



Seawater Carbonate Chemistry Distributions Across the Eastern South Pacific Ocean Sampled as Part of the GEOTRACES Project and Changes in Marine Carbonate Chemistry Over the Past 20 Years

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The US GEOTRACES Eastern Pacific Zonal Transect in 2013 that sampled in the South Pacific Ocean has provided an opportunity to investigate the biogeochemical cycling of trace elements and isotopes (TEIs) and seawater carbon dioxide (CO₂)–carbonate chemistry. Across the Peru to Tahiti section, the entire water column was sampled for total alkalinity (TA) and dissolved inorganic carbon (DIC), in addition to core hydrographic and chemical measurements conducted as part of the GEOTRACES cruise. From the nutrient-rich, low-oxygen coastal upwelling region adjacent to Peru to the oligotrophic central Pacific, very large horizontal gradients in marine carbonate chemistry were observed. Near the coast of Peru, upwelling of CO₂-rich waters from the oxygen-deficient zone (ODZ) impinged at the surface with very high partial pressures of CO₂ ($p\text{CO}_2$; >800–1,200 μatm), and low pH (7.55–7.8). These waters were also undersaturated with respect to aragonite, a common calcium carbonate (CaCO₃) mineral. These chemical conditions are not conducive to pelagic and shelf calcification, with shelf calcareous sediments vulnerable to CaCO₃ dissolution, and to the future impacts of ocean acidification. A comparison to earlier data collected from 1991 to 1994 suggests that surface seawater DIC and $p\text{CO}_2$ have increased by as much as 3 and 20%, respectively, while pH and saturation state for aragonite ($\Omega_{\text{aragonite}}$) have decreased by as much as 0.063 and 0.54, respectively. In intermediate waters (~200–500 m), dissolved oxygen has decreased (loss of up to $-43 \mu\text{moles kg}^{-1}$) and nitrate increased (gain of up to $5 \mu\text{moles kg}^{-1}$) over the past 20 years and this likely reflects the westward expansion of the ODZ across the central Eastern South Pacific Ocean. Over the same period, DIC and $p\text{CO}_2$ increased by as much as $+45 \mu\text{moles kg}^{-1}$ and $+145 \mu\text{atm}$, respectively, while pH and $\Omega_{\text{aragonite}}$ decreased by -0.091 and -0.45 , respectively. Such rapid change in pH and CO₂–carbonate chemistry over the past 20 years reflects substantial changes in the ODZ and water-column remineralization of

organic matter with no direct influence from uptake of anthropogenic CO₂. Estimates of anthropogenic carbon (i.e., C_{ANT}) determined using the TrOCA method showed no significant changes between 1993 and 2014 in these water masses. These findings have implications for changing the thermodynamics and solubility of intermediate water TEIs, but also for the marine ecosystem of the upper waters, especially for the vertically migrating community present in the eastern South Pacific Ocean.

Keywords: seawater carbonate chemistry, marine biogeochemistry, GEOTRACES, Pacific Ocean, oxygen-deficient zone, anthropogenic carbon

INTRODUCTION

The primary goal of the international GEOTRACES program has been “to understand the sources, sinks, and internal cycling of trace elements and isotopes (TEIs) based on their distributions across the global ocean” (GEOTRACES, 2006). As part of the effort to understand the sources and sinks of TEIs, it is helpful to place TEI data into the context of entire water column hydrographic properties (i.e., temperature, salinity, nutrients) and their preformed distributions. Such information elucidates the processes that influence TEI in the ocean, and the physical and biogeochemical processes that influence their distributions.

As part of the context for deciphering the physical and biogeochemical dynamics of TEIs, it is also important to understand the controls imparted by changes in seawater carbonate chemistry, and pH in particular. Seawater pH has a strong influence on the speciation of trace elements (TEs; e.g., Turner et al., 1981; Byrne et al., 1988; Millero et al., 1995, 2009; Zeebe and Wolf-Gladrow, 2001; Byrne, 2002; Millero, 2013), thermodynamics and kinetic activity of metal TEs (e.g., Millero, 2001a,b), and potentially the influence of TEs complexed to organic ligands, complexation in seawater, and growth of marine organisms. Those trace elements that form strong complexes such as Copper (Cu²⁺) and rare earth elements are those that are the most strongly influenced by pH. For example, a decrease in pH due to natural water-column changes or ocean acidification (OA) induced change will increase free ionic Cu by ~30% (with a change in pH from 8.1 to 7.4; Millero et al., 2009), a change that is significant considering that free Cu is potentially toxic to marine organisms (e.g., Sunda and Ferguson, 1983). A shift in pH also influences the solubility of many TEs, and, for example, Fe(III) solubility increases by 40% with a decrease in pH from 8.1 to 7.4 (Millero et al., 2009). Chemical reaction rates such as those that influence Fe(II) are also influenced by pH conditions. In addition, the thermodynamic influence of pH on trace element complexed organic matter is not well characterized or understood due to a lack of knowledge about the composition and reactivity of organic ligands (GEOTRACES, 2006).

The increase in atmospheric carbon dioxide (CO₂) due to human activities and its uptake by the global ocean (Sabine et al., 2004; Khatiwala et al., 2013) has altered ocean chemistry and the marine CO₂-carbonate system over the past few decades (e.g., Bates and Peters, 2007; González-Dávila et al., 2007; Dore et al., 2009; Olafsson et al., 2009, 2010; González-Dávila et al., 2010; Bates et al., 2012, 2014). The observed decline in ocean pH and saturation states of calcium carbonate (CaCO₃) minerals (i.e., Ω)

as a result of OA and future changes in ocean chemistry (e.g., Caldeira and Wickett, 2003; Orr et al., 2005) has potential direct and indirect consequences for marine biogeochemical cycles, and ocean organisms, and taxa, especially given that many trace elements are biochemically important for marine phytoplankton (Morel et al., 2003; Shi et al., 2010).

The US GEOTRACES Eastern Pacific Zonal Transect (i.e., GEOTRACES cruise GP16) conducted in 2013 has not only provided new information about the physical and biochemical cycling of TEIs in a region with one of the largest, permanently stratified oxygen-deficient zones (ODZs) on the planet and venting of hydrothermal fluids from the East Pacific Rise (e.g., Resing et al., 2015; Jenkins et al., 2018; Moffett and German, 2018, studies therein; Schlitzer et al., 2018), but also context for understanding such TEI variability relative to pH and seawater carbonate chemistry. Across the Peru to Tahiti section, there are very large horizontal gradients in hydrography and biogeochemistry, including the region of nutrient-rich coastal upwelling region adjacent to the coastline of Peru, the presence of the thermocline ODZ on the eastern Pacific Ocean, and westward across the oligotrophic central Pacific Ocean. Across this part of the eastern South Pacific Ocean, there are also very large horizontal gradients in upper-ocean (e.g., Feely et al., 1995, 2006; Takahashi et al., 2009; Quay et al., 2011) and vertical changes in seawater carbonate chemistry and pH, in particular. For example, pH variability ranges from 7.9 to 8.2 in surface waters (depending on pCO₂ values of upwelled water), while pH decreases significantly in waters of the ODZ in this part of the Eastern Pacific Ocean.

The primary objectives of this paper are to report the observations of seawater carbonate chemistry across the ODZ of the Eastern South Pacific Ocean, and in particular, document the high pCO₂ and low pH values found in the anoxic zone. Although the region has relatively sparse data, the GEOTRACES data collected in 2013 are compared to data collected a couple of decade earlier. This comparison is used to determine if the marine carbon cycle has changed and the ODZ expanded recently, and, if so, to assess the rates of changes of seawater carbonate chemistry such as DIC, TA, pCO₂, pH, and the saturation states for calcium carbonate (CaCO₃) minerals such as aragonite and calcite. The TrOCA method updated by Touratier et al. (2007) is used to calculate anthropogenic CO₂ (C_{ANT}) contributions to the water column, if changes have occurred between 1994 and 2013, and if anthropogenic CO₂ has contributed to substantial changes in pCO₂ and low pH, for example, over the past 20 years.

SAMPLING, METHODS, AND ANALYTICAL PROTOCOLS

Cruise Information

The US GEOTRACES cruise GP16 was conducted in the Eastern Pacific Ocean from the R/V *Thomas G. Thompson* during October to December 2013 (Peters et al., 2018; data repository given therein). In the paper by Peters et al. (2018), details on the sampling and analysis of hydrography (e.g., potential temperature, salinity, inorganic nutrients, dissolved oxygen, and TEIs) with analytical methods and uncertainties given therein. The metadata and data for cruise GP16 are publically disseminated by the Biological and Chemical Oceanography Data Management Office¹, while the entire GEOTRACES program data have been reported elsewhere (Schlitzer et al., 2018). As discussed later, the fractional contributions of different water masses in the region through the water column have been determined (Peters et al., 2018) and partially summarized in **Table 1**.

The US GEOTRACES cruise GP16 cruise began in the nutrient-rich coastal upwelling region adjacent to the coastline of Peru, transited across the ODZ approximately at a latitude of ~11–13°S, and finished in oligotrophic of the South Pacific subtropical gyre at ~150°W and approximately 5° north of Tahiti (**Figure 1**). The deviation southward of the cruise track reached ~14°S.

Considerations of Seawater Carbonate Chemistry

In this paper, the description of seawater carbonate chemistry follows long-established knowledge (e.g., Zeebe and Wolf-Gladrow, 2001; Dickson et al., 2007; Millero, 2013). Of the measurable parameters of the seawater carbonate system, the chemical description of DIC is as follows (e.g., Zeebe and Wolf-Gladrow, 2001; Dickson et al., 2007):

$$\text{DIC} = [\text{CO}_2^*] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}] \quad (1)$$

¹<https://www.bco-dmo.org/project/499723>

In this equation, the term $[\text{CO}_2^*]$ represents the summed concentration of dissolved H_2CO_3 and CO_2 . The chemical description of alkalinity of seawater (TA) is defined as (e.g., Zeebe and Wolf-Gladrow, 2001; Dickson et al., 2007):

$$\begin{aligned} \text{TA} = & [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{B}(\text{OH})_4^-] + [\text{OH}^-] + [\text{HPO}_4^{2-}] \\ & + 2[\text{PO}_4^{3-}] + [\text{SiO}(\text{OH})_3^-] + [\text{HS}^-] + [\text{NH}_3] \\ & + \text{minor species} - [\text{H}^+] - [\text{HSO}_4^-] - [\text{HF}] - [\text{H}_3\text{PO}_4] \\ & - \text{minor species} \end{aligned} \quad (2)$$

In Equation (2), the summed concentrations of $[\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{B}(\text{OH})_4^-]$ represent the major chemical components of total alkalinity (TA) and the proton/charge balance of seawater. Here, other chemical species that contribute to alkalinity are typically minor constituents with negligible impact on TA (e.g., Zeebe and Wolf-Gladrow, 2001; Dickson et al., 2007; Millero, 2013). Given long-established guidelines (Dickson et al., 2007; and references therein); DIC and TA are both expressed as $\mu\text{moles kg}^{-1}$. In this paper, $p\text{CO}_2$ is used rather than fugacity of CO_2 (i.e., $f\text{CO}_2$; note that this parameter was also computed in data files), and this term refers to the partial pressure of CO_2 in equilibrium with water with units of μatm . pH in seawater is dimensionless and expressed on the total seawater scale (Dickson et al., 2007).

In well-established chemical understanding of the seawater carbonate system, the chemical equations governing the formation and dissolution of calcium carbonate (CaCO_3) minerals are as follows (e.g., Zeebe and Wolf-Gladrow, 2001; Dickson et al., 2007; Millero, 2013):

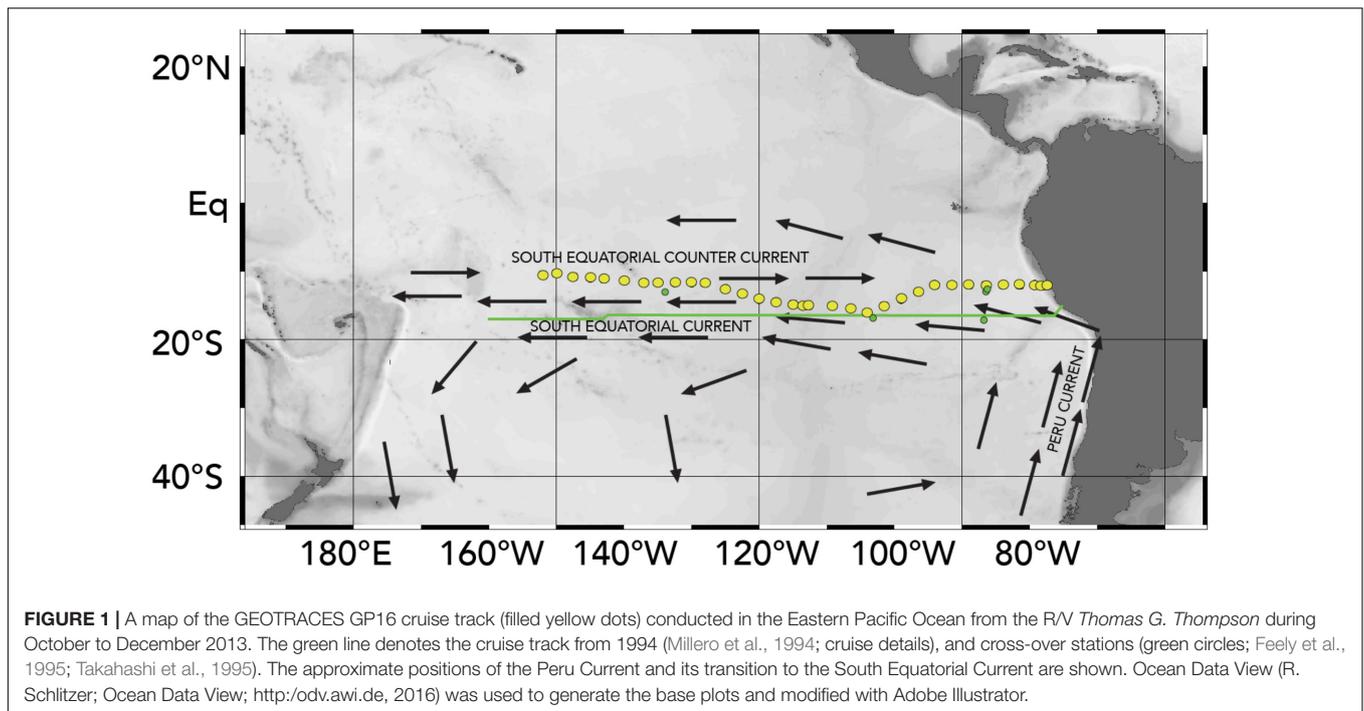


In typical seawater, the rates of CaCO_3 production and dissolution vary in general terms depending on CaCO_3 saturation state (Ω). The saturation state for CaCO_3 minerals such as aragonite and calcite is chemically defined by the following equations and relationships between calcium and carbonate ion

TABLE 1 | End-member definitions for water types included in the upper ocean, intermediate (I) and deep (D) OMPAs reported by Peters et al. (2018), with mean DIC and TA ranges given.

