The Inorganic Carbon System and Nutrient Cycling in the Equatorial North Pacific:

A study of the interactions between oceanographic features and seawater chemistry

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Stanford@SEA 2007
S211
June 12, 2007

Abstract

The world's oceans are an extremely important component of the global carbon cycle. As anthropogenic greenhouse gas emissions become a growing concern, increasing our understanding of the oceanic carbon system will be a key factor in projecting the affects of global climate change and the ability of the oceans to regulate increases in atmospheric CO_2. Extensive progress in this area has been made over the past 20 years, but significant gaps still exist. This study examines the carbon system and nutrient cycling processes occurring the north equatorial Pacific along a transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati. Total dissolved inorganic carbon (DIC) and in situ pCO_2 were calculated from the total alkalinity and pH measured at several depths down to 350 meters at eight stations along the transect. It was found that both pCO_2 and DIC were regulated by biological and oceanographic factors and that water mass characteristics played an important role in determining parameters of the carbon system. In addition, nutrient data was used to determine which areas along the transect show ratios similar to those projected by the Redfield Ratio. It was found that although slight variations occurred along the transect, the area as a whole demonstrated nutrient ratios which adhered very closely to the Redfield Ratio. While this study provides a baseline for the carbon system parameters in the equatorial north Pacific, further research will be needed to fully define the system and mechanisms taking place in the region.

Introduction

The world's oceans play an enormous role in the regulation of atmospheric carbon dioxide, the most significant anthropogenic greenhouse gas. The ocean is the largest of the global carbon cycle reservoirs with a relatively rapid rate of exchange, and therefore an understanding of the oceanic carbon cycle is critical to efforts to quantify the affects of increased atmospheric CO_2 concentrations over the next century and beyond. Over the past twenty years, our understanding of and ability to model the carbon cycle has made considerable advances. In that time, the Geochemical Ocean Section Study (GEOSECS) presented a much more complete picture of the inorganic carbon distribution in the oceans. The Global Ocean CO_2 Survey, a joint effort between the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) has generated a very large data set for which analysis and interpretation has just begun. Numerous global carbon cycle models have been developed and applied to a wide range of questions, but sizeable gaps still exist in our understanding of several key issues, one of which is the combination of mechanisms behind the regulation of atmospheric CO_2 over long time scales (Sarmiento et. al., 2006). Many more studies are needed to begin accurate predictions of how the oceanic carbon cycle will change as a result of anthropogenic CO_2 emissions, an effort which will be important in considering and planning for the affects of climate change.

Because the total data set on the oceanic carbon cycle is still relatively sparse, additional studies are useful simply to increase the area which has been studied. Furthermore, the establishment of a baseline with respect to CO_2 system parameters in seawater across the world's oceans will be important to tracking changes over time. One of the main purposes of this study is to contribute to the creation of a record of the carbon system parameters in the equatorial north Pacific.

In addition, It has been found that local physical processes, in addition to wind and global scale processes, may be an important factor in controlling the rate of CO_2 transfer between the ocean and atmosphere. Research suggests that regional parameterizations may be necessary to better understand global air-sea fluxes (McGillis, 2004). This study contributes to this effort to understand regional processes as well as to the general ongoing effort to better-define the carbon system processes occurring across the world's oceans.

It is important to establish the basic chemistry upon which this study is based. When gaseous CO_2 from the atmosphere dissolves in seawater, it is quickly hydrated to form aqueous CO_2, which soon reacts with water to form carbonic acid (H_2CO_3). Carbonic acid can then undergo two dissociation reactions to form bicarbonate (HCO_3-) and then carbonate (CO_3^{2-}). All of these reactions occur very rapidly, and thus for practical purposes it can be assumed that they are in thermodynamic equilibrium (Sarmiento, 2004). The equilibrium constant of the above reactions regulate the relative abundances of dissolved CO_2, HCO_3- and CO_3^{2-} (Sarmiento et. al., 2006).

The seawater CO_2 system is defined by four measurable parameters: total alkalinity (TA), total dissolved inorganic carbon (DIC), pH, and the partial pressure of carbon dioxide (pCO_2) in air which is in equilibrium with the sample. The pCO_2 is proportional to the dissolved CO_2 and is defined to be a measurement in wet (100% water saturated) air. Total alkalinity (TA) is defined as the measure of the excess of bases over acids, and operationally as the titration with H^+ of all weak bases in a solution (Sarmiento, 2004). TA is defined by the following equation:

$$[Alk] = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] + [B(OH)_4^-] + \text{minor bases}$$

Total dissolved inorganic carbon (DIC) is defined as:

$$[DIC] = [CO_2^*] + [HCO_3^-] + [CO_3^{2-}]$$

(where $CO_2^* = CO_2\ (aq) + H_2CO_3$)

The entire CO_2 system in seawater can be defined by any two of these parameters when combined with temperature, salinity, pressure, the relevant equilibrium constants, and abundances of other constituents in the seawater (Pelletier, 1998). In this study, I will measure pH total alkalinity to calculate the other two components of the carbon system in seawater: DIC and pCO_2.

The concept of the “biological pump”—the downward flux of organic carbon fixed by autotrophic activity—is extremely important to the cycling of carbon within the ocean. While surface water CO_2 concentrations tend to remain in equilibrium with the atmosphere, deeper water masses become oversaturated with dissolved carbon CO_2 because of the constant gravitational settling and decay of organic material (Longhurst, 1991).

An important biological factor in the distribution and cycling of nutrients in the oceans is described by the Redfield Ratio. During photosynthesis, inorganic carbon, nitrogen and phosphorus are taken up in the fixed ratio of 106 DIC : 16 N : 1 P. This process is summarized by the following equation:

$$106\ CO_2 + 16\ NO_3^- + HPO_4^{2-} + 18\ H^+ + 122\ H_2O \rightarrow (CH_2O)106(NH_3)16H_3PO_4 + 138\ O_2$$

Because of this basic chemistry, these components accumulate in all organic matter in this fixed ratio. As organic matter sinks through the water column, decomposes and is redistributed, it imprints this ratio of nutrients. By measuring the ratios of DIC and nutrients in seawater, it is possible to describe patterns related to the distribution of organic matter derived nutrients (Brown, 1989A).

