Zinc stimulation of phytoplankton in a low carbon dioxide, coastal Antarctic environment

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Abstract

Zinc (Zn) is a key micronutrient used by phytoplankton for carbon (C) acquisition, yet there have been few observations of its influence on natural oceanic phytoplankton populations. In this study, we observed Zn limitation of growth in the natural phytoplankton community of Terra Nova Bay, Antarctica, due to low (~220 μatm) pCO_2 conditions, in addition to primary iron (Fe) limitation. Shipboard incubation experiments amended with Zn and Fe resulted in significantly higher chlorophyll *a* content and dissolved inorganic carbon drawdown compared to Fe addition alone. Zn and Fe response proteins detected in incubation and environmental biomass provided independent verification of algal co-stress for these micronutrients. These observations of Zn limitation under low pCO_2 conditions demonstrate Zn can influence coastal primary productivity. Yet, as surface ocean pCO_2 rises with continued anthropogenic emissions, the occurrence of Zn/C co-limitation will become rarer, impacting the biogeochemical cycling of Zn and other trace metal micronutrients.

Significance Statement

Zinc has tremendous nutritional importance in life, and due to its central role in carbon acquisition in major phytoplankton species, Zn is directly connected to ocean carbon cycling. As a result, it has been hypothesized that co-limitation by zinc and CO_2 could influence primary productivity, but a connection between Zn and CO_2 has not yet been observed in field experiments. The present study demonstrates that Zn can be a limiting nutrient in natural waters, particularly in coastal environments where CO_2 is diminished by bloom events, and explores the implications for Zn-C co-limitation in the context of climate change— the oceans may have

decreased susceptibility to Zn-C co-limitation in the future due to the rapid input of anthropogenic CO_2 to the atmosphere.

Introduction

Primary productivity in the oceans is a key component of the global carbon cycle and is largely controlled by the availability of nitrogen (N), phosphorus (P), and iron (Fe). Yet there is increasing evidence that other micronutrients such as zinc (Zn), cobalt (Co), and vitamin B_{12} can also influence phytoplankton productivity, often as secondary limiting nutrients after N, P, or Fe are added[1]. Zn can be particularly scarce in the photic zone[2,3] where total dissolved Zn (dZn_T) can be as low as 0.1 nM in seawater due to biological uptake and complexation by organic ligands[4,5] which further lower Zn bioavailability[6–8]. Marine eukaryotic algae and copiotrophic bacteria possess a large metabolic demand for Zn that is on par with that of Fe[6,9] and polar phytoplankton in particular demonstrate an enhanced Zn demand based on genomic and laboratory analyses[10]. Despite the scarcity of bioavailable Zn in the surface ocean and its high cellular demand, there have been relatively few experimental studies examining the ability of Zn addition to stimulate natural phytoplankton communities **(Supplementary Table 1),** with findings that include negative results[11–13], slight Zn stimulatory results[14], Zn stimulation within Fe and Si uptake experiments[15], Zn primary and secondary limitation in the North Pacific in an unreplicated experiment[3], and secondary Zn limitation after primary Si limitation in the Costa Rica Dome[16].

In contrast to the limited field evidence, laboratory studies have unequivocally demonstrated that marine phytoplankton can easily be Zn-limited in culture due to their large Zn requirement and that this effect is exacerbated at low pCO_2[17,18] due to the use of Zn as a required catalytic cofactor within carbonic anhydrase (CA) metalloenzymes[18]. CAs catalyze the reversible

dehydration of HCO_3^- to CO_2, the substrate required by the carbon fixing enzyme RUBISCO. As HCO_3^- constitutes about 90% of the dissolved inorganic carbon (DIC) pool in the surface ocean, sufficient CA activity works to prevent carbon stress in marine phytoplankton by ensuring adequate CO_2 supply to RUBISCO. In some CA classes, the Zn cofactor can be substituted for by Co[19,20], and in some species, alternate CAs can be produced that use Cd or manganese (Mn)[21,22] as the cofactor, conferring a biochemical substitution flexibility with respect to metal availability known as cambialism[7]. While low pCO_2 events are frequently observed in coastal environments due to high biological productivity[23–25], a connection between Zn and CO_2 has not yet been observed in field experiments, and it has remained unclear under what conditions Zn can act as a limiting oceanic micronutrient. However, a connection between Cd, which can metabolically substitute for Zn when Zn is depleted[26], and CO_2 has been observed, with enhanced Cd uptake and increased particulate Cd in productive coastal Californian waters experiencing low pCO_2 conditions[27,28].