	θ (°C)	S ($\mu\text{mol kg}^{-1}$)	$[\text{NO}_3^-]$ ($\mu\text{mol kg}^{-1}$)	$[\text{PO}_4^{3-}]$ ($\mu\text{mol kg}^{-1}$)	$[\text{Si}(\text{OH})_4]$ ($\mu\text{mol kg}^{-1}$)	$[\text{O}_2]$ ($\mu\text{mol kg}^{-1}$)	"NO" ($\mu\text{mol kg}^{-1}$)	DIC	TA
ESSW	12–15	34.90	NG	NG	~40	NG	NG	2280–2320	2290–2310
ESPIW	6–12	34.65	NG	NG	~40–45	NG	NG	2260–2280	2285–2295
SPCW	12–15	34.90	NG	NG	~15–20	NG	NG	2220–2260	2290–2310
AAIW	5.53	34.25	25.3	1.75	13	250	495	2280–2320	2340–2360
EqPIW	7.86	34.83	40.9	2.86	42	20	416	2280–2340	2300–2330
UCDW	2.44	34.57	34.5	2.40	77	168	502	2310–2330	2380–2400
PDW	1.44	34.67	38.6	2.57	166	116	490	2320–2360	2400–2430
LCDW	1.67	34.73	31.9	2.20	92	190	500	2270–2290	2390–2410
ABW	0.01	34.70	33.1	2.29	144	216	536	2260–2280	2370–2390

In the table, "NO" refers to the conservative water-mass tracer $\text{NO} = 9[\text{NO}_3^-] + [\text{O}_2]$. In the table, the term NG refers to values not given in Peters et al. (2018).



concentrations, thus:

$$\Omega_{\text{aragonite}} = [\text{Ca}^{2+}][\text{CO}_3^{2-}]/K_{\text{sp}^*(\text{aragonite})}^* \quad (4)$$

$$\Omega_{\text{calcite}} = [\text{Ca}^{2+}][\text{CO}_3^{2-}]/K_{\text{sp}^*(\text{calcite})}^* \quad (5)$$

In Equations (4) and (5), the solubility product for CaCO_3 , $K_{\text{sp}^*(\text{aragonite})}^*$, and $K_{\text{sp}^*(\text{calcite})}^*$, varies primarily as a function of temperature, salinity, and pressure conditions. In general terms, although aragonite and calcite dissolution is favored in seawater when $\Omega_{\text{aragonite}}$ and Ω_{calcite} values that are lower than one (i.e., $\Omega < 1$), and aragonite and calcite formation generally occurs at $\Omega_{\text{aragonite}}$ and Ω_{calcite} values that are greater than one (i.e., $\Omega > 1$), dissolution and production of CaCO_3 can occur above 1 and below 1, respectively.

Sampling Protocols for Seawater Carbonate Chemistry

Seawater samples for carbonate chemistry were collected for the entire water column at all of the GEOTRACES CTD-hydrocast stations. Samples for both TA and DIC were withdrawn from the Niskin samplers (after dissolved oxygen and salinity) using well-established gas sampling methods (Bates et al., 1996a; Dickson et al., 2007), and collected into the clean 500 ml size Pyrex glass reagent bottles. For each sample, a headspace of <1% of the bottle volume was left to allow for water expansion and contraction during storage and shipping. All of the TA and DIC samples were poisoned with $\sim 100 \mu\text{l}$ volume of saturated HgCl_2 solution in order to prevent biological alteration, bottles were then sealed with Apiezon silicon vacuum grease and ground-glass stoppers, and stored in the dark. TA and DIC data here are not corrected for the volume of HgCl_2 added. Samples were returned to the

marine biogeochemistry laboratory at the Bermuda Institute of Ocean Sciences (BIOS) for analysis. Similar sampling protocols were established at BIOS for sampling at the BATS (Bates et al., 1996a,b; Bates, 2001). Samples were typically analyzed within 3 months of collection in the laboratory at BIOS.

Analytical Determination of Seawater DIC and TA

Seawater DIC contents of each sample were measured using a well-established gas extraction/coulometric method [see Bates et al. (1996a,b) for details]. At BIOS, two nearly identical automated instruments (SOMMA; Single-Operator Multi-Metabolic Analyzer; VINDTA 3C, Marianda Com) were used to deliver a known volume of sample seawater, and with weak phosphoric acid, convert all carbonate species to dissolved CO_2 . UIC CO_2 coulometer detectors were then used to measure the amount of CO_2 evolved from the seawater sample in order to determine DIC content (Bates et al., 2012). Replicate sample analyses of >5,000 seawater samples analyzed at BIOS from 1992 to present indicate the analytical precision of DIC at better than 0.025% ($\sim 0.5 \mu\text{moles kg}^{-1}$), with more than 50 replicates for this cruise giving similar results. In addition, seawater certified reference materials (CRMs; prepared by A.G. Dickson, Scripps Institution of Oceanography) were routinely analyzed to provide an estimate of analytical accuracy of DIC at 0.05% ($\sim 1 \mu\text{moles kg}^{-1}$). Such precision and accuracy are typical for more than 10,000 DIC samples analyzed in the laboratory at BIOS over the past 20 years. This is due in part to analyses being primarily devoted to time-series analysis (e.g., Bates et al., 2014), rigorous methodologies, and a very stable analytical environment in the laboratory.

For, each sample, TA was measured by potentiometric titration with a weak solution of HCl [see Bates et al. (1996a,b, 2012) for details]. Replicate sample analyses of >5,000 seawater samples analyzed at BIOS indicated an analytical precision for TA of 0.04% ($\sim 1 \mu\text{moles kg}^{-1}$), while concurrent analyses of CRM samples typically gave results within 0.15% ($\sim 1\text{--}2 \mu\text{moles kg}^{-1}$) of certified TA values reported by A.G. Dickson (Scripps Institution of Oceanography²). The use of CRM samples for both DIC and TA analyses is a critically important approach for assessing seawater chemistry over time and accurate calculation of $p\text{CO}_2$ and pH for seawater samples (e.g., Bates et al., 2012, 2014). CRM batch numbers 134 and 140 were used for this suite of DIC and TA sample analyses.

Seawater CO_2 –Carbonate Chemistry Computations and Propagation of Uncertainty

The full suite of seawater carbonic acid system parameters (i.e., $[\text{CO}_2]$, $[\text{H}_2\text{CO}_3]$, $[\text{HCO}_3^-]$, $[\text{CO}_3^{2-}]$, $[\text{H}^+]$) can be determined from the measurement of two parameters (i.e., DIC, TA, $p\text{CO}_2$, and pH), along with temperature and salinity (e.g., Zeebe and Wolf-Gladrow, 2001; Millero, 2013). In this paper, the seawater carbonic acid system parameters of $[\text{CO}_3^{2-}]$, $[\text{HCO}_3^-]$, $p\text{CO}_2$, $f\text{CO}_2$, pH, $\Omega_{\text{aragonite}}$, and Ω_{calcite} values were determined from DIC, TA, temperature, and salinity data using the dissociation constants of Mehrbach et al., 1973 (as refit by Dickson and Millero, 1987), and borate dissociation constant of Dickson (1990), and the software program of Robbins et al. (2010). In this paper, $p\text{CO}_2$ was used rather than $f\text{CO}_2$, with small differences of $\sim 1\text{--}3 \mu\text{atm}$ between both parameters, while SOCAT data are expressed as $f\text{CO}_2$ (e.g., Bakker et al., 2016). pH is expressed on the seawater scale. Nitrate data were not used in the computation which introduced very minor uncertainty for the calculation of $p\text{CO}_2$, pH, $\Omega_{\text{aragonite}}$, and Ω_{calcite} values.

The error estimates for calculation of $p\text{CO}_2$, pH, $\Omega_{\text{aragonite}}$, and Ω_{calcite} values were undertaken using standard procedures for propagation of uncertainty. Given the analytical uncertainty of the two seawater carbonate chemistry parameters (i.e., DIC and TA; $\pm 1 \mu\text{moles kg}^{-1}$) from replicate measurements of CRMs, the error is estimated at $3 \mu\text{atm}$, 0.003, 0.021, and 0.021, for $p\text{CO}_2$, pH, and $\Omega_{\text{aragonite}}$ and $\Omega_{\text{aragonite}}$ for surface waters, respectively. The calculation error is larger for high $p\text{CO}_2$ ($> 1,000 \mu\text{atm}$)/low pH (< 7.7) waters at up to $15 \mu\text{atm}$, 0.004, 0.023, and 0.026, for $p\text{CO}_2$, pH, and $\Omega_{\text{aragonite}}$ and $\Omega_{\text{aragonite}}$, respectively. Please note that pH, $\Omega_{\text{aragonite}}$, and $\Omega_{\text{aragonite}}$ are dimensionless and thus do not have units. The use of other sets of dissociation constants for calculation of the complete seawater carbonic acid system would introduce additional range of calculation error due to uncertainties in the dissociation constants used, but prescriptions of the calculations are included in the prior paragraph.

Estimates of the Anthropogenic Carbon

Estimates of anthropogenic carbon (i.e., C_{ANT}) were determined using the TrOCA (Tracer combining Oxygen, inorganic Carbon,

and TA) methods first proposed by Touratier and Goyet (2004a,b) and updated by Touratier et al. (2007). This approach allows comparison with recent estimates determined for the western South Pacific Ocean by Wagener et al. (2018). In the Touratier et al.'s (2007) method, changes in the quasi-conservative tracer, TrOCA in individual water masses accounts for changes in carbonate chemistry due to biological influences (e.g., remineralization of organic matter and dissolution of CaCO_3). Differences between current and pre-industrial TrOCA values provide an estimate of anthropogenic carbon (i.e., C_{ANT}) contribution to the water mass. Here, the formulation proposed by Touratier et al. [2007; their equation (11)] is used:

$$C_{\text{ANT}} = ([\text{O}_2] + 1.279 \times (\text{DIC} - \text{TA}/2) - \text{EXP}(7.511 - 1.087 \times 10^{-2} \times \Phi - \times 10^5/\text{TA}^2))/1.279 \quad (6)$$

where Φ is the potential temperature. The uncertainty of the estimate is $\sim 6 \mu\text{moles kg}^{-1}$ (Touratier et al., 2007) with the limitations of the method discussed in this paper and other subsequent papers (e.g., Wagener et al., 2018).

C_{ANT} estimates determined using the TrOCA method for the mixed layer cannot be considered or verified due to euphotic zone biological activity and air–sea gas exchange (Touratier et al., 2007). As with the recent analysis of C_{ANT} by Wagener et al. (2018) in the western South Pacific, C_{ANT} estimates for the Peru–Tahiti section are given below $\sim 100 \text{ m}$ depth.

Comparison With Other Marine Carbonate Chemistry Datasets

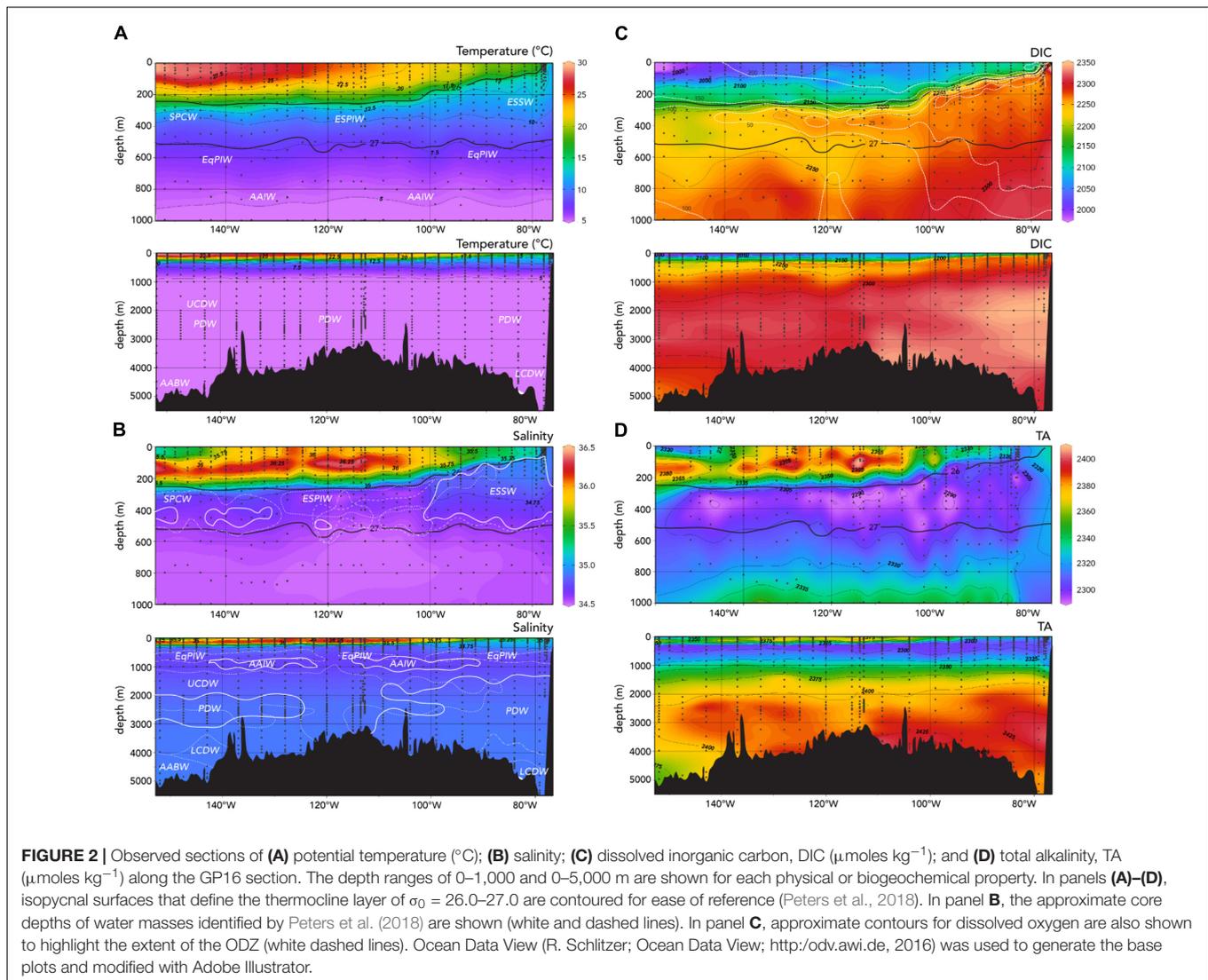
In the section “Discussion,” the GEOTRACES data collected herein are compared with historical data collected in the region. As with other analyses of historical data (e.g., GLODAP-v2; Key et al., 2015; Olsen et al., 2016), deep water is assumed to remain unaltered over the past couple of decades. In the deep eastern Pacific Ocean ($< 3,000 \text{ m}$ deep), Peters et al. (2018) identified the presence of varying amounts of Pacific Deep Water (PDW), Lower Circumpolar Deep Water (LCDP), and Antarctic Bottom Water (ABW). In these deep-water masses, no systematic differences of greater than 0.01 and 0.003 for potential temperature and salinity, and $\leq 2 \mu\text{moles kg}^{-1}$ for DIC and TA between recent and historical data were determined. Thus, there does not appear to be any systematic analytical bias or offsets between historical and recent data for deep water or waters shallower than 3,000 m. As such, the historical data were not corrected for potential offsets given the absence of evidence for such systematic biases.