The purpose of this project is to gain a better understanding of the carbon system and nutrient cycle processes occurring in the north equatorial Pacific. The primary research questions of this study include: 1) How do carbon system parameters change along the transect from Kealakekua Bay, Hawaii at approximately 17 degrees north latitude to Christmas Island at approximately 3° latitude? 2) How are these shifts correlated to chemical and physical oceanographic features such as temperature, salinity, primary productivity, nutrient or oxygen concentrations, and currents? 3) Is it possible to determine which factors—physical or biological—are dominant in determining the partial pressure of CO_2 in surface waters? 4) How closely do the Redfield Ratio components adhere to the predicted ratio in different regions of the North Equatorial Pacific, how can the observed variations be explained, and what significance does this information have with respect to the biological pump?

In determining the concentrations of components of the carbon system, it is expected to find that they strongly correlate to variations in primary productivity. It is predicted that both DIC concentration and pCO_2 in surface waters will decrease with primary productivity and be significantly higher in oligotrophic areas. This hypothesis is based on the fact that photosynthetic activity takes up CO_2, thereby lowering the partial pressure. A lowering of pCO_2 will shift the concentrations of DIC components based on the equilibrium constant, which will result in a net uptake of DIC as well. Thus pCO2 will be lowest in highly productive regions and highest in oligotrophic waters. Furthermore, both of these parameters are expected to increase with depth. This is because below the euphotic zone, respiration and breakdown of organic matter occurs without the reverse effects of photosynthesis, leading to a decrease in O_2 and while pCO_2 and DIC concentrations increase. Also, the solubility of CO_2 increases with higher pressures and lower temperatures. Additionally, it is expected to see a positive correlation between DIC and PO_4 as well as between NO_3 and PO_4 concentrations, each of which should increase with depth due to the accumulation and break down of organic matter, which results in higher DIC and nutrient concentrations. These components are expected to adhere Redfield Ratios to varying degrees along the transect. For instance, it is hypothesized that the parameters will exhibit ratios closer to Redfield in productive areas, including 17° north latitude in the cyclonic eddy and between 10° and 5° north latitude in the highly productive North Pacific Equatorial Waters. In oligotrophic, the ratios are expected to be skewed away from the ideal Redfield Ratios due to the fact that oligotrophic waters are often nutrient limited. The nutrient which is limiting should be found in lower concentrations relative to others than predicted by Redfield.

Sample Locations and Parameters Measured

Water samples were collected at 8 locations along a transect from Hawaii to Christmas Island, ranging from approximately 20° to 3° north latitude and 162° to 157° west longitude. The first sample were taken offshore from Kealakekua Bay at 16° 54.9′ north and the last 3° 3.0′ north (Figure 1). Samples were collected at several oceanographic features or boundaries along the transect, including a cyclonic eddy, the North Equatorial Current, the Eastern Pacific Equatorial Front and the North Equatorial Counter Current. Hydrocasts equipped with Niskin Bottles, a CTD, a Dissolved Oxygen Meter and a fluorometer were deployed at each location, and water samples were collected from the surface and at depths of 90, 150, 210, 270 and 350 meters. Sample water was used to determine pH, Total Alkalinity, Nitrate, Phosphate and

Chlorophyll A concentrations. Currents were continually measured along the transect using an Acoustic Doppler Current Profiler (ADCP).

Water Sampling Procedure

Collection of the samples occurred as soon as possible after opening the Niskin bottle in order to minimize exchange of CO_2 at the head space of the bottle. Before collecting the sample, the appropriate storage bottle was rinsed three times using the new sample water to eliminate traces of the previous sample. The bottle was then filled from the bottom using a plastic drawing tube. The water was allowed to over flow slightly, and then the lid was closed, minimizing the air in the sample bottle. The samples were stored in a sea water bath taken directly from the surface so as to keep them at a relatively constant temperature. Titrations of the samples occurred promptly to limit any changes that may have occurred in the sample during storage due to biological activity or gas exchange with excess air in the sample bottle. All of these procedures were consistent with those which are outlined in the Standard Operating Procedures *Water sampling for the parameters of the oceanic carbon dioxide system* (SOP1, 1996).

pH Measurements and Determination of Total Alkalinity

Before running each set of samples, a World Ocean Circulation Experiment (WOCE) standard bottle of Dickson 75 was run. Over the course of the data collection period, these standards ran consistently, and were later used to calculate a calibrated total alkalinity.

A solution of 0.5 Normal hydrochloric acid was be used to titrate each sample. Before the titration began, a few critical steps were taken to ensure the quality of the data collected: 1. The titration cell and magnetic stirrer were rinsed with deionized water three times. 2. The inside of the titration cell and stirrer were dried completely with a clean paper towel 3. Before measuring the sample, the pipette was rinsed with water from the next sample so as to remove any traces of the previous sample. 4. The pH meter bulb was rinsed with deionized water and patted dry so as to minimize contamination from the previous sample.

After these steps were carried out, 100 ml of the sample to be titrated was measured and transferred to the titration cell. The magnetic stirrer was set at a medium speed, and once the temperature of the sample stabilized, the initial pH reading and temperature were recorded. Initially, enough acid volume was added from the burette to bring the e.m.f. as close to 170.0 mV as possible. This volume and e.m.f. were recorded, and then the titration proceeded by the addition of HCl solution in increments of 0.004 ml. The volume and e.m.f. were recorded for each incremental increase. Once the e.m.f. reading reached 200 mV, acid solution was added in increments of 0.010 ml. This process was continued until the e.m.f. reached 230 mV or slightly above. The above procedures were consistent with the Standard Operating Procedures outlined in *Determination of total alkalinity in sea water* (SOP3, 1997).