As low CO_2 conditions often result during algal blooms in coastal environments, it has been hypothesized that the combination of high biomass and resulting low CO_2 in these environments may cause severe Zn depletion that may limit algal growth rates[18]. In this study, we assessed these environments for evidence of Zn limiting conditions in the field by performing Zn addition experiments with the natural phytoplankton assemblage in Terra Nova Bay (TNB), Antarctica. As TNB is located at the western edge of the Ross Sea and hosts large seasonal blooms dominated by diatoms[29] and the prymnesiophyte *Phaeocystis antarctica*[30,31] (*Phaeocystis* hereon) that result in low CO_2 [29,32], TNB was an ideal site to test for Zn/C co-limitation in the field.

Results and discussion

Biogeochemical characterization of Terra Nova Bay

We begin by biogeochemically characterizing the study site within Terra Nova Bay (TNB), Antarctica, which was temporally sampled for over one month (January 9 – February 18, 2018) during the 2017-2018 CICLOPS expedition **(Fig. 1a; Supplementary Table 2)** to concurrently characterize the natural phytoplankton bloom progression and biogeochemical changes in the water column. Low (~200 μatm) pCO_2 surface waters throughout TNB (**Fig. 1b**) resulted in a potentially Zn/C co-limiting environment for native phytoplankton.

TNB hosted a large phytoplankton bloom as indicated by high (> 3000 ng L^{-1}) chlorophyll *a* concentrations in January that waned into February (**Fig. 1c**), that is characteristic of Antarctic polynya environments. This phytoplankton community initially consisted of a mixed assemblage of both diatoms as indicated by fucoxanthin (fuco, **Fig. 1d**) and *Phaeocystis* as verified by shipboard microscopy and as indicated by 19'-hexanoyloxyfucoxanthin (19'-hex, **Fig. 1e**). Surface fucoxanthin concentrations >200 ng L^{-1} were observed at the late TNB stations (**Fig. 1d**) while 19'-hex decreased to ~20 ng L^{-1} (**Fig. 1e**), indicating that the stations sampled in late February were dominated by diatoms rather than *Phaeocystis*. This was consistent with historical observations of phytoplankton succession patterns in TNB[30,31,33]. Pronounced and progressively deepening total dissolved Zn (dZn_T) depletion was observed in our temporal, upper water column sampling study of the TNB region spanning over a month (January-February 2018; **Fig. 1f**). dZn was depleted down to an average of 0.82 ± 0.47 nM at 10 m over all TNB stations with Zn-depleted areas of the water column progressively deepening to 50 m and then to ~100 m throughout January and February **(Fig. 1f)** indicative of strong Zn uptake and export from the euphotic zone. In the Ross Sea, dissolved iron (dFe) has previously been demonstrated to be the primary limiting nutrient for phytoplankton growth[12,34,35]. Consistent with this, across all TNB

stations, dFe_T in the upper 50 m remained below 1 nM **(Supplementary Figure 1a**) as observed previously in this region[36].

Temporal dynamics of the TNB bloom (**Supplementary Figure 12**) further showed that total Zn uptake (ρZn, measured concurrently using a new stable isotope tracer method[37]) was highest in the shallow euphotic zone in early January and waned into February (**Fig. 1g**), following trends seen in chlorophyll *a* (chl *a*, **Fig. 1c**) and the phytoplankton pigments fucoxanthin (**Fig. 1d**) and 19'-hex (**Fig. 1e**). This ρZn trend was consistent with laboratory studies demonstrating the substantial Zn requirements of both diatoms and *Phaeocystis antarctica*[20,38]. Within TNB, the negative linear relationship (n = 15, R^2 = 0.63) between surface seawater (5 m underway system) pCO_2 partial pressure and ρZn (10 m) (**Fig. 1h**), as well as the positive linear relationship (n=9, R^2= 0.65) between chlorophyll *a* concentrations and ρZn, both measured at 10 m (**Fig. 1i**), demonstrated that the combination of high biomass and low CO_2 lead to substantial increases in Zn uptake. A positive linear trend (n = 27, R^2 = 0.87) comparing surface seawater pCO_2 and DIC concentrations confirmed this biological influence on carbon dynamics, with pCO_2 responding to DIC rather than alkalinity or salinity (**Supplementary Figure 2**).

