficult to conclude this due to the limitations of data collection.

4.2. Concentrations of pCO_2 increase with increasing latitude along 149 °E

At 4 °N, 149 °E, pCO_2 concentrations hit a maximum in concentration. This peak was caused by these waters originating from the equatorial upwelling of deeper carbon-rich waters mixed into the surface water (Yasunaka et al. 2019). Upwelling was indicated by slightly higher salinity measured at 34.3 PSU with the temperature measured at 30.5 °C and an increase in NO_3 and PO_4 (Fig.4; Claire Sheppard, Personal Communication).

After this peak in pCO_2 concentrations, temperatures began decreasing down to 28.8 °C for the rest of the northward transect along 149 °E. Salinity was increasing with this decrease and was measured up to 34.9 PSU (Fig. 4). There were two small increases in salinity aligned with the maxima in pCO_2 concentrations at about 8 °N and 9 °N due to the depth becoming shallow at these areas. There was a steep decline in salinity and pCO_2 concentrations and a 0.75 °C increase at 15 °N where the lowest biological productivity was found (Parthasarathy, Personal Communication).

The general trend along 149 °E showed pCO_2 increasing along increasing latitudes. This is the opposite of what was expected, where Yasunaka et al. (2019) found the long-term mean of pCO_2 increasing at the equator to about 5 °N, though if measurements continued closer to the equator, they could have shown the increase continuing from the 4 °N peak due to the equatorial upwelling of CO_2.

4.3. Study region is a sink

All the ΔpCO_2 calculations resulted in negative values. Therefore, this study region was determined to be a sink for CO_2. The pCO_2 over the atoll reaches 424.5 ppm and the atmospheric pCO_2 was at an average of 424.7 ppm for the time of the cruise (Fig. 6). Though a small difference, this is where it becomes crucial to conduct long-term regional-scale studies to identify sources. The atmosphere and ocean will continue to reach equilibrium as pCO_2 concentrations change.

4.4. Increase at Nam-2 Atoll vs. decrease at Namonuito Guyot in pCO_2 Concentrations

Seamounts with shallower depths, specifically tested at the Caroline Seamount in the tropical western Pacific, bring on a higher abundance of virioplankton, a marine virus that accounts for a high proportion of bacterial mortality which leads to decay that releases carbon.

The combination of a shallow seamount and local currents can support the bacteria's production and abundance (Zhao et al. 2020). The highest pCO_2 concentrations of 424 ppm were also at the deepest section of the Nam-2 Atoll (9.25 °N with a depth of 1000 m) and the steep decrease to 393 ppm on 1 January 2025 was seen at the shallowest section where the depth was around 100 m at 9.8 °N (Fig. 3). Nam-2 Atoll was found to have the highest biological productivity but the decrease in pCO_2 concentrations disproves the hypothesis (Sheppard & Parthasarathy, Personal Communication).

However, with the guyot which has a depth of 1500 m, pCO_2 concentrations steadily decreasing throughout the day closer to the guyot (Fig. 7). This would be due to the weaker vertical mixing in this subtropical region causing the vertical mixing to not reach the surface as it did at the atoll location (Guo et al. 2024). Since Nam-2 Atoll is closer to the surface, higher pCO_2 concentrations come from the mixing while the shallowest section is photosynthesizing and therefore decreasing the concentrations. Namonuito Guyot is deeper and so the local, vertical mixing is not reaching the surface where the pCO_2 measurements were being taken. Additionally, there were no increases in both salinity and temperature, indicating no upwelling of colder, saltier subsurface waters at either location.

5. Conclusion

The key is the shift from sink to source. Seamounts' influences on pCO_2 are localized and small but cause variations from seamount to seamount. The depth of the seamount can be part of whether the area is a source or a sink, and their biological inhabitants are essential to the biogeochemical cycle. Their health is dependent on the ocean's health and vice versa. As marine heatwaves increase in intensity and frequency, subtropical regions such as the one tested in this

study need to be measured to ensure conditions do not go beyond irreparable, destroying the habitats and their inhabitants.

Spatially, concentrations of pCO_2 can vary enough to make one area a sink and another area a source of CO_2. The local variability leads to difficulty in predictions of CO_2 uptake and further widens the gaps in understanding the biogeochemical cycle. As politics divide around the world about climate change, it becomes even more crucial to accurately inform to place solutions and preventative measurements. This data collection improves the ability to build upon current understanding and further modeling for future predictions.

The short duration of the cruise limited data collection and therefore, the analysis of the effects of SST on pCO_2 concentrations. Further long-term study of regional analyses where specific factors, such as bathymetry, wind speeds, and oxygen, are needed to connect the regional spatial-temporal variations because specific regions will react differently based on these factors. Regional-scale analysis, specifically increased sampling of varying seamounts features and the variability of pCO_2 concentrations across them must be emphasized for regional sea-air flux measurements and understanding, especially as anthropogenic CO_2 emissions and temperatures continue rising.

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