Titration data was converted into Total Alkalinity using a modified Gran Function. This raw total alkalinity value was adjusted to a calculated total alkalinity which was calibrated based on titrations of the WOCE Dickson 75 standard.

Nutrient and Chlorophyll A Data

In addition to pH and alkalinity data, nitrate, phosphate and chlorophyll A concentrations were measured. The nitrate, phosphate and Chlorophyll A concentrations were determined using the procedures outlined in (Parsons, 1989). In this study, Chlorophyll A concentration was used as a proxy for primary productivity.

Data Reduction

The program co2sys.xls (version 1.0) was utilized to calculate in situ parameters of the carbon system. By entering the pH, TA, salinity, temperature and pressure at which the titration was performed, in situ temperature and pressure of the sample and phosphorus, data was obtained which included in situ pH, in situ pCO_2 and Total Dissolved Inorganic Carbon (DIC).

All data was imported into Ocean Data View for analysis. Acoustic Doppler Current Profiler (ADCP) data was used to determine currents along the entire transect, and a section of the transect was used to consider possible explanations for other results based on currents and ocean circulation.

For each individual station as well as the entire transect ratios of DIC : Phosphate (Figure 8) and Nitrate : Phosphate (Figure 9) were determined and compared to the predicted Redfield ratios of 106 DIC: 16 NO3: 1 PO4.

Results

Across the transect, surface pCO2 remained relatively stable, between 330 and 390 ppm. The pCO2 tended to increase with depth, with the highest concentrations of around 1200 ppm observed between 15° and 7° north latitude, at depths below 200 meters (Figure 2).

Dissolved oxygen concentrations also remained fairly constant at the surface along the entire transect, with values close to 4.5 ml/l. The O_2 decreased with depth, with the lowest concentrations ranging from 0.1 to 0.4 ml/l and corresponding to the upwelling system between 12° and 7° north latitude, at depths below 200 meters (Figure 3).

Similarly, surface pH remained relatively stable across the transect, staying at approximately 8.1. The pH tended to decrease with depth, with the lowest concentrations of around 7.6 observed between 15° and 7° north latitude, at depths below 200 meters (Figure 4).

The total Dissolved Inorganic Matter (DIC) shows several variations along the transect. At the surface, low points of 1900 to 1950 uM occur near 17° north, 11° north and between 7° and 5° north latitude. The highest concentrations of approximately 2300 uM occur below 200 meters from 14° to 7° north, where an upwelling system can be observed, causing a shoaling of the gradient with movement south along the transect (Figure 5).

Comparison of the ratios of DIC : PO4 (Figure 8) and NO3 : PO4 (Figure 9) in the samples shows that nutrient content follows Redfield Ratios fairly consistently throughout the transect. The observed ratios for the entire track were approximately 136 : 12 : 1, although some individual stations show ratios which adhere slightly more closely to those predicted by Redfield. The stations exhibiting ratios which adhere most closely to Redfield Ratios are found from 17° to 13° north latitude. One station was in the cyclonic eddy at approximately 17° north, but stations in the oligotrophic North Pacific Central Water were also included in this area.

Discussion

Across the transect the partial pressure of CO_2 demonstrated distinctive trends and strong correlations to dissolved oxygen, pH and nutrients, as well as with the currents. The most obvious trend is a negative correlation between pCO_2 (Figure 2) and dissolved oxygen (Figure 3). This negative correlation is indicative of biological activity as a dominant regulator of pCO_2, and it is in agreement with my hypothesis. It is important to note that both pCO_2 and O_2 are at fairly consistent levels at the surface across the entire transect. This can be attributed to the fact that in the mixed layer, air-sea gas exchange is relatively rapid, allowing seawater to move toward equilibrium with the atmosphere. It is seen that surface CO_2 levels are very similar to current atmospheric concentrations, staying approximately within the 350 to 400 ppm range.

Moving deeper in the water column, however, it is apparent that pCO_2 is regulated by other factors. With decreasing temperature and increasing pressure, the solubility of carbon dioxide increases, leading to higher partial pressures at greater depths. In addition, because photosynthesis does not take place below the euphotic zone, respiration and the break down of organic matter are the dominant biological processes occurring. Because the CO_2 produced by these reactions is not readily taken up or outgassed. an accumulation of CO_2 occurs with increasing depth.

The opposite trend is expected and observed in the collected data for oxygen: in deeper waters, the surplus of respiration over processes which release oxygen results in the depletion of oxygen in deep waters. Furthermore, older water masses tend to have high pCO_2 and DIC levels and low O_2 concentrations due to the cumulative affect of these processes over time. Therefore, water's age can be qualitatively assessed by the extent of oxygen depletion. Because deep water has lower O_2 concentration combined with higher DIC concentrations and pCO_2 and levels, it can be determined that the strong trend of decreasing O_2 and increasing DIC and pCO_2 observed below approximately 200 meters between 5° and 15° north latitude is indicative of a strong upwelling system.

One notable aspect of the pCO_2 (Figure 2), O_2 (Figure 3) and pH (Figure 4) data is the distinctive change at approximately 5° north latitude and southward. The pCO_2 drops and the O_2 concentration rises along with an increasing pH. This region appears to be the edge of the upwelling system, and it coincides with the start of the strong eastward flowing current observed from data collected by the Acoustic Doppler Current Profiler (Figure 7). The eastward-flowing current observed in the ADCP data is determined to be the North Equatorial Counter Current (NECC), which is bringing younger, less productive water from the Western Pacific region. This water mass develops in the warm surface waters of the equatorial west Pacific, from which it moves eastward across the Pacific. The water mass is driven eastward by the pressure gradient force created by the Northeast Trade Winds and the resulting North Equatorial Current, which lead to the accumulation of water along the western Pacific coasts (Brown, 1989B). This water mass is younger, warmer and has lower nitrate concentrations, which may correspond to lower primary productivity; all of these factors contribute to the higher pCO2 level and DIC concentrations, lower O2 concentrations and lower pH observed in the NECC region.