RESULTS

Water Mass Identification

In a recent paper, Peters et al. (2018) identified nine different water masses below the seasonal thermocline (up to $\sim 200 \text{ m}$)

²<http://www.dickson.ucsd.edu>



using Optimum Multiparameter Analysis (OMPA; Tomczak, 1981). This method provides the fractional composition of a water mass for each sample using definitions of hydrographic properties for individual water mass end members (Table 1). The OMPA identification of water mass using hydrographic properties of potential temperature, salinity, inorganic nutrients (i.e., nitrate, phosphate, silicate), and dissolved oxygen (i.e., Peters et al., 2018) provides useful context for understanding seawater carbonate chemistry across the section from 77°W to 155°W (Figure 2A).

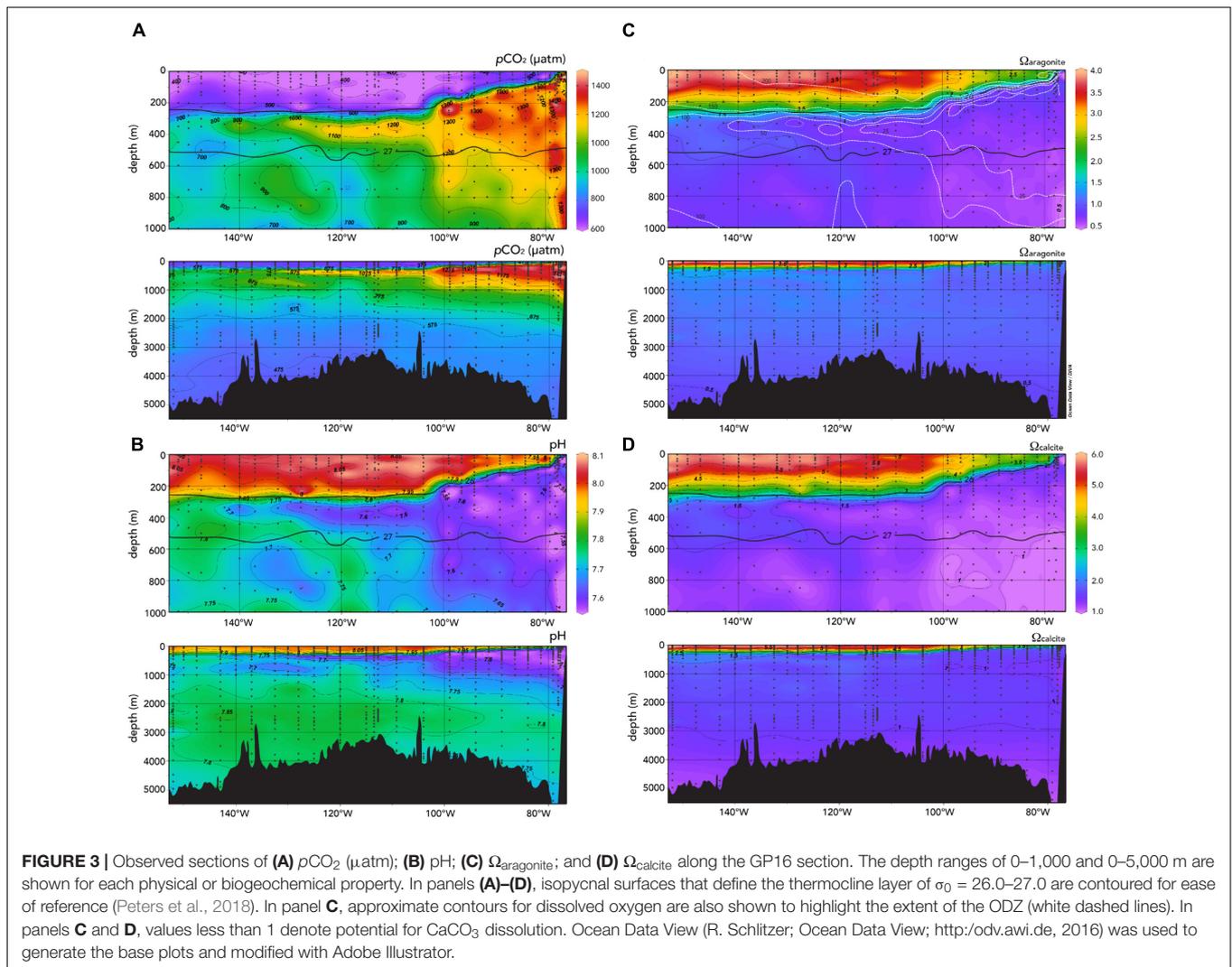
In the thermocline, between the approximate sigma theta density horizons of 26.0 – 27.0 kg m^{-3} , Equatorial Subsurface Water (ESSW) dominates the upper ocean and in particular, it constitutes the low oxygen waters of the eastern tropical South Pacific (~ 100 – 500 m deep; contributions of greater than 60% to the water mass). Moving westward, the water mass merges with Eastern South Pacific Intermediate Water (ESPIW; ~ 220 – 500 m deep) which tends to contribute up to 30% of the water present. In the westernmost part of the section (~ 130 – 155°W) is dominated

by South Pacific Central Water (SPCW; ~ 220 – 500 m deep; Figure 2B); in thermocline waters that are typically less dense than 27.0 kg m^{-3} , and with a fractional contribution up to 60% (Peters et al., 2018). The end-member properties are given in Table 1.

Nutrient-rich intermediate waters below the thermocline (between the approximate sigma theta density horizon of 27.0 and 27.8 kg m^{-3}) can be characterized by the contributions of: (1) Equatorial Pacific Intermediate Waters (EqPIW; ~ 600 – 800 m deep); and (2) Antarctic Intermediate Water (AAIW; ~ 800 – 1000 m deep). Other deeper waters included Upper Circumpolar Deep Water (UCDW), LCDW, and ABW (Figure 2A; see Peters et al., 2018).

Horizontal Gradients in Upper Ocean Variability of Carbonate Chemistry

Surface waters across the Peru–Tahiti section can be conveniently subdivided into three zones, from east to west: (1) upwelling



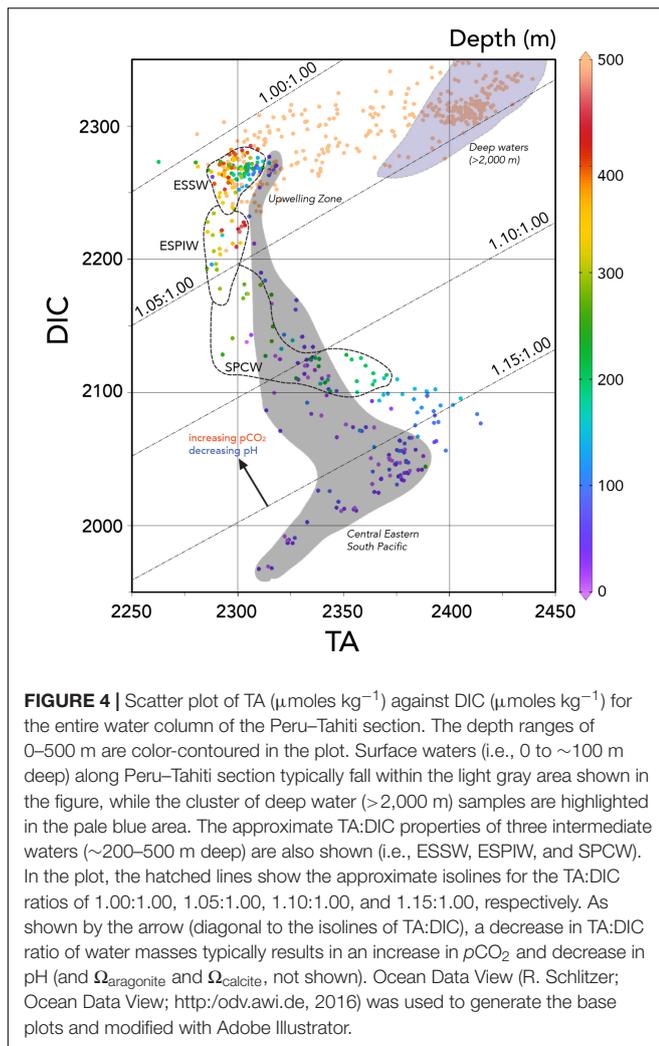
zone near the Peru Coast; (2) Peru current (~ 80 – 90°W); and (3) central eastern South Pacific waters (~ 90 – 150°W).

Surface Waters in the Upwelling Zone Near Peru (~ 76 – 80°W)

The US GEOTRACES Peru–Tahiti section fortunately sampled the upwelling zone close to the Peru coast. In the zone of upwelling, water mass properties of the mixed layer and upper 100 m were as expected for an ODZ influenced region with cooler ($\sim 15^\circ\text{C}$; **Figure 2A**) and fresher (~ 35) waters (**Figure 2B**) that were low in dissolved oxygen ($< 25 \mu\text{moles kg}^{-1}$; **Figure 2C**) and high in inorganic nutrients (i.e., nitrate $> 20 \mu\text{moles kg}^{-1}$).

In this upwelling region, there is very little prior data about marine carbonate chemistry with the exception of earlier transects in 1994 (Millero et al., 1994) and 2009 (Uchida et al., 2011). In the fresher upwelled waters, TA was low ($< 2,310 \mu\text{moles kg}^{-1}$; **Figure 2D**), while DIC was high at $> 2,200 \mu\text{moles kg}^{-1}$ (**Figure 2C**) relative to surface waters elsewhere.

In the upper 100 m, very high $p\text{CO}_2$ values of $> 1,200 \mu\text{atm}$ were observed with surface values as much as $> 800 \mu\text{atm}$ (**Figure 3A**). Such high $p\text{CO}_2$ values would be expected with the very low TA:DIC ratios ($\sim 1.055:1.000$) of the upwelled waters compared to surface waters further west in the central Eastern South Pacific with higher TA:DIC ratios ($\sim 1.15:1.000$; **Figure 4**). The large longitudinal change in surface water carbonate chemistry from the upwelling zone to the central Eastern South Pacific is also shown in **Figure 4** (data shown in the figure under the gray region) and **Figure 5**. Surface waters in the upwelling zone have much higher DIC (by as much as $200 \mu\text{moles kg}^{-1}$) compared to central Eastern South Pacific waters, without much change in alkalinity reflecting the long-term gain of CO_2 in deep and intermediate waters through remineralization of organic matter back to CO_2 . In the plots of **Figure 5**, the relatively cool (15 – 20°C) and fresh (< 35.25), high DIC ($> 2,100 \mu\text{moles kg}^{-1}$) and $p\text{CO}_2$ ($> 600 \mu\text{atm}$), and low pH (< 7.95) waters were observed in the uppermost 5 m in the upwelling region (~ 76 – 80°W).



Previously, surface $p\text{CO}_2$ measurements have not been collected in the upwelling zone close to the Peru coast (i.e., within 2° of latitude of the coast). Limited surface data compiled as part of the Surface Ocean Carbon Atlas effort (e.g., SOCAT, Bakker et al., 2014, 2016) reveal the highest $p\text{CO}_2$ values a little farther offshore at $\sim 600 \mu\text{atm}$ (Figure 6). The US GEOTRACES Peru–Tahiti section observations of the upwelling zone indicate that surface waters have much higher $p\text{CO}_2$ ($> 600 \mu\text{atm}$) than the atmosphere ($\sim 395 \mu\text{atm}$; mean atmospheric $p\text{CO}_2$ values from Easter Island from the NOAA flask sampling network³) with the driving force of air–sea CO_2 gas exchange strongly directed toward a loss of CO_2 from the ocean.

The upwelled water also exhibited pH values lower than 7.55 in the upper 100 m, and less than 7.80 in surface waters (Figures 3B, 5). Furthermore, the CaCO_3 saturation states of the upwelled water were close to 1 and 2.5 for $\Omega_{\text{aragonite}}$ and Ω_{calcite} , respectively (Figures 3C,D). $\Omega_{\text{aragonite}}$ values lower than 1 were observed at 50 m deep indicating conditions favorable for aragonite dissolution. The implication of this finding is that

³<https://www.esrl.noaa.gov/gmd/ccgg/flask.php>

the upwelling is highly likely to bring waters that are potentially corrosive for aragonite (but not calcite) onto the shelf of the Peru coast. As with other coastal zones influenced by upwelling (e.g., Feely et al., 2008), this part of the Peru coast and its marine ecosystem (particularly benthic or pelagic calcifying taxa) will be vulnerable to CaCO_3 dissolution and any augmentation of this driver by OA.

The US GEOTRACES Peru–Tahiti section data revealed high DIC and $p\text{CO}_2$, and low pH waters in the upwelling zone of the eastern South Pacific Ocean. Such ranges in ocean carbonate chemistry are not shown in the interpolated and extrapolated global ocean mean climatologies of DIC, TA, $p\text{CO}_2$, pH, and Ω (e.g., Takahashi et al., 2014), and undersampling of the region.