Biogeochemical characterization of the incubation study site

We next describe the biogeochemistry of the water column at one TNB station (station 27, referred to as the "experimental site" herein) as this particular site was chosen for the multifactor shipboard incubation experiment (**Fig. 1a,b**; red star). This experimental site harbored a coastal bloom and was biologically and chemically characterized as having high *in situ* chlorophyll *a* levels (maximum of 3259 ng L^{-1} at 30 m; **Supplementary Figure 3a**), and a decrease in total dissolved inorganic carbon (DIC_T; 2186 μmol kg^{-1} at 5 m compared to the deep

water (200-1065 m) average of 2224 ± 2.1 μmol kg^{-1}**, Supplementary Figure 3b**). Within the water column, dZn demonstrated a pronounced decrease from 5.1 nM at 50 m to 0.9 nM at 10 m, representing an 82% decrease (and a 76% decrease comparing the minimum dZn_T value at 10 m to the average deepwater (210 – 1000 m) concentration of 3.9 nM ± 0.4; **Supplementary Figure 3c**), consistent with prior observations of surface dZn depletion in this region[36]. While Zn speciation was not measured in this study, it is likely that Zn organic complexation further depleted total bioavailable Zn. A concurrent study of Co speciation observed complete complexation of dissolved Co in the upper water column in TNB, consistent with this idea[39]. Consistent with high macronutrient abundance in this region (as observed previously and in the present study; **Supplemental Figure 1b,c,d**), surface macronutrient concentrations (nitrate and nitrite, phosphate, and silicic acid) were partially depleted at the experimental site with 64%, 46%, and 29% decreases in N+N, P, and Si, respectively, comparing 10 m and average deep water (200 – 1000 m) values (**Supplementary Figure 3d**). Observations of rapid Zn uptake at the experimental site (**Supplementary Figure 3e**) can explain the dZn_T drawdown described above—Zn uptake rates of 46 pmol L^{-1} d^{-1} (at 10 m) are of the appropriate scale to induce the multi-nanomolar surface water depletion during the austral spring and summer season.

Evidence for Zn stimulation of phytoplankton in shipboard incubations

A multifactor incubation experiment was conducted using surface waters collected by trace metal clean fish sampler (7 m) fed into a shipboard cleanroom at the experimental site to examine controls on primary productivity, with triplicate treatments of Zn amended (+Zn; 2 nM as $ZnCl_2$), Fe amended (+Fe; 1 nM as $FeCl_2$), and Fe and Zn amended (+Fe+Zn) incubations, in addition to unamended controls. Addition of Fe alone (+Fe) resulted in significantly higher chl *a*

content compared to controls (p = 9.5e-5) after six days (T6) (**Fig. 2a**), demonstrating primary Fe limitation as observed previously in the Ross Sea[31,34]. However, addition of Zn alone (+Zn) also resulted in significantly higher chl *a* content compared to the controls (p = 0.011), implying that a subset of the incubated phytoplankton population benefitted from the addition of Zn alone, without additional Fe, and was thus experiencing primary Zn limitation (**Fig. 2a**). The combined addition of +Fe+Zn resulted in the highest average chl *a* content among all treatments at T6, with 4.5 ± 0.21 μg L^{-1} compared to 3.9 ± 0.35 μg L^{-1} and 2.8 ± 0.15 μg L^{-1} achieved by +Fe and +Zn alone, respectively, demonstrating additive co-limitation between Zn and Fe[40]. The Zn stock solution was analyzed to confirm these results were not caused by inadvertent iron contamination (see Methods). Moreover, significant differences between controls and metal treatments (and low variance within treatments) indicated source seawater was also not metal contaminated. Significant differences in seawater chemistry were also observed within these incubations over time, with larger decreases in DIC_T in all metal treatments compared to the control (-12.7 μmol kg^{-1} for +Fe (p = 5.3e-6), -8.2 μmol $kg^{-1}$for +Zn (p = 5e-5), and -18.5 μmol kg^{-1} for +Fe+Zn (p = 2.2e-16); **Fig. 2b**). The decrease in DIC_T observed with +Fe+Zn was significantly larger than that achieved with +Fe alone (p = 4.4e-3; **Fig. 2b**). Statistically significant differences in measured parameters among treatments are summarized in **Supplementary Table 3.**

The application of algal Fe- and Zn-stress proteins provided an independent line of evidence corroborating the results described above. This included the detection of the recently described Zn/Co responsive protein ZCRP-A (a putative Zn chaperone)[41] as a biomarker of Zn stress as well as the iron starvation-induced proteins ISIP1A, ISIP2A and ISIP3 (ISIPs) as biomarkers of Fe stress (**Supplementary Table 4**). The ISIPs represent a group of unrelated proteins that are upregulated under Fe limitation in various algal species. ISIP1 proteins are