Some trends relating to productivity, which is qualitatively defined by the chlorophyll A concentrations, emerged in the DIC data. First, the DIC concentrations have three noticeable low points—at approximately 17° north, 12° to 13° north, and 7° to 4° north (Figure 5). These low DIC levels correspond strongly with the observed changes in chlorophyll A levels (Figure 6). For instance, the low point in DIC at approximately 16° to 17° north latitude corresponds directly with the cold-core cyclonic eddy feature which was the earliest station. This result is expected since the upwelling eddy is a highly productive region, meaning that a lot of DIC is being absorbed due to high photosynthetic activity. The low DIC region south of 7° north latitude may also be explained by a high chlorophyll A level corresponding to the highly productive North Pacific Equatorial Water created by upwelling at the equatorial divergent zone.

The occurrence of low DIC from 12° to 13° north latitude, however, requires a more complicated explanation since it corresponds to oligotrophic surface waters, which would be expected to result in a higher DIC concentration. Upon examination of the ADCP data (Figure 7), however, it is apparent that currents may be significantly influencing the system. At approximately the same latitude as the low DIC level, an eastward current anomaly may be observed at depths of 200 to 400 meters, which could be bringing more productive water from farther south in the Equatorial North Pacific Water.

A consistent difference in nutrient ratios was not found between the oligotrophic waters and more productive waters. Rather, the ratios showed fairly consistent values across the transect. Within the slight variations, the oligotrophic region around 15° north latitude exhibited one of the ratios closest to Redfield. This result was does not agree with the proposed hypothesis, as it was expected that nutrient concentrations in oligotrophic areas would not adhere to Redfield as closely as in productive regions.

Although the differences in adherence to Redfield Ratios between stations are not large, a few points can be made about the slight variations that do occur. A ratio of 83 : 16 : 1 was observed at the first site (Figure 10), which is located in a cyclonic eddy. This ratio is likely closer Redfield than some of the later stations due to the increased primary productivity of the area, which works to shift concentrations of the components toward Redfield Ratios.

An additional feature of the observed ratios across the transect is a spike in the ratios of DIC and NO3 relative to PO4 at approximately 10° north latitude (Figure 10). One possible explanation for this spike is that in that region, phosphorus is the limiting nutrient; as a result, DIC and nitrate concentrations have increased relative to that of phosphate. Another possibility takes into account the physical oceanography of the location, which is at the frontal boundary of two water masses. It is the edge of the North Pacific Central Water, which is oligotrophic, and the more productive North Pacific Equatorial Water. Perhaps this feature has some impact upon the nutrient concentrations, although more research would be needed to determine what processes may be at work.

Conclusion

Across the transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati, several trends were observed in the parameters of the carbon cycle which indicate a combination of physical and biological factors as regulators of carbon concentrations in the equatorial north Pacific.

The partial pressure of CO_2 at the surface was observed to be regulated by mixing, which resulted in oceanic concentrations remaining fairly close to the current atmospheric concentration of approximately 380 ppm. At depth, pCO_2 trends indicated that it was regulated by water mass age, origin and physical characteristics such as temperature. Because of this link, pCO_2 levels were seen to vary according to regional currents and ocean circulation systems.

The DIC concentrations along the transect were determined to be regulated by similar factors to those which affect pCO_2 below the mixed layer. At the surface, however, DIC concentration was found to be negatively correlated to chlorophyll A concentration, indicating that DIC is highly regulated by primary productivity.

The ratios of DIC : PO_4 and NO_3 : PO_4 across the entire transect were found to adhere very closely to the predicted Redfield Ratios. While all sample stations showed ratios which were fairly comparable to Redfield Ratios, some stations did adhere more closely than others. In particular, samples in the oligotrophic waters were very close to Redfield Ratios, which was the opposite of the expected result. It was evident from this study that there are multiple factors affecting the ratios of nutrients in seawater, and adherence to Redfield Ratios cannot necessarily be predicted based on primary productivity alone. An interesting addition to this study would be to consider adherence to Redfield at different depths.

Increasing our knowledge about the oceanic carbon system is an important step to understanding the potential impacts of anthropogenic increases in atmospheric CO_2. Thjs study aimed to increase the understanding of oceanographic and biological factors affecting the carbon system on regional a regional scale in the equatorial north Pacific. In future years pCO2 may be measured directly, which could increase the accuracy of pCO_2 data and would be an important extension to this project. Having this baseline data set will allow future studies to observe changes in these parameters over the years, which is an important endeavor for understanding how increasing atmospheric CO_2 and anthropogenic climate change may be impacting equatorial Pacific ocean chemistry. Many more studies are needed to gain a full picture of the ways in which the oceanic carbon cycle interacts with and regulates atmospheric pCO_2, and it is an critical area of research if we are to predict the changes which will occur due to anthropogenic climate change.