Peru Current Region Surface Waters ($\sim 80\text{--}90^\circ\text{W}$)

Away from the upwelling zone near the Peru coast, the Peru–Tahiti section sampled across waters associated with the northward flow of the Peru Current (from ~ 80 to 90°W). In this zone, salinity was about 35.2 and temperatures ranged from 18 to 20°C (Figures 2A,B, 5A). The TA values ($\sim 2,330 \mu\text{moles kg}^{-1}$) were higher and DIC ($\sim 2,100\text{--}2,125 \mu\text{moles kg}^{-1}$) concentrations lower than the upwelling zone, but both generally lower than the central eastern South Pacific west of 90°W (Figures 2C,D).

Surface and mixed layer $p\text{CO}_2$ values ranged from about 400 to $450 \mu\text{atm}$ (Figure 3A). Such $p\text{CO}_2$ values are similar to previous north–south observations collected in the SOCAT data (Figure 5, $\sim 450\text{--}550 \mu\text{atm}$; Bakker et al., 2014, 2016). The pH of these northward flowing waters ranged from 7.95 to 8.00 (Figure 3B), while the $\Omega_{\text{aragonite}}$ and Ω_{calcite} values ranged from 2.0 to 2.5 and 3.5 to 4.0, respectively (Figures 3C,D).

Central Eastern South Pacific Surface Waters ($\sim 90\text{--}150^\circ\text{W}$)

In the central Eastern South Pacific, salinity ranged from 35.5 to 36.0 (highest between 100 and 140°W ; Figure 5B), while west of the Peru Current, surface temperatures increased from ~ 20 to $> 28^\circ\text{C}$ (Figures 2A,B, 5A). TA distributions followed a similar pattern to salinity across the section from 90°W (ranging from 2,330 to $2,390 \mu\text{moles kg}^{-1}$; Figure 5D), but DIC decreased from $\sim 2,100$ to $2,000 \mu\text{moles kg}^{-1}$ westward toward 150°W (Figures 2C,D, 5C).

Interestingly, across the section from 90 to 150°W , surface $p\text{CO}_2$ remained fairly constant in the range of $\sim 390\text{--}420 \mu\text{atm}$ (Figures 3C, 5E), while pH ranged from ~ 8.00 to 8.10 (Figure 5F). In Figure 4, surface waters in the central Eastern South Pacific generally lie along a TA:DIC ratio line of $\sim 1.16:1.00$. This underlying chemical state primarily pre-conditions surface waters to have similar $p\text{CO}_2$, pH, $\Omega_{\text{aragonite}}$, and Ω_{calcite} values with secondary modulation of these properties by temperature variations across the region. As shown in Figure 6, there is little $p\text{CO}_2$ data across the region except for transects around 120°W , with this sparse data showing similar ranges to observations collected from the Peru–Tahiti section.

The lack of east to west variability of surface water $p\text{CO}_2$ in the central Eastern South Pacific reflects a competition between a couple of dominant processes: (1) $p\text{CO}_2$ increasing due to

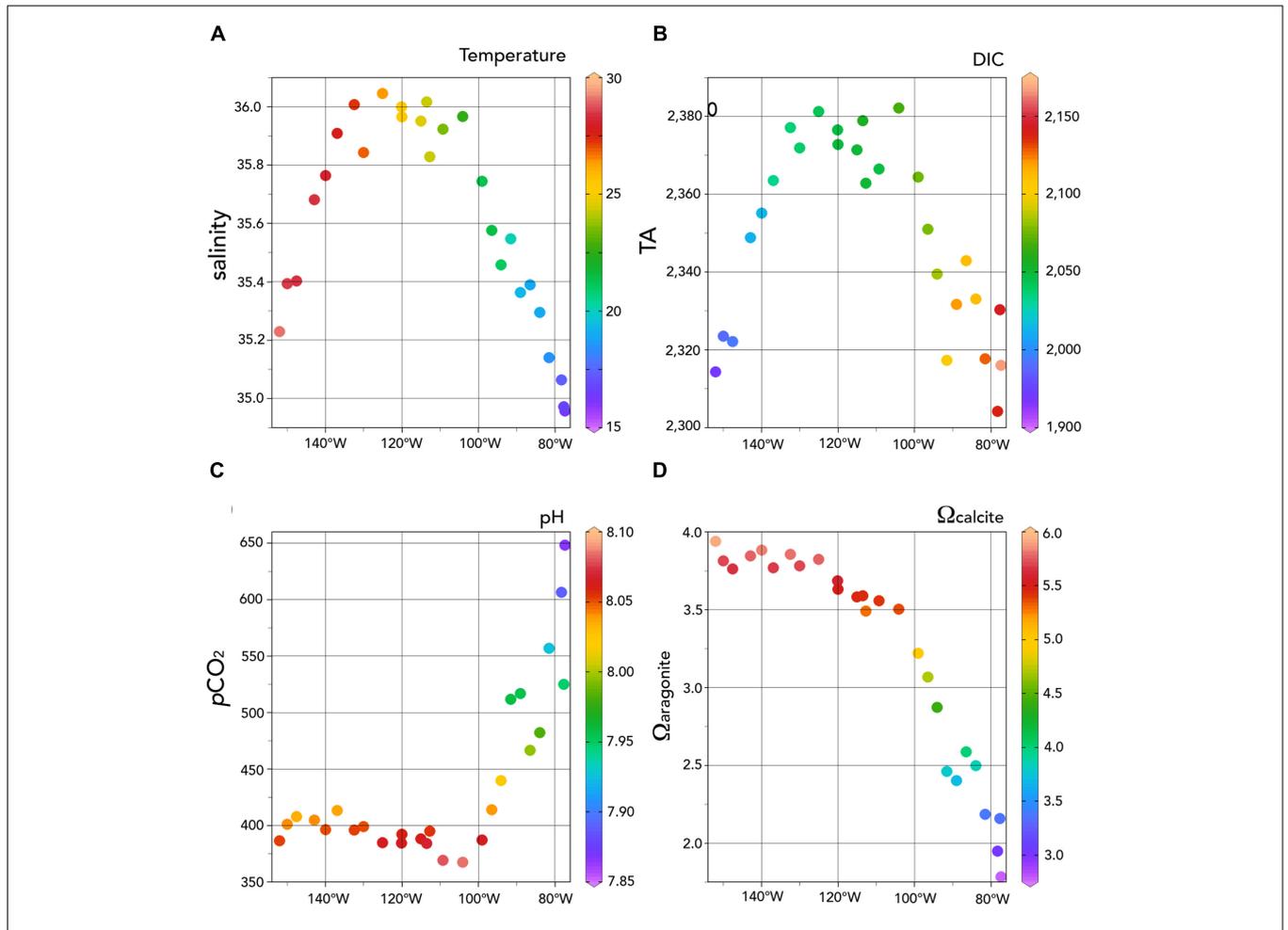


FIGURE 5 | Surface variations of carbonate chemistry for the upper 5 m of the water-column for the 2013 Peru-Tahiti section. **(A)** salinity and temperature (°C); **(B)** TA and DIC ($\mu\text{moles kg}^{-1}$); **(C)** $p\text{CO}_2$ (μatm) and pH; and **(D)** Ω_{calcite} and $\Omega_{\text{aragonite}}$. Ocean Data View (R. Schlitzer; Ocean Data View; <http://odv.awi.de>, 2016) was used to generate the base plots and modified with Adobe Illustrator.

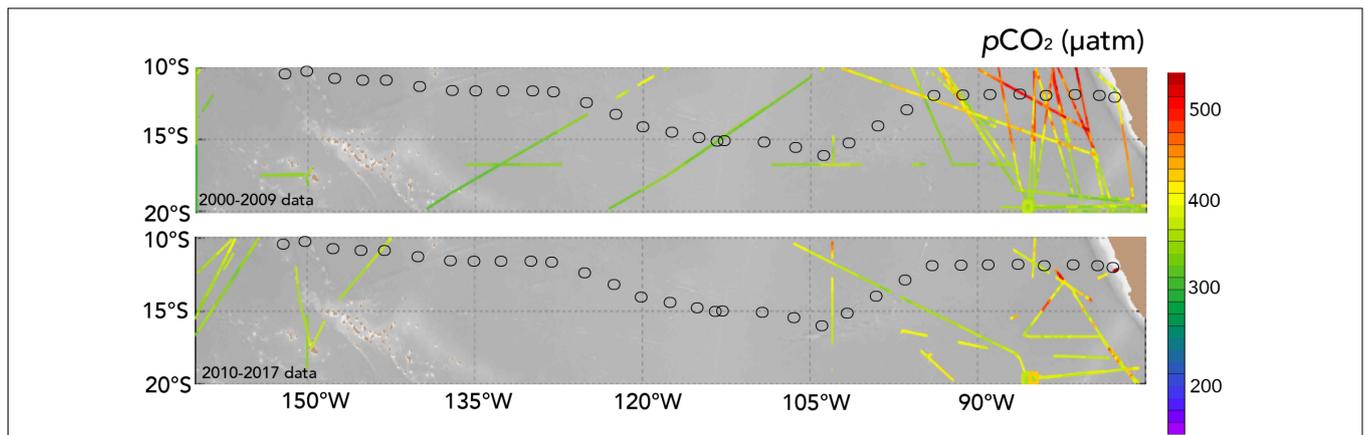


FIGURE 6 | Surface scatter plot of $p\text{CO}_2$ taken from the SOCAT database (Bakker et al., 2014, 2016; version 6) with data from 2000–2009 and 2010–2017. The cruise stations of the Peru–Tahiti section are shown in both panels.

increasing temperature and (2) decreasing due to loss of DIC from east to west. For example, warming acts to increase $p\text{CO}_2$ by $\sim 4.2\%$ per $^\circ\text{C}$ due to thermodynamics of the carbonate system (Zeebe and Wolf-Gladrow, 2001). Thus, a warming of $\sim 8^\circ\text{C}$ will increase by $\sim 160 \mu\text{atm}$. However, the westward loss of DIC of $\sim 100 \mu\text{moles kg}^{-1}$ acts oppositely to decrease $p\text{CO}_2$ by $\sim 170 \mu\text{atm}$. The range of surface $p\text{CO}_2$ values was similar to atmospheric $p\text{CO}_2$ with a small driving force for gas exchange. This finding suggests that CO_2 sink-sources status of the region is close to neutral. Across this zone, pH is also fairly constant (~ 8.05 ; **Figures 3B, 5F**) as are $\Omega_{\text{aragonite}}$ (> 3.5) and Ω_{calcite} (> 5.5), with strong oversaturation with respect to both CaCO_3 minerals (**Figures 3C,D**).

Three intermediate waters have been identified as present across the Peru–Tahiti section, including ESSW, ESPIW, and SPCW (**Figure 2A**; Peters et al., 2018). As the source for upwelled waters, the ESSW waters found near the Peru coast represent the core region of the ODZ (**Figure 2C**). The carbonate chemistry in the core of the ODZ (< 50 m to nearly 600 m) has relatively low TA values relative to other water masses in the Eastern South Pacific ($< 2,310 \mu\text{moles kg}^{-1}$; **Figure 2D**), and high DIC values at $> 2,200 \mu\text{moles kg}^{-1}$ (**Figure 2C**). The TA and DIC properties of the ESSW in the core of the ODZ were very similar to upwelled water (**Figure 4**). The only difference between these two water masses is that the TA value of surface waters is approximately 10–20 $\mu\text{moles kg}^{-1}$ higher. This can be explained by the difference in nitrate concentrations between the ESSW (~ 20 – $35 \mu\text{moles kg}^{-1}$) and surface waters (~ 10 – $15 \mu\text{moles kg}^{-1}$). Since nitrate contributes to alkalinity, the TA + nitrate values from the ESSW and surface waters were very similar.

The OMPA analyses of Peters et al. (2018) indicated a transition westward from ESSW waters to ESPIW water, and further west merging into SPCW. Across the Peru–Tahiti section, DIC decreases by ~ 100 – $150 \mu\text{moles kg}^{-1}$ from the waters of the ESSW to the SPCW, while TA does not change substantively (**Figure 4**). In concert with these latitudinal water mass changes, and changes in DIC and TA, $p\text{CO}_2$ values decrease westward along the section (**Figure 3A**), while pH, $\Omega_{\text{aragonite}}$, and Ω_{calcite} all increase (**Figures 3B–D**).

Deep Water Variability of Carbonate Chemistry

The deeper water masses of the Eastern South Pacific have also been identified through the OMPA analyses of Peters et al. (2018). As one would expect, the deep water DIC and TA increase with depth (**Figures 2C,D, 7A,B**) reflecting the gain over time of CO_2 from remineralization of sinking organic matter, dissolution of CaCO_3 minerals. The increase of TA to DIC is approximately in the ratio of two to one (i.e., $\sim 100 \mu\text{moles kg}^{-1}$ TA increase compared to $\sim 50 \mu\text{moles kg}^{-1}$ DIC increase in deep waters compared to intermediate waters). While there is source water variability in the carbonate chemistry of the different deep-water masses, dissolution of CaCO_3 at depth seems to dominate relative to the biological pump of carbon. The highest $p\text{CO}_2$ ($> 1,500 \mu\text{atm}$; **Figure 7C**) and lowest pH values (**Figure 7D**) were observed in intermediate waters (~ 200 – $1,000$ m deep)

across the section. The profiles of Ω_{calcite} and $\Omega_{\text{aragonite}}$ shown in **Figures 7C,D** show highly variable depth ranges for lysocline depth (i.e., $\Omega = 1$). In the ODZ region, the lysocline depths are shallow for calcite (~ 100 m) and aragonite (~ 100 m). They are much deeper in the central Pacific at $> 4,000$ and $\sim 1,000$ m for calcite and aragonite, respectively.

In the deep waters below 2,000 m, there is little change of $p\text{CO}_2$, pH, $\Omega_{\text{aragonite}}$, and Ω_{calcite} relative to the shallower intermediate waters (**Figures 3A–D, 7C,D**).

Is Different Seawater Carbonate Chemistry Observable in the Deep Hydrothermal Plume Originating at the East Pacific Rise?