responsible for endocytosis of siderophore-bound iron, ISIP2 proteins are involved in Fe^{3+} uptake, and ISIP3 has been suggested to act as an Fe storage protein[42,43]. Within the T6 incubation biomass, there was an increased abundance of ISIPs in the control and +Zn treatment and a corresponding decrease in ISIP protein abundance within the +Fe and +Fe+Zn treatments, consistent with primary Fe limitation and the expected response to Fe addition (**Fig. 2c**). ISIPs were taxonomically assigned to diatoms, *Phaeocystis*, and dinoflagellates (**Supplementary Figure 4a).** Similarly, we detected the presence of ZCRP-A in the T6 control, indicating the predilection for Zn limitation. The strongest expression of ZCRP-A was detected in the +Fe treatment (**Fig. 2c**) indicative of Fe addition driving the community towards increased Zn stress. Notably, ZCRP-A was still detected in the +Fe+Zn treatment (**Fig. 2c**), implying that the added Zn was unable to completely satiate Zn demand as phytoplankton biomass increased (as indicated by the increase in chl *a* at T6, **Fig. 2a**), despite added Zn (2 nM) being double that of added Fe (1 nM). Sequence analysis of the contigs identified as ZCRP-A homologs in these incubations revealed that all contigs contained one or more canonical conserved motifs found in COG0523 family proteins such as ZCRP-A (**Supplementary Figure 5)**. Coupled with evidence from prior laboratory studies[41], this provides further support for the role of ZCRP-A in responding to Zn scarcity. The substantial drawdown of surface seawater pCO_2 to 221 μatm at the incubation site (**Fig. 2d**) (a ~45% decrease compared to offshore waters in the Ross Sea measured during the same time frame; **Fig. 1b**), is consistent with an increased Zn demand resulting from low pCO_2 conditions resulting in the detection of Zn stress proteins.

ZCRP-A proteins were taxonomically assigned to chlorophytes, prasinophytes, dinoflagellates, and *Phaeocystis* (**Supplementary Figure 4a)**, with the detection of *Phaeocystis* ZCRP-A only in the +Fe treatment. The detection of ZCRP-A attributed to *Phaeocystis*, but the

nondetection of ZCRP-A attributed to diatoms, implies that diatoms present were outcompeting *Phaeocystis* for Zn. In addition to these metal stress-responsive proteins, variations in other functional proteins were observed among treatments. For example, RUBISCO and RNA polymerase were most abundant under +Zn+Fe conditions, and the latter was co-located within the same hierarchical cluster as ZCRP-A, consistent with their shared connection to cellular carbon metabolism (**Fig. 2c).** Our observations of Fe and Zn biomarkers shifting in abundance in response to their respective metal treatment provides independent evidence for Zn/Fe co-limitation and additional verification that neither incubation treatment (+Zn nor +Fe) was contaminated with the other metal throughout the experiment.

A third independent line of evidence for the nutritional influence of Zn on TNB phytoplankton was obtained from *in situ* cellular stoichiometry. Particulate Zn:P ratios (Zn:P) analyzed from biomass collected at the surface of this experimental station were consistent with ratios from Zn limited culture studies. Particulate Zn:C ratios reported previously in Zn-limiting culture studies of the diatom *Thalassiosira pseudonana*[18] were converted to Zn:P ratios using the Redfield ratio[44] (**Supplementary Table 6**). We then compared these ratios and associated growth rates with Zn:P measured within biomass collected at 10, 25, 50 and 100 m at the experimental site. At all of these surface depths, Zn:P measured at the experimental site was ~ 2E-4 mol:mol, which, in comparison to cultured diatom Zn:P ratios, fell within in the range of severely Zn-limited growth rates (**Supplemental Figure 6**), again demonstrating the propensity for Zn limited growth in this region and corroborating the incubation results.

Further consistent with the observed Zn stimulation of biomass in the incubations, the largest decreases in macronutrient (P and N+N) concentrations in these incubations at T6 were observed in the +Fe+Zn treatment (**Supplementary Figure 7a,b**), as was the largest increase in

particulate organic carbon (POC; **Supplementary Figure 7c**). POC collected from the +Zn and +Fe+Zn incubations was characterized by larger C:N atomic ratios (5.9 and 6.2, respectively) compared to the +Fe and T6 control (5.2 and 5.3; **Supplementary Figure 7d**) consistent with the stimulation of carbon uptake upon Zn addition alleviating carbon stress. Significantly higher bacterial abundances in both +Fe (p = 9.1e-4) and +Fe+Zn (p = 6.3e-4) treatments relative to the T6 control (**Supplementary Figure 7e**) indicated the alleviation of bacterial Fe limitation, consistent with prior reports[45–47].