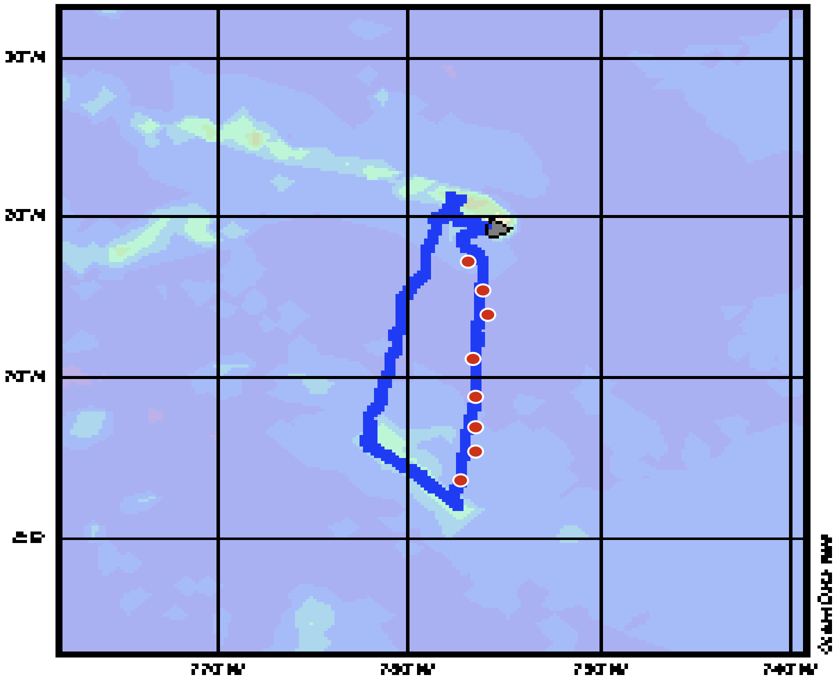

Figure 1. Map of sample locations along the transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati. The first sample was taken at 16° 54.9′ North x 156° 20.6′ West and the last at 3° 30′ North x 156° 53.2′ West. Data was collected during the S211 cruise from May 10 to May 22, 2007.

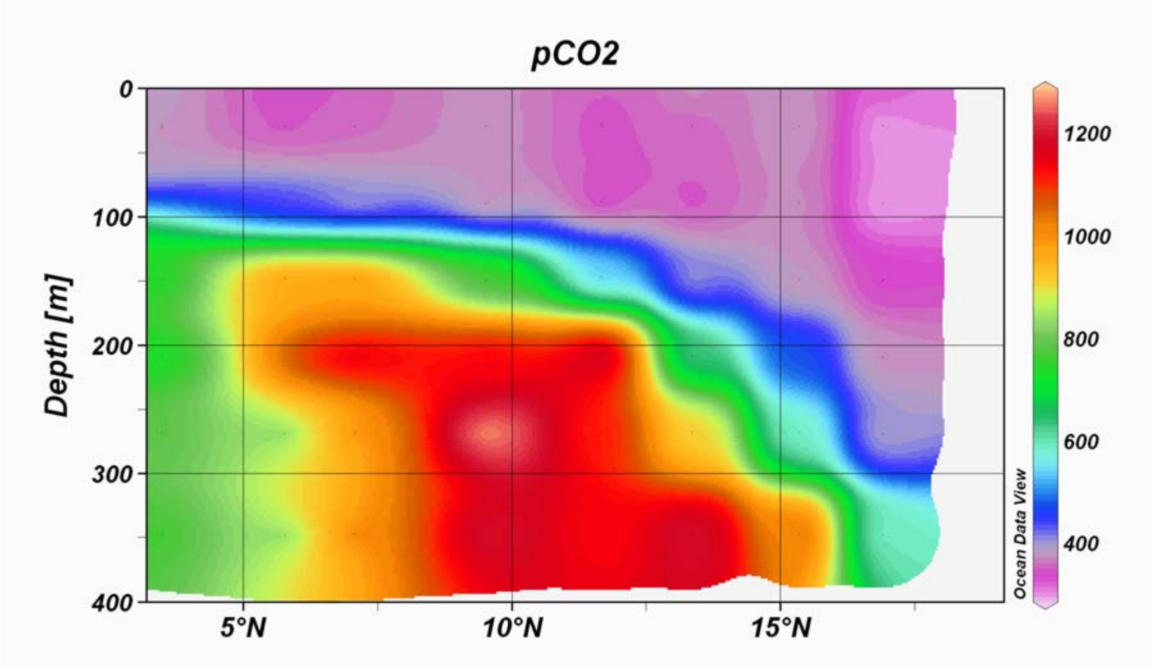

Figure 2. Section of the partial pressure of CO_2 (z variable) versus depth (y variable) and latitude (x variable), interpolated across the entire cruise track. Data was collected at 8 stations along the S211 transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati from May 10 to May 22 2007.

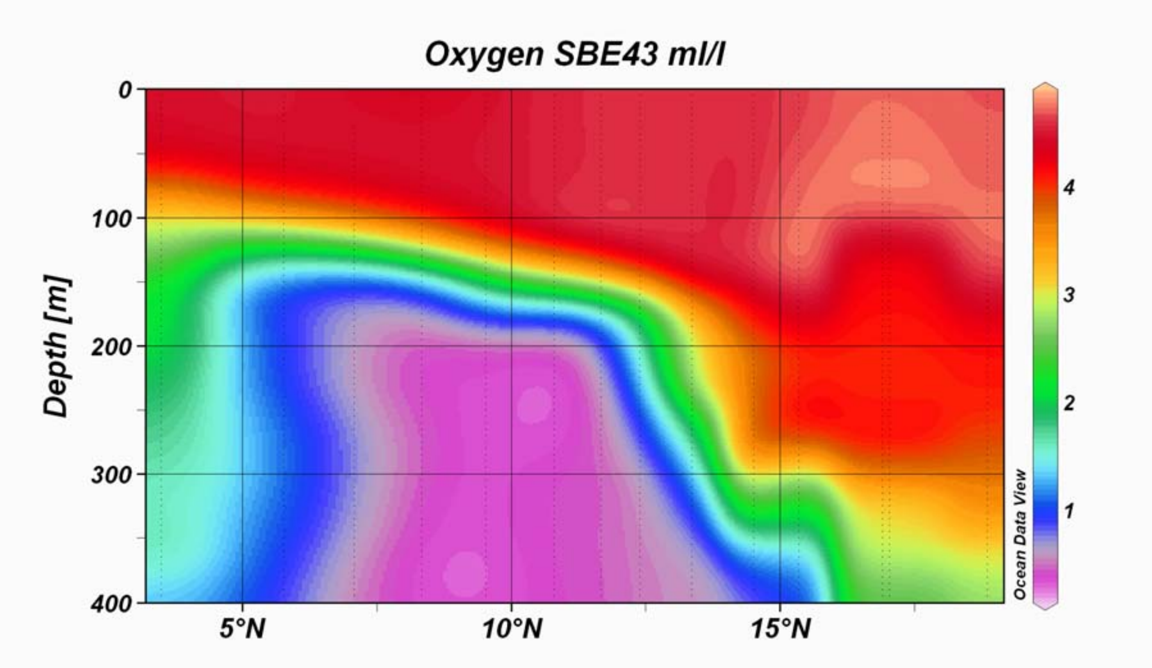

Figure 3. Section of dissolved oxygen (z variable) versus depth (y variable) and latitude (x variable), interpolated across the entire cruise track. Data was collected at 9 stations along the S211 transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati from May 10 to May 22 2007.