As reported previously, a large trace element and isotope enriched hydrothermal plume (i.e., Eastern Boundary Plume, EBP; Peters et al., 2018), originating from the East Pacific Rise (located at $\sim 113^\circ\text{W}$), has been shown to extend 4,000 km westward across the Pacific (Resing et al., 2015; Lupton and Jenkins, 2017; Jenkins et al., 2018; **Figures 2C,D**). Hydrothermal plume tracers such as ^3He , radiocarbon, and other noble gases were primarily found at depths of $2,500 \pm 200$ m, and associated with altered TEI chemistry and scavenging in the plume waters (Fitzsimmons et al., 2017; Buck et al., 2018; Moffett and German, 2018; Pavia et al., 2018). Co-located at depth with the EBP, the DIC and TA, and other carbonate parameters were not markedly different to shallower and deeper waters of the PDW. Thus, the EBP was not observable with marine carbonate parameters on this section.

DISCUSSION

Changes in Carbonate Chemistry Across the Section

The Eastern South Pacific Ocean has been significantly undersampled compared to other regions of the global ocean with regard to marine biogeochemical properties and carbonate chemistry. Over the last 30 years, only two other cruises collecting high-quality carbonate data have been conducted (Millero et al., 1994; Uchida et al., 2011) at similar latitude to the US GEOTRACES Peru–Tahiti section. The CLIVAR P6 cruise sampled in the South Pacific at 30°S but considerably south of the GEOTRACES section (~ 10 – 15°S). Other data include north–south section collected between 1991 and 1994 (e.g., Feely et al., 1994; Takahashi et al., 1995; Rubin et al., 1998). The sampling in 1991, 1994, and 2013 also occurred during neutral El Niño–Southern Oscillation (ENSO) phases, and thus do not represent periods undergoing climatic episodes of either El Niño or La Niña phases.

As demonstrated by Santer et al. (2011), it can take a decade or more for significant changes in the ocean and atmosphere to become evident upon data analysis. Keller et al. (2014) have demonstrated $p\text{CO}_2$ and pH observations needed to be made for at least 12 years and ~ 10 – 30 years for DIC in the ocean, while long-term open-ocean time-series have demonstrated decadal trends with data collected for more than 20 years (e.g., Bates et al., 2014). Here, the Peru to Tahiti section data seawater carbonate

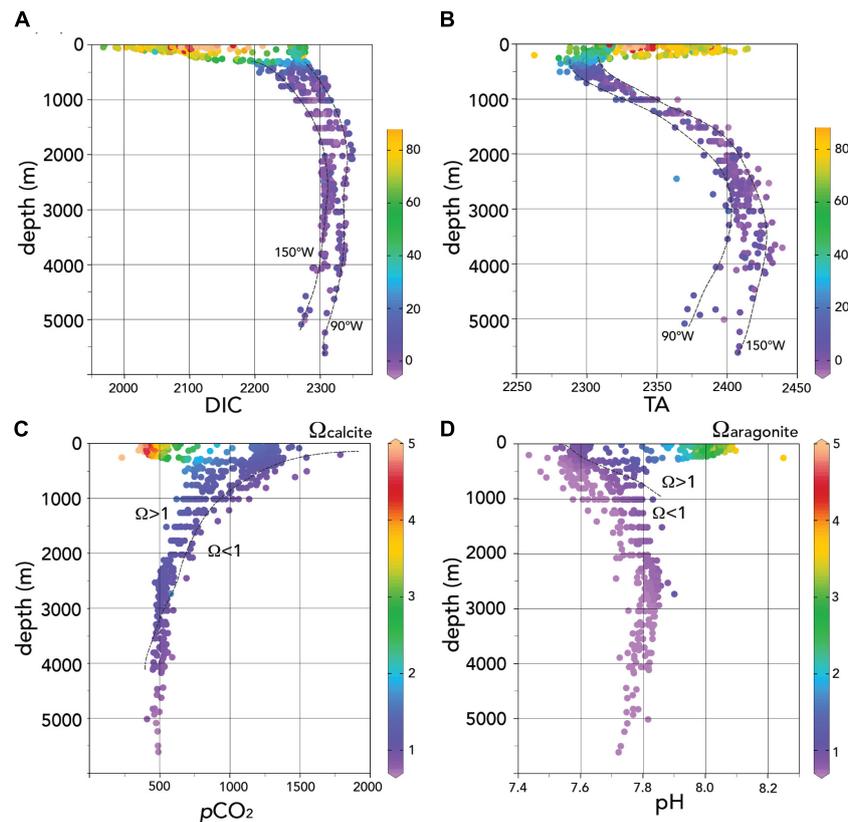


FIGURE 7 | Water column profiles of seawater carbonate chemistry data for the entire 2013 Peru–Tahiti section. **(A)** DIC ($\mu\text{moles kg}^{-1}$) shown against depth (m). The color range indicates the C_{ANT} values ($\mu\text{moles kg}^{-1}$) determined using the TrOCA approach (Touratier et al., 2007). **(B)** TA ($\mu\text{moles kg}^{-1}$) shown against depth (m). The color range indicates the C_{ANT} values ($\mu\text{moles kg}^{-1}$) determined using the TrOCA approach (Touratier et al., 2007). **(C)** $p\text{CO}_2$ (μatm) shown against depth (m). The color range indicates the Ω_{calcite} values. **(D)** pH shown against depth (m). The color range indicates the $\Omega_{\text{aragonite}}$ values. In panels **A** and **B**, the easternmost and westernmost profiles are shown by the dashed lines. In panels **C** and **D**, Ω values of approximately 1 are shown by the dashed lines (with $\Omega > 1$ and $\Omega < 1$ shown on the plots). Ocean Data View (R. Schlitzer; Ocean Data View; <http://odv.awi.de>, 2016) was used to generate the base plots and modified with Adobe Illustrator.

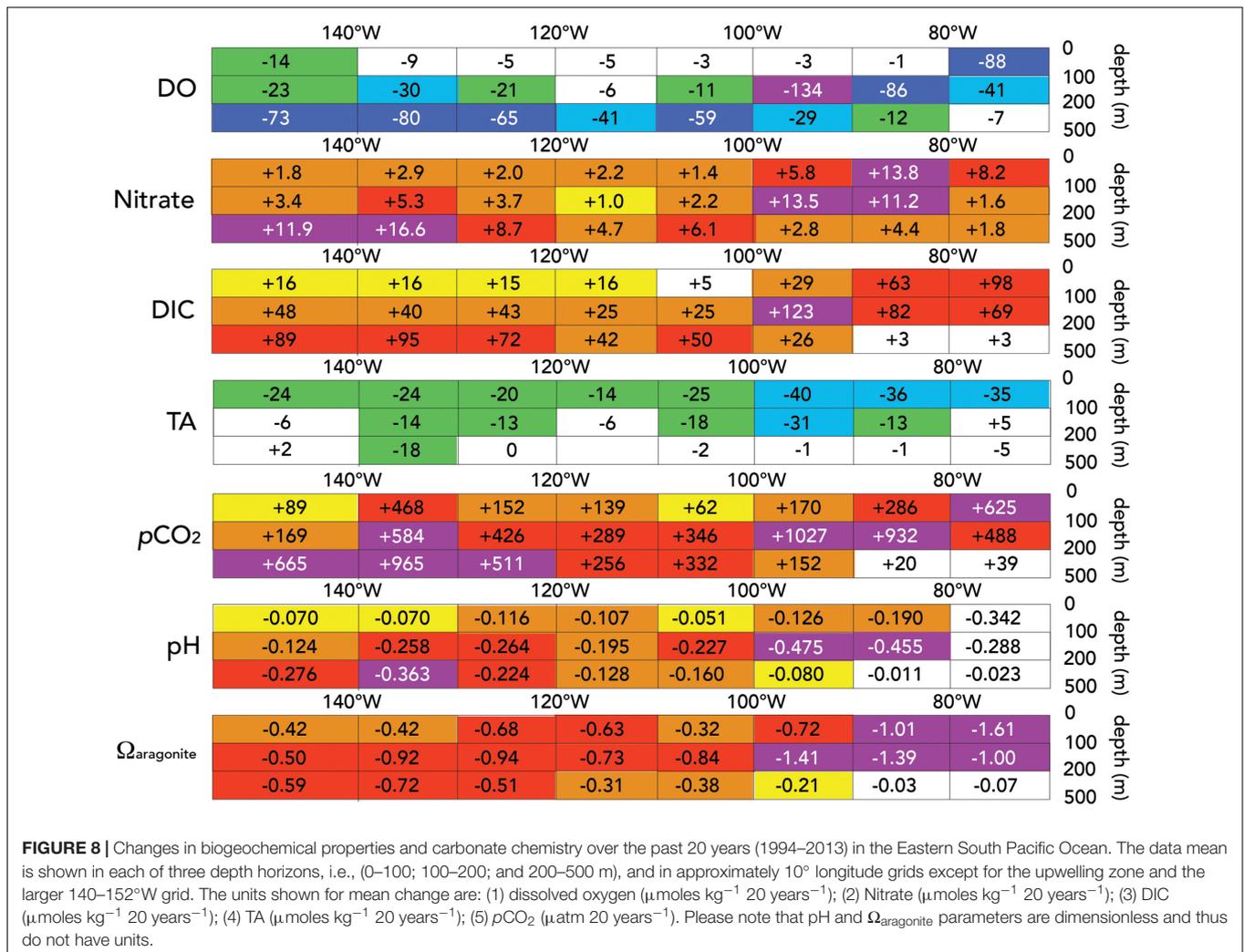
chemistry data are compared to the Millero et al.'s (1994) data and crossover data to establish if marine biogeochemical changes can be determined over the past 20 years. The sampling interval between the Uchida et al. (2011) data collection are, however, too short to establish more than direction and possible magnitude of change in the region of the US GEOTRACES Peru–Tahiti section data.

In other ocean basins, the repeat hydrography and carbonate chemistry sampling has been very useful for demonstrating inventories of anthropogenic CO_2 using tracers such as C^* (Gruber et al., 1996; Sabine et al., 2004), TrOCA (Touratier et al., 2007), and other tracers (e.g., Khatiwala et al., 2013). In the Pacific Ocean, changes in these tracers over time using data from sections very close to each other have been used to examine rates of anthropogenic CO_2 uptake (e.g., Azouzi et al., 2009; Murata et al., 2010; Kouketsu et al., 2013; Carter et al., 2017; Wagener et al., 2018). The Millero et al. (1994) sampling across the Eastern South Pacific in 1994 was conducted farther south by about 4° of latitude (Figure 1), while the mean difference in station longitude was about 0.2° , compared to the 2013 cruise track. The sampling intervals were also

different with higher vertical resolution of the upper water column undertaken during the US GEOTRACES Peru–Tahiti section.

Here, in the first approach, dissolved oxygen, nitrate, and carbonate chemistry data are compared between both sections (1994 and 2013) by binning data into three depth zones of interest (i.e., 0–100; 100–200; and 200–500 m), and grids of 10° longitude. This provides sufficient data to compare surface (0–100 m, the section “Horizontal Gradients in Upper Ocean Variability of Carbonate Chemistry”) and intermediate waters (200–500 m; the section “Deep Water Variability of Carbonate Chemistry”) across the Peru–Tahiti section (Figure 8).

In Figure 8, a comparison of Millero et al. (1994) and GEOTRACES data (this data) are shown for dissolved oxygen, nitrate, DIC, TA, $p\text{CO}_2$, pH, and $\Omega_{\text{aragonite}}$ for the three depth zones of interest. There were small differences in dissolved oxygen content of surface waters (0–100 m) with a greater mean decrease of $\sim 14 \mu\text{moles kg}^{-1}$ in the westernmost part of the section (Figure 8). However, in surface of the upwelling zone, DO contents were substantially lower by an average $\sim 88 \mu\text{moles kg}^{-1}$. In transition waters (below 100 m) and



the intermediate waters from ESSW to SPCW, very significant differences in dissolved oxygen of ~ 40 – 134 $\mu\text{moles kg}^{-1}$ were observed (Figure 8). Nitrate contents also showed significant differences from ~ 2.8 to 16.6 $\mu\text{moles kg}^{-1}$ higher in 2013 (Figure 8). The largest DO nitrate differences appeared to occur in the core of the ESSW and the SPCW at the westernmost part of the Peru–Tahiti section.

Seawater DIC was also higher in 2013 across the Peru to Tahiti section. In contrast, TA had much smaller changes (Figure 8) with the mean change over the section close to zero. In the surface waters, higher values of ~ 16 $\mu\text{moles kg}^{-1}$ west of 100°W in 2013 compared to 1994. Such findings were expected given that similar changes would be expected from uptake of anthropogenic CO_2 by the ocean (Figure 8; Bates et al., 2014). However, in the intermediate waters, DIC was higher in 2013 compared to 1994 by ~ 40 – 120 $\mu\text{moles kg}^{-1}$ across the Peru–Tahiti section (Figure 8C), about three to eight times that expected from uptake of anthropogenic CO_2 into the ocean from the atmosphere. The mean $p\text{CO}_2$ in intermediate waters appeared higher by ~ 200 – $1,000$ μatm (Figure 8E), particularly west of 80°W and in the region of the SPCW (~ 120 – 155°W ; Peters et al., 2018). The

pH of intermediate waters was also lower in 2013 by 0.10 to as much as 0.45 (Figure 8F), while $\Omega_{\text{aragonite}}$ was lower by 0.2 to 1.4 (Figure 8).

Such changes in dissolved oxygen, nitrate, and carbonate chemistry appear difficult to reconcile with previous estimate of DO increases in the ODZ (e.g., Stramma et al., 2008). Direct comparison of the 1994 and 2013 sections may not be applicable here due to the latitudinal difference of at least 4° of latitude between the two sections. It seems likely that the 1994 section did not sample the core of the ODZ, whereas the 2013 US GEOTRACES section did.

The second approach is to compare stations from the 2013 US GEOTRACES section with proximal crossover stations sampled between 1991 and 1994 (i.e., Feely et al., 1994; Millero et al., 1994; Takahashi et al., 1995; Rubin et al., 1998; as part of the World Ocean Circulation Experiment, WOCE, datasets). From east to west, these crossover locations approximate the locations of the three intermediate waters, ESSW, ESPIW, and SPCW. A comparison to earlier data collected from 1991 to 1994 suggests that surface DIC and $p\text{CO}_2$ have increased by as much as 3 and 20%, respectively, while pH and saturation state for

TABLE 2 | Carbonate chemistry changes from 1991/1994 to 2013 at select crossover locations in the South Pacific Ocean.

Crossover location	DO	Nitrate ($\mu\text{moles kg}^{-1}$)	DIC	$p\text{CO}_2$ (μatm)	pH	$\Omega_{\text{aragonite}}$	Reference
Surface (0–100 m)							
~84°W	+37.4	+7.3	+45.9	+21	−0.018	−0.34	Rubin et al., 1998
~102°W	+3.7	+0.9	+2.6	+3	−0.001	−0.20	Takahashi et al., 1995
~135°W	−10.3	+0.3	+5.0	+62	−0.063	−0.49	Feely et al., 1994
Intermediate waters (~200–500 m)							
~84°W	−2.0	+2.0	+9.0	+78	−0.045	−0.13	Rubin et al., 1998
~102°W	−43.5	+4.9	+31.5	+147	−0.091	−0.31	Takahashi et al., 1995
~135°W	−17.4	+5.3	+45.4	+98	−0.078	−0.45	Feely et al., 1994

aragonite ($\Omega_{\text{aragonite}}$) have decreased by as much as 0.063 and 0.54, respectively (Table 2).

In intermediate waters (~200–500 m), dissolved oxygen has decreased (loss of up to $-43 \mu\text{moles kg}^{-1}$) and nitrate increased (gain of up to $5 \mu\text{moles kg}^{-1}$) over the past 20 years (Table 2). This coincides with previous reports of increased denitrification, increased anoxia, and expansion of Pacific Ocean and other ODZs (e.g., Stramma et al., 2008; Keeling et al., 2010; Stramma et al., 2010; Bopp et al., 2013; Horak et al., 2016). The comparison of GEOTRACES data here with older data appears to confirm a westward expansion of the ODZ across the central Eastern South Pacific Ocean. Such changes have substantial implications for the studies of TEIs, their variability, and scavenging, in the Eastern Pacific Ocean (e.g., Black et al., 2018; Buck et al., 2018; Lam et al., 2018; Moffett and German, 2018). Such changes in the DIC content of intermediate waters (~200–500 m) suggest the expansion of high-DIC waters westward in conjunction with the expansion of the ODZ from off the Peru coast. Over the same period, DIC and $p\text{CO}_2$ increased by as much as $+45 \mu\text{moles kg}^{-1}$ and $+145 \mu\text{atm}$, respectively (Table 2), while pH and $\Omega_{\text{aragonite}}$ decreased by -0.091 and -0.45 , respectively (Table 2). These changes are much greater than the open-ocean surface water pH changes (e.g., $0.017 \text{ decade}^{-1}$) over the past 30 years associated with uptake of anthropogenic CO_2 and OA (Bates et al., 2014). The changes in the seawater carbonate chemistry of intermediate waters (~200–500 m) in the eastern Pacific Ocean suggest the expansion of high-DIC and high CO_2 , and low pH and low $\Omega_{\text{aragonite}}$ waters westward in conjunction with the expansion of the ODZ from off the Peru coast.

The Potential Contribution of Anthropogenic CO_2 to the Observed Changes in the Eastern South Pacific Ocean

A third approach is to use the TrOCA method (Touratier et al., 2007) to determine the contribution of anthropogenic CO_2 to carbonate chemistry as undertaken for the South and tropical Pacific Ocean (e.g., Murata et al., 2007; Azouzi et al., 2009; Kouketsu et al., 2013; Wagener et al., 2018). The TrOCA values of C_{ANT} for the 2013 US GEOTRACES Peru–Tahiti are shown in Figure 9. The highest values of C_{ANT} range from ~40 to $70 \mu\text{moles kg}^{-1}$ in the upper 100 to 200 m which is similar to TrOCA-derived C_{ANT} values reported by Wagener et al. (2018)

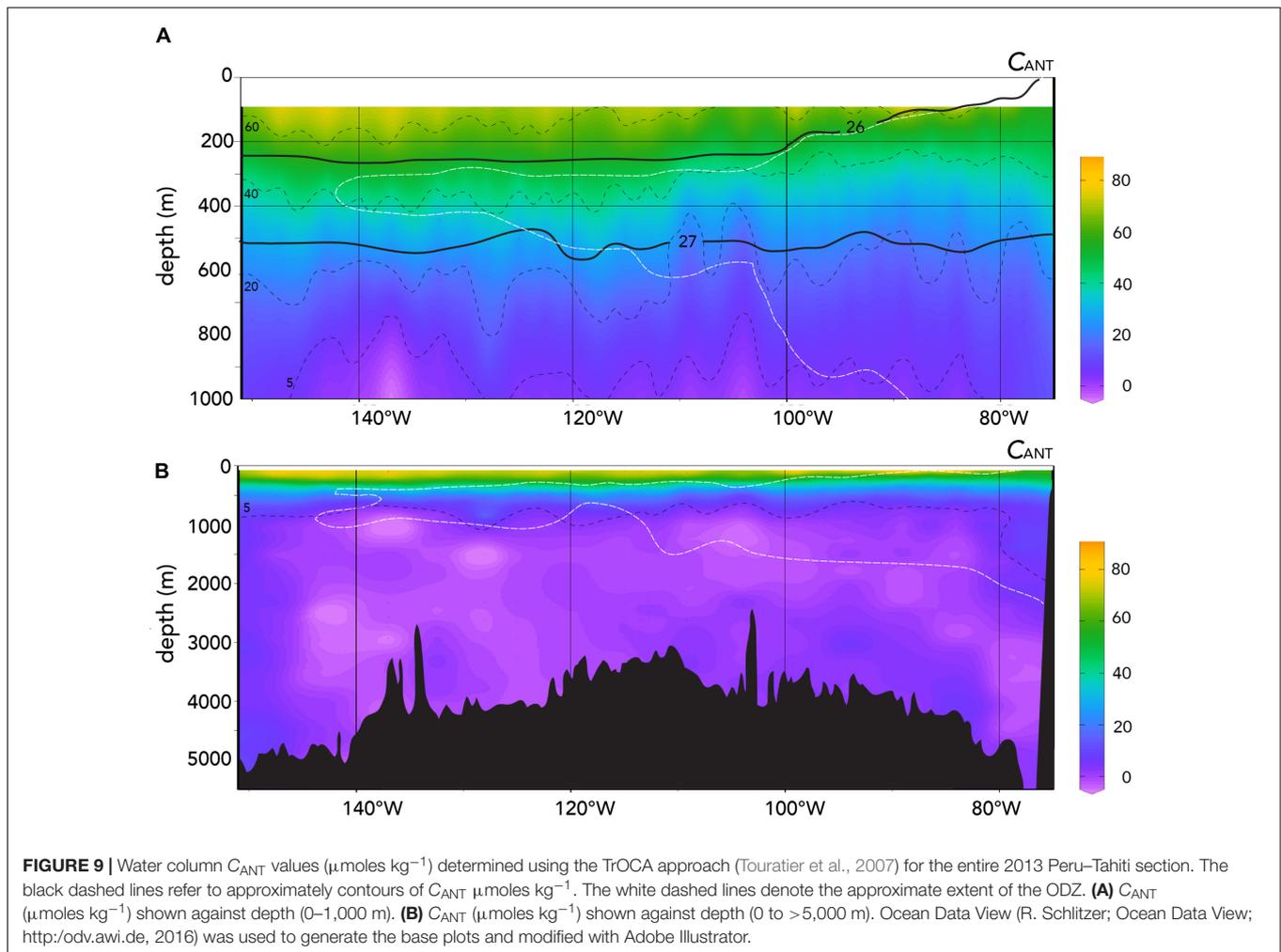
in the western South Pacific Ocean. The TrOCA values of C_{ANT} values rapidly decrease with depth in the ~300–600 m zone (i.e., in σ_θ range of 26–27; Figure 9A). Below ~600 m (and especially in deep waters) and in water masses with a density higher than 27.0, C_{ANT} values are low (<7 to $-3 \mu\text{moles kg}^{-1}$; Figures 9A,B and Table 3). Such C_{ANT} values are within the error of the TrOCA method (e.g., Touratier et al., 2007; Wagener et al., 2018) and indicate negligible contributions of anthropogenic CO_2 to water mass carbonate chemistry.

A comparison of TrOCA values for C_{ANT} for 1994 (Millero et al., 1994) and 2013 US GEOTRACES Peru–Tahiti sections in the eastern South Pacific Ocean is given in Table 3. The values for C_{ANT} and its change of the 1994–2013 period (i.e., ΔC_{ANT}) were determined for four depth zones (i.e., 100–200; 200–500; 500–1000; $>1,000$ m) for three geographic regions (i.e., 76–100; 100–125; and 125–125°W), and for density classes previously used and defined as a range of σ_θ values by Kouketsu et al. (2013). The classification of C_{ANT} and ΔC_{ANT} by depth zone given in Table 3 for 1994 and 2013 data also coincides with near-identical density classes and ranges. Although the 1994 and 2013 Peru–Tahiti sections did not overlap geographically (Figure 1), both datasets for the depth ranges chosen, and σ_θ definitions had nearly identical mean and range σ_θ values (Table 3). The similarity of water mass density provides confidence that near-identical water masses are compared here between 1994 and 2013.

Surface Water (100–200 m) Attribution of Carbonate Chemistry Changes

In the region of upwelling and the Peru current (i.e., 76–100°W), the ΔC_{ANT} change between 1994 and 2013 in the 100–200 m depth zone is close to zero ($+0.4 \mu\text{moles kg}^{-1}$; Table 3). The near zero change in ΔC_{ANT} compares to observed DIC changes of 69–123 $\mu\text{moles kg}^{-1}$ over the 1994–2014 period (Figure 8) indicating that anthropogenic CO_2 uptake has not influenced DIC and other carbonate chemistry changes, but likely reflects changes in the upwelling and expansion of the ODZ in the region (given the decreases in oxygen and increases in inorganic nutrients; Figure 8).

To the west of 100°W, C_{ANT} values are higher in the 75–80 $\mu\text{moles kg}^{-1}$ range (Table 3A) with the mean ΔC_{ANT} increasing from $+12.5$ to $+22.5 \mu\text{moles kg}^{-1}$ in the 125–155°W zone for the 1994–2013 period. By density class, waters with σ_θ values of <25.6 (that approximate the 100–200 m depth) show an increase of ΔC_{ANT} of $18.7 \mu\text{moles kg}^{-1}$ (Table 3B). Such increases in



anthropogenic CO_2 contents of the uppermost waters (below the mixed layer) are about 50% of the observed DIC changes of $\sim 25\text{--}48 \mu\text{moles kg}^{-1}$ (Figure 8). In the $125\text{--}155^\circ\text{W}$, the ΔC_{ANT} increase is about $1.1 \mu\text{moles kg}^{-1} \text{ year}^{-1}$ increase between 1994 and 2013, and very similar to the upper ocean estimate of $1.1\text{--}1.2 \mu\text{moles kg}^{-1} \text{ year}^{-1}$ increase due to anthropogenic CO_2 determined for the western South Pacific Ocean by Azouzi et al. (2009) and Wagener et al. (2018). Such changes in carbonate chemistry due to the uptake of anthropogenic CO_2 are equivalent to decreases of pH and $\Omega_{\text{aragonite}}$ of $-0.0018 \text{ year}^{-1}$ and -0.01 year^{-1} in the South Pacific Ocean. Such recent changes of pH and $\Omega_{\text{aragonite}}$ are lower by 20–50% than observed in the central Pacific by Carter et al. (2017) and the western South Pacific Ocean by Wagener et al. (2018), but within the typical range observed at the global ocean time-series sites over the past 30 years (Bates et al., 2014).

Waters examined in the region with σ_θ values of <25.6 , ranged in thickness from <100 to 200 m at most across the Peru–Tahiti section. The ΔC_{ANT} changes observed between 1994 and 2013 are equivalent to a change of approximately $+0.1$ to $+0.2 \text{ mol m}^{-2} \text{ year}^{-1}$ due to anthropogenic CO_2 uptake. This

rate is significantly lower than the rates determined by Kouketsu et al. (2013; $+0.4$ to $+0.6 \text{ mol m}^{-2} \text{ year}^{-1}$) and Murata et al. (2010; $+0.5$ to $+1.0 \text{ mol m}^{-2} \text{ year}^{-1}$) in other regions of the South Pacific Ocean.

Upper Ocean (200–500 m) Attribution of Carbonate Chemistry Changes

In waters with σ_θ values of 25.6–26.8 range (Table 3B), or waters at depths of 200–500 m (Table 3A), the ΔC_{ANT} changes observed between 1994 and 2013 are slightly positive ($+2.46 \mu\text{moles kg}^{-1}$ for σ_θ of 25.6–26.8) to negative (-2.6 to $-8.4 \mu\text{moles kg}^{-1}$, 200–500 m). Similar observations are reported by Kouketsu et al. (2013) for mode and intermediate waters of the South Pacific Ocean. In the $125\text{--}150^\circ\text{W}$, the reduction of anthropogenic CO_2 in these water masses partly mitigates the substantial increases in DIC of $72\text{--}95 \mu\text{moles kg}^{-1}$ (Figure 8) by 10–20%. The substantial changes in carbonate chemistry in waters with σ_θ values of 25.6–26.8 or found at 200–500 m depth appear primarily related to the shoaling of the high DIC and $p\text{CO}_2$, and low pH and $\Omega_{\text{aragonite}}$ waters of the ODZ.

The caveat to the above finding of changes in the chemistry of the ODZ is that there remains disagreement about the expansion

TABLE 3 | Mean and standard deviation estimates of C_{ANT} values for our depth zones (i.e., 100–200; 200–500; 500–1,000; and >1,000 m depth) for 1994 and 2013 data (**A**).