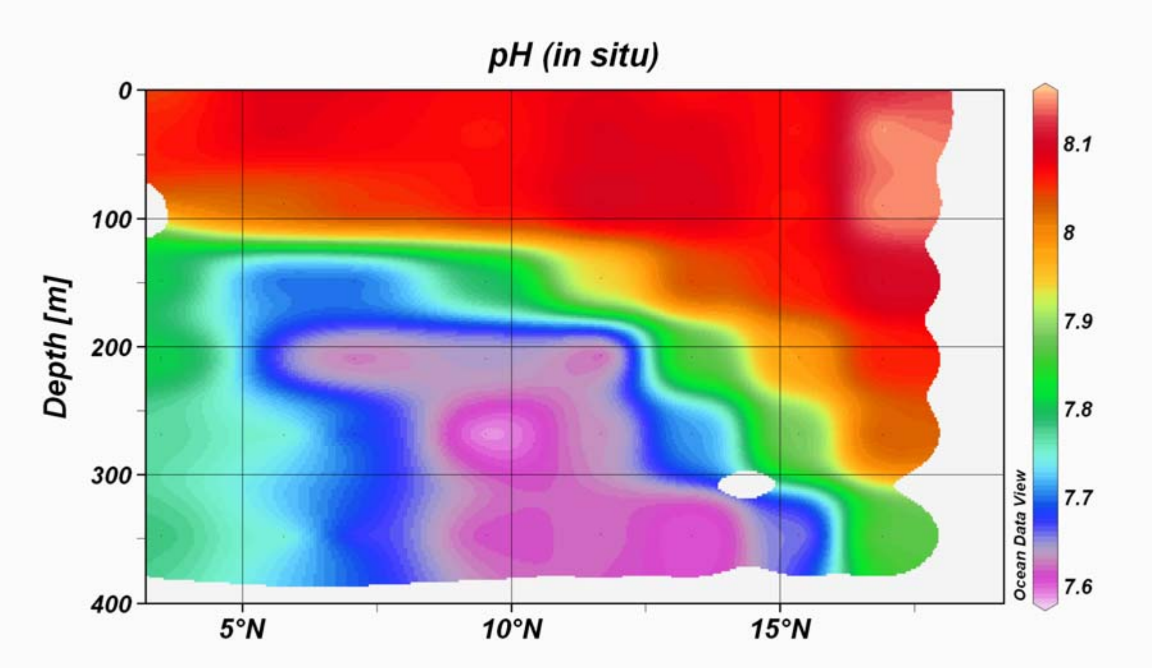

Figure 4. Section of the in situ pH (z variable) versus depth (y variable) and latitude (x variable), interpolated across the entire cruise track. Data was collected at 8 stations along the S211 transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati from May 10th to May 22nd 2007.

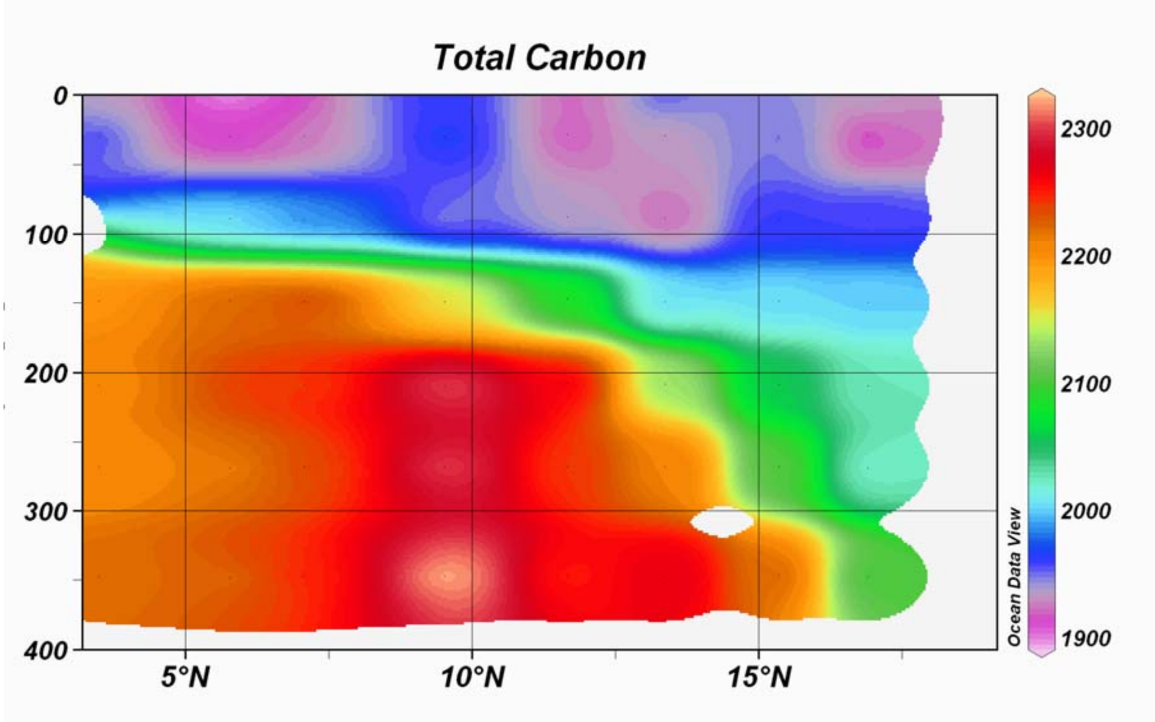

Figure 5. Section of the Total Dissolved Inorganic Carbon (z variable) versus depth (y variable) and latitude (x variable), interpolated across the entire transect. Data was collected at 8 stations along the S211 transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati from May 10 to May 22 2007.