A	100–200 m		ΔC_{ANT}	200–500 m		ΔC_{ANT}	500–1000 m		ΔC_{ANT}	>1,000 m		ΔC_{ANT}
	1994	2013		1994	2013		1994	2013		1994	2013	
Geographic zone and depth												
76–100°W												
<i>n</i>	37	35		101	54		137	37		454	57	
C_{ANT}	51.2	52.6	+0.4	26.8	24.1	–2.6	6.3	3.7	–2.6	3.2	1.9	–1.9
Std. dev. C_{ANT}	13.9	17.9		11.4	11.0		4.7	5.18		3.0	4.0	
Mean σ_θ	25.93	26.19		26.64	26.71		27.21	27.21		27.65	27.67	
Low σ_θ	25.32	25.29		26.07	26.29		26.93	27.00		27.35	27.38	
High σ_θ	26.51	26.49		27.04	27.01		27.40	27.39		27.75	27.74	
100–125°W												
<i>n</i>	26	12		70	32		77	22		291	101	
C_{ANT}	64.0	76.5	+12.5	43.7	35.3	–8.4	12.99	2.81	–10.2	6.5	–0.3	–6.8
Std. dev. C_{ANT}	3.8	4.3		17.8	21.2		7.7	4.5		3.6	3.4	
Mean σ_θ	25.01	25.18		25.97	26.40		27.17	27.21		27.64	27.68	
Low σ_θ	24.48	24.75		25.48	25.46		26.93	26.99		27.35	27.37	
High σ_θ	25.61	25.46		27.03	26.99		27.37	27.37		27.75	27.72	
125–155°W												
<i>n</i>	36	17		87	34		87	25		264	81	
C_{ANT}	56.2	78.5	+22.3	41.3	36.0	–5.2	18.5	4.1	–14.1	9.9	0.7	–9.3
Std. dev. C_{ANT}	6.0	5.4		11.2	20.2		5.6	9.5		3.1	5.3	
Mean σ_θ	24.64	24.62		25.91	26.37		27.15	27.22		27.66	27.67	
Low σ_θ	24.09	23.54		24.92	25.40		26.76	27.00		27.36	27.36	
High σ_θ	25.06	25.32		26.95	27.00		27.40	27.37		27.78	27.79	
B			<i>n</i>	1994				<i>n</i>	2013		ΔC_{ANT}	
By density class (σ_θ values)												
$\sigma_\theta < 25.6$			99	58.1 ± 9.7				64	76.8 ± 6.4		+18.7	
$\sigma_\theta 25.6–26.8$ (mode waters)			258	36.9 ± 11.6				120	39.3 ± 17.9		+2.5	
$\sigma_\theta 26.8–27.6$ (intermediate)			301	9.3 ± 7.9				84	4.9 ± 7.7		–4.4	
$\sigma_\theta > 27.6$ (deep waters)			1001	5.8 ± 4.0				239	0.8 ± 4.3		–5.0	

This includes mean σ_θ value and σ_θ ranges for these water masses, and ΔC_{ANT} changes between 1994 and 2013. In **B**, C_{ANT} and ΔC_{ANT} values are given for four water-masses defined by σ_θ values (Kouketsu et al., 2013). In both approaches, the definitions of water masses by depth range or σ_θ have near-identical mean σ_θ values and ranges.

of global ODZs and timing relative to past contractions of ODZs (e.g., Deutsch et al., 2014; Tems et al., 2014; Yang et al., 2017). If such rapid change in pH and CO_2 –carbonate chemistry has occurred over the past 20 years in the central Eastern South Pacific (and especially in waters of the ODZ), then there are significant implications for changing the thermodynamics and solubility of intermediate water TEIs in the south Pacific Ocean (e.g., Moffett and German, 2018).

Intermediate and Deep Ocean (>500 m) Attribution of Carbonate Chemistry Changes

In deeper waters, classified by depth range or σ_θ the ΔC_{ANT} changes are all negative from –1.9 to –14.1 $\mu\text{moles kg}^{-1}$ (almost –0.7 $\mu\text{moles kg}^{-1} \text{ year}^{-1}$; Table 3). The contribution of anthropogenic CO_2 to the water column below 500 m also decreases from east to west. Such findings of negative ΔC_{ANT} values over the past 20 years suggest that intermediate and deep water may be more influenced by mixing and

entrainment of older waters through PDW circulation with negligible anthropogenic CO_2 contributions to carbonate chemistry.

CONCLUSION

The carbonate chemistry observations of the 2013 US GEOTRACES Peru–Tahiti section show a substantial change from 1994 to 2013 in the chemical environment (e.g., DIC, $p\text{CO}_2$, pH), of intermediate waters across the Eastern South Pacific associated with the apparent expansion of the ODZ. In the shallow waters masses (~200–800 m), such as the ESSW in the eastern section of the South Pacific, $p\text{CO}_2$ has increased over the past 20 years by as much as 20–40 μatm , with decreases in pH of 0.011–0.023, and $\Omega_{\text{aragonite}}$ of 0.03. In waters with the greatest contribution of SCPW, ESPIW and to a lesser extent ESSW water masses, the westward expansion of the anoxic zone has substantially changed the chemical environment of waters

resident between 200 and 600 m deep. In such waters, $p\text{CO}_2$ has increased over the past 20 years by as much as 600 μatm , with pH decreasing by up to 0.36, and $\Omega_{\text{aragonite}}$ by 0.72. Given such chemical changes in the 200–600 m deep zone of the South Pacific, greater remineralization of sinking organic carbon (and perhaps minor contributions from dissolution of CaCO_3) would be expected. Particle production, aggregation, and disaggregation dominate carbon cycling and, interception and transformation of the sinking particle flux in this region (Lam et al., 2018). As such, and in light of the chemical changes in the relatively shallow thermocline, substantial alteration of the rain-ratio of organic carbon and CaCO_3 has likely occurred over the past two decades. It appears that the contribution of anthropogenic CO_2 to waters deeper than 200 m or σ_θ values greater than 25.6 has actually declined of the past 20 years. As such, uptake of anthropogenic CO_2 has not contributed to the substantial changes in carbonate chemistry observed in this region of the eastern South Pacific Ocean. The exception to this finding is that uptake of anthropogenic CO_2 has contributed $\sim 50\%$ to carbonate chemistry changes in the uppermost 100–200 m (or waters with $\sigma_\theta < 25.6$), and similar to the previous findings in the Pacific Ocean (e.g., Azouzi et al., 2009; Murata et al., 2010; Kouketsu et al., 2013; Carter et al., 2017; Wagener et al., 2018).

An additional conclusion is that, as Millero et al. (2009) and others have suggested, such large decreases in pH and $\Omega_{\text{aragonite}}$ observed in the ODZ of this region will have influenced the TEI solubilities and kinetics in intermediate waters across the Peru–Tahiti section. It is also expected that the upper ocean and intermediate water marine ecosystem will have been influenced by these pH and $\Omega_{\text{aragonite}}$ changes, and in particular, the vertically migrating zooplankton community in the eastern South Pacific Ocean (e.g., Siebel, 2011; Wishner et al., 2013; Maas et al., 2016).

REFERENCES

- Azouzi, L., Goyet, C., Gonçalves Ito, R., and Touretier, F. (2009). Anthropogenic carbon distribution in the eastern Pacific Ocean. *Biogeosciences* 6, 149–156.
- Bakker, D. C. E., Pfeil, B., Landa, C. S., Metzl, N., O'Brien, K. M., Olsen, A., et al. (2016). A multi-decade record of high quality $f\text{CO}_2$ data in version 3 of the Surface Ocean CO_2 Atlas (SOCAT). *Earth Syst. Sci. Data* 8, 383–413. doi: 10.5194/essd-8-383-2016
- Bakker, D. C. E., Pfeil, B., Smith, K., Hankin, S., Olsen, A., Alin, S. R., et al. (2014). An update to the surface ocean carbon atlas (SOCAT version 2). *Earth Syst. Sci. Data* 6, 69–90. doi: 10.5194/essd-6-69-2014
- Bates, N. R. (2001). Interannual variability of oceanic CO_2 and biogeochemical properties in the Western North Atlantic subtropical gyre. *Deep Sea Res.* 48, 507–501. doi: 10.1016/S0967-0645(00)00151-X
- Bates, N. R., Astor, Y. M., Church, M. J., Currie, K., Dore, J. E., Gonzalez-Davila, M., et al. (2014). Changing ocean chemistry: a time-series view of ocean uptake of anthropogenic CO_2 and ocean acidification. *Oceanography* 27, 121–141. doi: 10.5670/oceanog.2014.16
- Bates, N. R., Best, M. H., Neely, K., Garley, R., Dickson, A. G., and Johnson, R. J. (2012). Indicators of anthropogenic carbon dioxide uptake and ocean acidification in the North Atlantic Ocean. *Biogeosciences* 9, 2509–2522. doi: 10.5194/bg-9-2509-2012
- Bates, N. R., Michaels, A. F., and Knap, A. H. (1996a). Alkalinity changes in the Sargasso Sea: geochemical evidence of calcification? *Mar. Chem.* 51, 347–358. doi: 10.1016/0304-4203(95)00068-2
- Bates, N. R., Michaels, A. F., and Knap, A. H. (1996b). Seasonal and interannual variability of oceanic carbon dioxide species at the US JGOFS Bermuda Atlantic Time-series Study (BATS) site. *Deep Sea Res.* 43, 347–383. doi: 10.1016/0967-0645(95)00093-3
- Bates, N. R., and Peters, A. J. (2007). The contribution of atmospheric acid deposition to ocean acidification in the subtropical North Atlantic Ocean. *Mar. Chem.* 107, 547–558. doi: 10.1016/j.marchem.2007.08.002
- Black, E. E., Buesseler, K. O., Pike, S. M., and Lam, P. J. (2018). ^{234}Th as a tracer of particulate export and remineralization in the southeastern tropical Pacific. *Mar. Chem.* 201, 35–50. doi: 10.1016/j.marchem.2017.06.009
- Bopp, L., Resplandy, L., Orr, J., Doney, S., Dunne, J., Gehlen, M., et al. (2013). Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences* 10, 6225–6245. doi: 10.5194/bg-10-6225-2013
- Buck, K., Sedwick, P., Sohst, B., and Carlson, C. (2018). Organic complexation of iron in the eastern tropical South Pacific: results from US GEOTRACES Eastern Pacific Zonal Transect (GEOTRACES cruise GP16). *Mar. Chem.* 201, 229–241. doi: 10.1016/j.marchem.2017.11.007
- Byrne, R. H. (2002). Inorganic speciation of dissolved elements in seawater: the influence of pH on concentration ratios. *Geochem. Trans.* 3, 11–16. doi: 10.1186/1467-4866-3-11
- Byrne, R. H., Kump, L. R., and Cantrell, K. J. (1988). The influence of temperature and pH on trace metal speciation in seawater. *Mar. Chem.* 25, 163–181. doi: 10.1016/0304-4203(88)90062-X
- Caldeira, K., and Wickett, M. F. (2003). Anthropogenic carbon and ocean pH. *Nature* 425:365. doi: 10.1038/425365a

AUTHOR CONTRIBUTIONS

NB designed the study, analyzed and interpreted the results, produced the figures and tables, and wrote the manuscript.

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- Carter, B. R., Feely, R. A., Mecking, S., Cross, J. N., MacDonald, A. M., Siedlecki, S. A., et al. (2017). Two decades of Pacific anthropogenic carbon storage and ocean acidification along Global Ocean Ship-based Hydrographic Investigations Program sections P16 and P02. *Glob. Biogeochem. Cycles* 31, 306–327. doi: 10.1002/2016GB005485
- Deutsch, C., Berelson, W., Thunell, R., Weber, T., Tems, C., McManus, J., et al. (2014). Centennial changes in North Pacific anoxia linked to tropical trade winds. *Science* 345, 665–668. doi: 10.1126/science.1252332
- Dickson, A. G. (1990). Thermodynamics of the dissociation of boric acid in synthetic seawater from 273.15 to 318.15 K. *Deep Sea Res.* 37, 755–766. doi: 10.1016/0198-0149(90)90004-F
- Dickson, A. G., and Millero, F. J. (1987). A Comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media. *Deep Sea Res.* 34(Part A), 733–731. doi: 10.1016/0198-0149(87)90021-5
- Dickson, A. G., Sabine, C. L., and Christian, J. R. (2007). *Guide to Best Practices for Ocean CO₂ Measurements*. Sidney: North Pacific Marine Science Organization.
- Dore, J. E., Lukas, R., Sadler, D. W., Church, M. J., and Karl, D. M. (2009). Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proc. Natl. Acad. Sci. U.S.A.* 106, 235–212. doi: 10.1073/pnas.0906044106
- Feely, R., Bullister, J., and Roberts, M. (1994). *Hydrographic, Chemical and Carbon Data Obtained During the R/V Discoverer cruise in the Pacific Ocean during WOCE Section P18 (EXPOCODE 31DSCG94_1,2,3)*. Washington, DC: US Department of Energy.
- Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Ianson, D., and Hales, B. (2008). Evidence for upwelling of corrosive “acidified” water onto the continental shelf. *Science* 320, 490–491. doi: 10.1126/science.1155676
- Feely, R. A., Takahashi, T., Wanninkhof, R., McPhaden, M. J., Cosca, C. E., Sutherland, S. E., et al. (2006). Decadal variability of the air-sea CO₂ fluxes in the equatorial Pacific Ocean. *J. Geophys. Res. Oceans* 111:C08S90. doi: 10.1029/2005JC003129
- Feely, R. A., Wanninkhof, R., Cosca, C. E., Murphy, P. P., Lamb, M. F., and Steckley, M. D. (1995). CO₂ distributions in the equatorial Pacific during the 1991–1992 ENSO event. *Deep Sea Res.* 42, 365–386. doi: 10.1016/0967-0645(95)00027-N
- Fitzsimmons, J. N., John, S. G., Marsay, C. M., Hoffman, C. L., Nicholas, S. L., Toner, B. M., et al. (2017). Iron persistence in a distal hydrothermal plume supported by dissolved-particulate exchange. *Nat. Geosci.* 10, 195–201. doi: 10.1038/ngeo2900
- GEOTRACES (2006). GEOTRACES: an international study of marine biogeochemical cycles of trace elements and their isotopes: a Science Plan. *Sci. Committee Ocean Res.* 67, 85–131.
- González-Dávila, M., Santana-Casiano, J. M., and González-Dávila, E. F. (2007). Interannual variability of the upper ocean carbon cycle in the northeast Atlantic Ocean. *Geophys. Res. Lett.* 34:L07608. doi: 10.1029/2006GL028145
- González-Dávila, M., Santana-Casiano, J. M., Rueda, M. J., and Llinas, O. (2010). The water column distribution of carbonate system variables at the ESTOC site from 1995 to 2004. *Biogeochemistry* 7, 67–63. doi: 10.5194/bg-7-3067-2010
- Gruber, N., Sarmiento, J. L., and Stocker, T. F. (1996). An improved method for detecting anthropogenic CO₂ in the oceans. *Glob. Biogeochem. Cycles* 10, 809–837. doi: 10.1029/96GB01608
- Horak, R. E. A., Reuf, W., Ward, B. B., and Devol, A. H. (2016). Expansion of denitrification and anoxia in the easter tropical North Pacific from 1972 to 2012. *Geophys. Res. Lett.* 43, 5252–5260. doi: 10.1002/2016GL068871
- Jenkins, W. J., Lott, D. E., German, C. R., Cahill, K. L., Goudeau, J., and Longworth, B. (2018). The deep distributions of helium isotopes, radiocarbon, and noble gases along the U.S. GEOTRACES East Pacific Zonal Transect (GP16). *Mar. Chem.* 201, 167–182. doi: 10.1016/j.marchem.2017.03.009
- Keeling, R., Körtzinger, A., and Gruber, N. (2010). Ocean deoxygenation in a warming world. *Ann. Rev. Mar. Sci.* 2, 199–229. doi: 10.1146/annurev.marine.010908.163855
- Keller, K. M., Joos, F., and Raible, C. C. (2014). Time of emergence of trends in ocean biogeochemistry. *Biogeochemistry* 11, 3647–3659. doi: 10.5194/bg-11-3647-2014
- Key, R. M., Olsen, A., van Heuven, S., Lauvset, S. K., Velo, A., Lin, X., et al. (2015). *Global Ocean Data Analysis Project, Version 2 (GLODAPv2)*, ORNL/CDIAC-162, ND-P093. Oak Ridge, TN: Oak Ridge National Laboratory. doi: 10.3334/CDIAC/OTG.NDP093_GLODAPv2
- Khatiwala, S., Tanhua, T., Mikaloff Fletcher, S., Gerber, M., Doney, S. C., Graven, H. D., et al. (2013). Global ocean storage of anthropogenic carbon. *Biogeochemistry* 10, 2169–2191. doi: 10.5194/bg-10-2169-2013
- Kouketsu, S., Murata, A., and Doi, T. (2013). Decadal changes in dissolved inorganic carbon in the Pacific Ocean. *Glob. Biogeochem. Cycles* 27, 65–76.
- Lam, P. J., Lee, M.-J., Heller, M. I., Mehic, S., Xiang, Y., and Bates, N. R. (2018). Size-fractionated distributions of suspended particle concentration and major phase composition from the U.S. GEOTRACES Eastern Pacific Zonal Transect (GP16). *Mar. Chem.* 201, 90–107. doi: 10.1016/j.marchem.2017.08.013
- Lupton, J. E., and Jenkins, W. J. (2017). Evolution of the south Pacific helium plume over the past three decades. *Geochem. Geophys. Geosyst.* 18, 1810–1823. doi: 10.1002/2017GC006848
- Maas, A. E., Lawson, G. L., and Wang, A. L. (2016). The metabolic response of thecosome pteropods from the North Atlantic and North Pacific oceans to high CO₂ and low O₂. *Biogeochemistry* 13, 6191–6210. doi: 10.5194/bg-13-6191-2016
- Mehrbach, C., Culberson, C. H., Hawley, J. E., and Pytkowicz, R. M. (1973). Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. *Limnol. Oceanogr.* 18, 897–907. doi: 10.4319/lo.1973.18.6.0897
- Millero, F., Winn, C., and Goyet, C. (1994). *Hydrographic, Chemical and Carbon Data Obtained During the R/V Melville cruise in the Pacific Ocean during WOCE Section P21EW (EXPOCODE 318MWESTW_4_5)*. Oak Ridge, TN: Oak Ridge National Laboratory. doi: 10.3334/CDIAC/otg.318MWESTW_4_5
- Millero, F. J. (2001a). *Physical Chemistry of Natural Waters*. Hoboken, NY: John Wiley & Sons, 654.
- Millero, F. J. (2001b). Speciation of metals in natural water. *Geochem. Trans.* 2, 56–64. doi: 10.1186/1467-4866-2-57
- Millero, F. J. (2013). *Chemical Oceanography*, 4th Edn. Boca Raton, FL: CRC Press, 552.
- Millero, F. J., Woosley, R., DiTrollo, B., and Waters, J. (2009). Effect of ocean acidification on the speciation of metals in seawater. *Oceanography* 22, 72–85. doi: 10.5670/oceanog.2009.98
- Millero, F. J., Yao, W., and Aicher, J. (1995). The speciation of Fe(II) and Fe(III) in natural waters. *Mar. Chem.* 50, 21–39. doi: 10.1016/0304-4203(95)00024-L
- Moffett, J. W., and German, C. R. (2018). The U.S. GEOTRACES eastern tropical Pacific transect. *Mar. Chem.* 201, 1–5. doi: 10.1016/j.marchem.2017.12.001
- Morel, F. M. M., Milligan, A. J., and Saito, M. A. (2003). Marine bioinorganic chemistry: The role of trace metals in the oceanic cycles of major nutrients. *Treatise Geochem.* 6, 113–143. doi: 10.1016/B0-08-043751-6/06108-9
- Murata, A., Kumamoto, Y., Sasaki, K., Watanabe, S., and Fukasawa, M. (2010). Decadal increases in anthropogenic CO₂ along 20°S in the South Indian Ocean. *J. Geophys. Res.* 115:C12. doi: 10.1029/2010JC006250
- Ólafsson, J., Ólafsdóttir, S. R., Benoit-Cattin, A., Danielsen, M., Arnarson, T. S., and Takahashi, T. (2009). Rate of Iceland Sea acidification from time series measurements. *Biogeochemistry* 6, 661–662. doi: 10.5194/bg-6-2661-2009
- Ólafsson, J., Ólafsdóttir, S. R., Benoit-Cattin, A., and Takahashi, T. (2010). The Irminger Sea and the Iceland Sea time series measurements of sea water carbon and nutrient chemistry 1983–2006. *Earth Syst. Sci. Data* 2, 99–104. doi: 10.5194/essd-2-99-2010
- Olsen, A., Key, R. M., van Heuven, S., Lauvset, S. K., Velo, A., Lin, X., et al. (2016). The Global Ocean Data Analysis Project version 2 (GLODAPv2) - an internally consistent data product for the world ocean. *Earth Syst. Sci. Data* 8, 297–323. doi: 10.5194/essd-8-297-2016
- Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., et al. (2005). Anthropogenic ocean acidification over the twenty-first century and its impacts on calcifying organisms. *Nature* 437, 681–686. doi: 10.1038/nature04095
- Pavia, F., Anderson, R., Vivanos, S., Fleisher, M., Lam, P., Lu, Y., et al. (2018). Intense hydrothermal scavenging of ²³⁰Th and ²³¹Pa in the deep Southeast Pacific. *Mar. Chem.* 201, 212–228. doi: 10.1016/j.marchem.2017.08.003
- Peters, B. D., Casciotti, K. I., Jenkins, W. J., Swift, J. H., German, C. R., James, W., et al. (2018). Water mass analysis of the 2013 U.S. GEOTRACES Eastern Pacific Zonal Transect (GP16). *Mar. Chem.* 201, 6–19. doi: 10.1016/j.marchem.2017.09.007
- Quay, P. D., Sutsman, J., Feely, R. A., and Juraneck, L. W. (2011). Net community production rates across the subtropical and equatorial Pacific Ocean estimated from air-sea δ¹³C disequilibrium. *Glob. Biogeochem. Cycles* 23:GB2006. doi: 10.1029/2008GB003193

- Resing, J. A., Sedwick, P. N., German, C. R., Jenkins, W. J., Moffett, J. W., Sohst, B., et al. (2015). Basin-scale transport of hydrothermal dissolved metals across the South Pacific Ocean. *Nature* 523, 200–203. doi: 10.1038/nature14577
- Robbins, L. L., Hansen, M. E., Kleypas, J. A., and Meylan, S. C. (2010). *CO₂calc: a User-Friendly Seawater Carbon Calculator for Windows, Mac OS X, and iOS (iPhone): U.S. Geological Survey Open-File Report, 2010–1280*. Available at: <http://pubs.usgs.gov/of/2010/1280/>
- Rubin, S., Goddard, J. G., Chipman, D. W., Takahashi, T., Sutherland, S. C., Reid, J. L., et al. (1998). *Carbon Dioxide, Hydrographic, and Chemical Data Obtained in the South Pacific Ocean (WOCE Sections P16A/P17A, P17E/P19S, and P19C, R/V Knorr, October 1992–April 1993. ORNL/CDIAC-109, NDP-065*. Oak Ridge, TN: Oak Ridge National Laboratory. doi: 10.3334/CDIAC/otg.ndp065
- Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., et al. (2004). The oceanic sink for anthropogenic CO₂. *Science* 305, 367–371. doi: 10.1126/science.1097403
- Santer, B. D., Mears, C., Doutriaux, C., Caldwell, P., Gleckler, P. J., Wigley, T. M. L., et al. (2011). Separating signal and noise in atmospheric temperature changes: the importance of timescales. *J. Geophys. Res. Atmos.* 116:D22105. doi: 10.1029/2011JD016263
- Schlitzer, R., Anderson, R. F., Masferrer Dodas, E., Lohan, M., Geibert, W., Tagliabue, A., et al. (2018). The GEOTRACES Intermediate data product 2017. *Chem. Geol.* 493, 210–223. doi: 10.1016/j.chemgeo.2018.05.040
- Shi, D. L., Xu, Y., Hopkinson, B. M., and Morel, F. M. M. (2010). Effect of ocean acidification on iron availability to marine phytoplankton. *Science* 327, 676–679. doi: 10.1126/science.1183517
- Siebel, B. A. (2011). Critical oxygen levels and metabolic suppression in oceanic oxygen minimum zones. *J. Exp. Biol.* 214, 326–336. doi: 10.1242/jeb.049171
- Stramma, L., Johnson, G. C., Firing, E., and Schmidtko, S. (2010). Eastern Pacific oxygen minimum zones: supply paths and multidecadal changes. *J. Geophys. Res.* 115:C09011. doi: 10.1029/2009JC005976
- Stramma, L., Johnson, G. C., Sprintall, J., and Mohrholz, V. (2008). Expanding oxygen-minimum zones in the tropical oceans. *Science* 320, 655–658. doi: 10.1126/science.1153847
- Sunda, W. G., and Ferguson, R. L. (1983). “Sensitivity of natural bacterial communities to additions of copper and to cupric ion activity: a bioassay of copper complexation in seawater,” in *Trace Metals in Seawater*, eds C. S. Wong, E. Boyle, K. W. Bruland, J. D. Burton, and E. D. Goldberg (New York, NY: Plenum), 871–891.
- Takahashi, T., Goddard, J. G., Rubin, S., Chipman, D. W., Sutherland, S. C., and Goyet, C. (1995). *Carbon Dioxide, Hydrographic, and Chemical Data Obtained in the Central South Pacific Ocean (WOCE Sections P17S and P16S) During the TUNES-2 Expedition of the R/V Thomas Washington, July–August, 1991*. Oak Ridge, TN: Oak Ridge National Laboratory. doi: 10.3334/CDIAC/otg.ndp054
- Takahashi, T., Sutherland, S. C., Chipman, D. W., Goddard, J. G., Ho, C., Newberger, T., et al. (2014). Climatological distributions of pH, pCO₂, total CO₂, alkalinity, and CaCO₃ Saturation in the global surface ocean, and temporal changes at selected locations. *Mar. Chem.* 164, 95–124. doi: 10.1016/j.jmarchem.2014.06.004
- Takahashi, T., Sutherland, S. C., Wanninkhof, R., Sweeney, C., Feely, R. A., Chipman, D. W., et al. (2009). Climatological mean and decadal change in surface ocean pCO₂, and net sea–air CO₂ flux over the global oceans. *Deep Sea Res.* 56, 554–577. doi: 10.1016/j.dsr.2008.12.009
- Tems, C., Berelson, W., and Prokopenko, M. (2014). δ¹⁵N in laminated marine sediments provide a proxy for mixing between the California Undercurrent and the California Current: a proof of concept. *Geophys. Res. Lett.* 42, 419–427. doi: 10.1002/2014GL061993
- Tomczak, M. (1981). A multi-parameter extension of temperature/salinity diagram techniques for the analysis of non-isopycnal mixing. *Progr. Oceanogr.* 10, 147–171. doi: 10.1016/0079-6611(81)90010-0
- Touratier, F., Azouzi, L., and Goyet, C. (2007). CFC-11, Δ¹⁴C and 3He tracers as a means to assess anthropogenic CO₂ concentrations in the ocean. *Tellus* 59B, 318–325. doi: 10.1111/j.1600-0889.2006.00247.x
- Touratier, F., and Goyet, C. (2004a). Definition, properties, and Atlantic distribution of the new tracer TrOCA. *J. Mar. Syst.* 46, 169–179. doi: 10.1016/j.jmarsys.2003.11.016
- Touratier, F., and Goyet, C. (2004b). Applying the new TrOCA approach to assess the distribution of anthropogenic CO₂ in the Atlantic Ocean. *J. Mar. Syst.* 46, 181–197. doi: 10.1016/j.jmarsys.2003.11.020
- Turner, D. R., Whitfield, M., and Dickson, A. G. (1981). The equilibrium speciation of dissolved components of freshwater and seawater at 25°C and 1 atm pressure. *Geochim. Cosmochim. Acta* 44, 855–881. doi: 10.1016/0016-7037(81)90115-0
- Uchida, H., Murata, A., and Doi, T. (2011). *Carbon Dioxide, Hydrographic, and Chemical Data Obtained During the R/V Mirai Repeat Hydrography Cruise in the Pacific Ocean: CLIVAR CO₂ Section P21_2009 (10 April - 3 July, 2009)*. Oak Ridge, TN: Oak Ridge National Laboratory.
- Wagner, T., Metzl, N., Cuffin, M., Fin, J., Helias Nunige, S., Lo Monaco, C., et al. (2018). Carbonate system distribution, anthropogenic carbon, and acidification in the western tropical South Pacific (OUTPACE 2015 section). *Biogeosciences* 15, 5221–5236. doi: 10.5194/bg-15-5221-2018
- Wishner, K. F., Outram, D. M., Seibel, B. A., Daly, K. L., and Williams, R. L. (2013). Zooplankton in the eastern tropical north Pacific: Boundary effects of oxygen minimum zone expansion. *Deep Sea Res.* 79, 122–140. doi: 10.1016/j.dsr.2013.05.012
- Yang, S., Gruber, N., Long, M. C., and Vogt, M. (2017). ENSO-driven variability of denitrification and suboxia in the Eastern Tropical Pacific Ocean. *Glob. Biogeochem. Cycles* 31, 1470–1487. doi: 10.1002/2016GB005596
- Zeebe, R. E., and Wolf-Gladrow, D. (eds). (2001). *CO₂ in Seawater: Equilibrium, Kinetics, Isotopes*, 1st Ed, Vol. 65. Amsterdam: Elsevier Oceanography Series.

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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