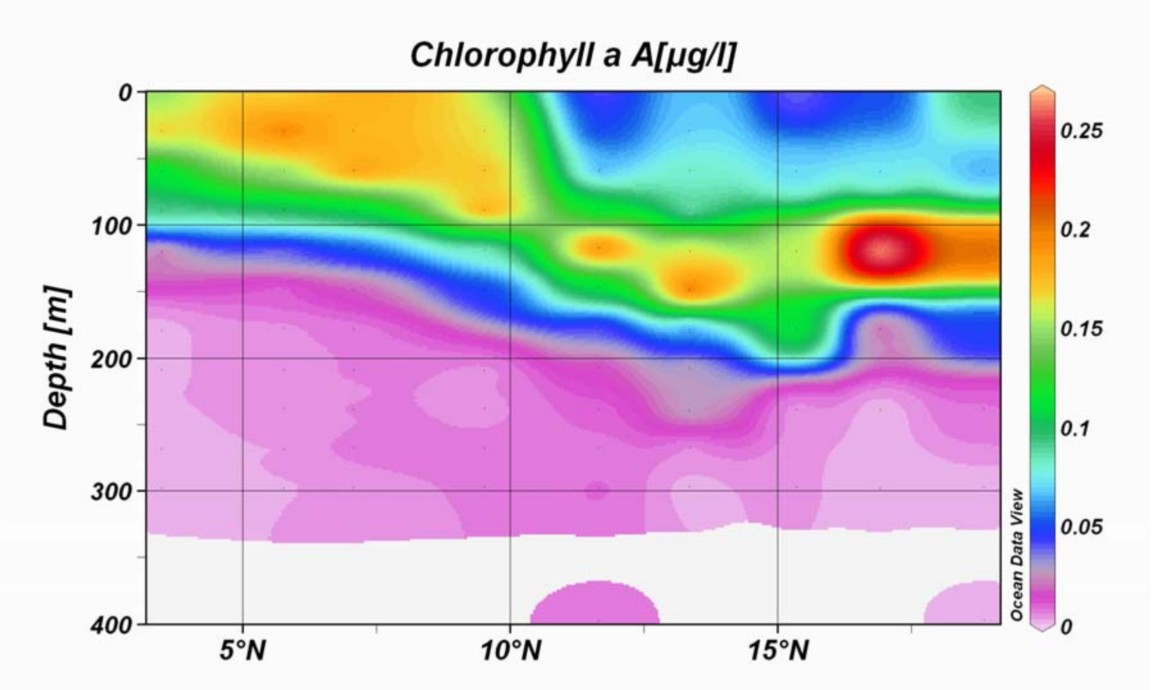

Figure 6. Section of the Chlorophyll A concentration (z variable) versus depth (y variable) and latitude (x variable), interpolated across the entire transect. Data was collected at 8 stations along the S211 transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati from May 10 to May 22 2007.

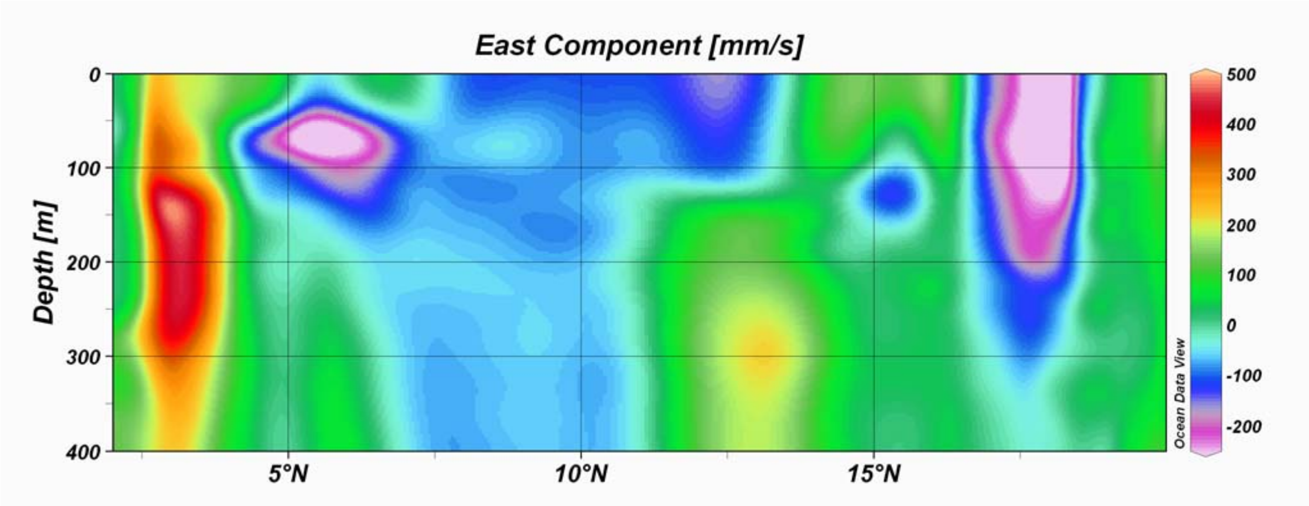

Figure 7. Section of the magnitude of the east component of currents crossed along the S211 transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati from May 10 to May 22 2007. Data was collected continuously using Acoustic Doppler Current Profiler.

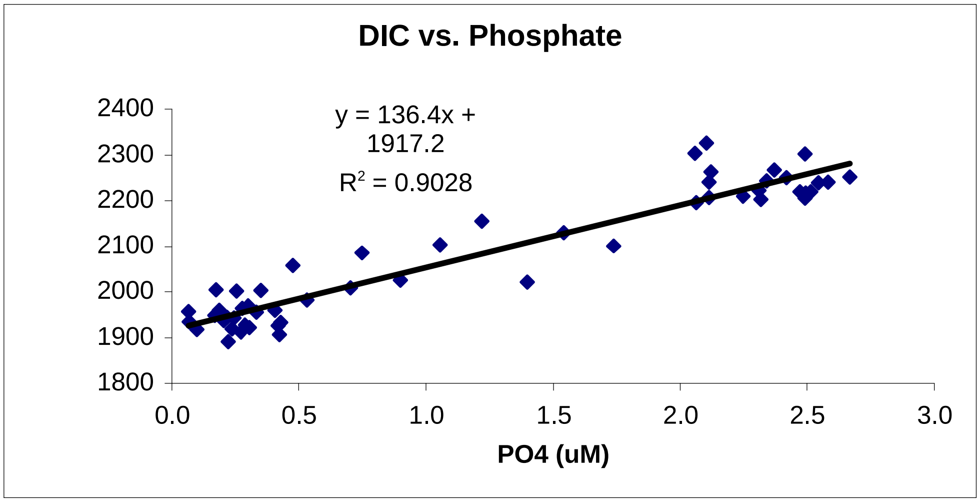

Figure 8. This graph plots Dissolved Inorganic Matter against Phosphate for all samples taken at each of 8 stations across the S211 transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati from May 10 to May 22, 2007. The slope of the trend line describes the ratio of DIC: PO4, which may be compared to the ideal Redfield Ratio.

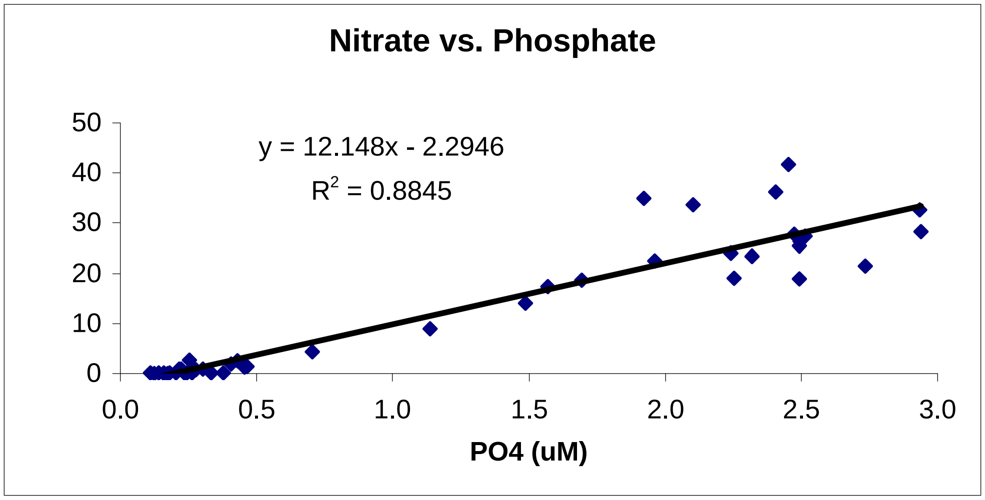

Figure 9. This graph plots Nitrate against Phosphate for all samples taken at each of 8 stations across the S211 transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati from May 10th to May 22nd, 2007. The slope of the trend line describes the ratio of NO3 : PO4, which may be compared to the ideal Redfield Ratio.

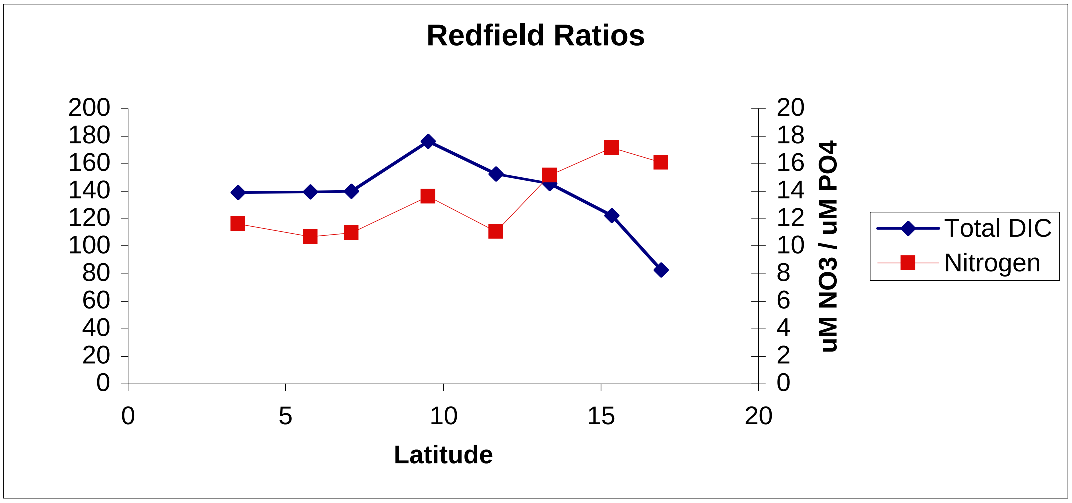

Figure 10. This graph plots the ratios of DIC : PO4 and NO3 : PO4 across the latitudes covered by the S211 transect from Kealakekua Bay, Hawaii to Christmas Island, Kiribati from May 10 to May 22, 2007. The slope of the trend line describes the ratio of DIC: PO4, which may be compared to the ideal Redfield Ratio.

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