Taxonomic characterization of incubation results

The measurement of phytoplankton pigments over time within the shipboard incubations revealed a diverse taxonomic response to metal amendments. Measured pigments included fucoxanthin (fuco), 19'-hexanoyloxyfucoxanthin (19'-hex), prasinoxanthin (prasino), chlorophyll *b* (chl *b*), and chlorophyll c3 (chl c3). Fuco is produced by both diatoms and by *Phaeocystis* under certain conditions, while 19'-hex and chl c3 are indicative of *Phaeocystis* in this region[48]. Fuco:19'-hex ratios significantly increased in the +Fe (p = 4.2e-4) and +Fe+Zn treatments (p = 2.7e-3) (**Supplementary Figure 8a**) due to no significant change in fuco (**Supplementary Figure 8b**) and decreased 19'-hex (**Supplementary Figure 8c**) relative to the T6 control. *Phaeocystis* contributions to total fuco concentrations are typically minimal at the low Fe levels of the Ross Sea, though *Phaeocystis* can revert to making fuco rather than 19'-hex when released from Fe limitation[48], as was evident in these incubations by decreased 19'-hex:chl c3 ratios with +Fe and +Fe+Zn (**Supplementary Figure 8d**). *Phaeocystis* therefore likely contributed to total fuco by responding to Fe addition. Notably, significant decreases in both fuco:chl *a* and 19'-hex:chl *a* (**Supplementary Figure 8e,f**) in all treatments compared to the T6 control indicated

that other phytoplankton groups contributed to chl *a* (**Fig. 2a**) without contributing fuco nor 19'hex. Increases in chl *b* (**Supplementary Figure 8g**) and prasinoxanthin (**Supplementary Figure 8h**) suggested that small green algae such as chlorophytes and prasinophytes also responded to +Fe and +Zn independently, consistent with the detection of chlorophyte ZCRP-A in these incubations (**Supplementary Figure 4a**). We used metaproteomic data from T6 incubation biomass to supplement the pigment data and to further describe the major phytoplankton taxa present in the incubations at T6. Taxonomically assigned protein spectral counts were summed by genus, and indicated that *Phaeocystis*, diatoms, dinoflagellates, and cryptophytes were the most abundant phytoplankton taxa as represented in the metaproteomic data, with cryptophytes, dinoflagellates, and *Phaeocystis* responding to metal treatments, consistent with the pigment results (**Supplementary Figure 8i).** Photosynthetic efficiency of photosystem II (Fv/Fm) significantly increased with +Fe ($p = 0.011$) and with +Fe+Zn ($p = 0.0036$) at T4 (96 hours) compared to T4 controls, (note that there was no difference among treatments at T6) but did not significantly increase with +Zn alone, implying Fv/Fm may not be useful as a diagnostic for Zn stress and that caution should be used in interpreting its signals universally (**Supplementary Figure 8j**).

Selective zooplankton grazing on small diatoms and solitary *Phaeocystis* cells may also have played a role in affecting phytoplankton biomass and the observed pigment:chl *a* ratios. For instance, higher ratios of phaeophytin:total phaeopigments were observed in +Fe and +Zn amended incubations (**Supplementary Figure 9**) which may reflect grazing on solitary *Phaeocystis* cells, as high phaeophytin:total phaeopigments ratios were previously observed in *Phaeocystis* dominated waters of the Ross Sea[33].

Detection of Zn- and Fe-stress protein biomarkers in the water column

Metaproteomic and metatranscriptomic analyses of biomass within the water column at the experimental site provided additional confirmation of the incubation results by demonstrating the occurrence of phytoplankton micronutrient Zn- and Fe- stress-response proteins within the water column, without influence from incubation conditions. In addition to ISIPs and ZCRP-A, we additionally detected ZCRP-B (a putative membrane-tethered Zn-binding protein)[41], Zrt/Irt-like (ZIP) Zn transporters, which are known to be used for Zn^{2+} and other divalent metal cation uptake in marine phytoplankton[42,49,50], and θ (theta) and δ (delta) carbonic anhydrases (CAs). θ-CAs with Zn^{2+} coordination sites have been documented in diatoms[51], including the polar diatom *Chaetoceros neogracile* RS19[52], but there are no studies to date investigating enzyme activity or efficiency with Co^{2+} or Cd^{2+}. In contrast, δ-CA (i.e, *Thalassiosira weissflogii* TWCA1) is known to function with either Co^{2+} or Zn^{2+} as a cofactor[53] conferring metabolic flexibility when Zn^{2+} is scarce.

Both proteins and transcripts of Fe and Zn stress biomarkers were observed throughout the water column at the experimental site. RUBISCO, ZCRP-A, and ISIP protein spectral counts within the 3μm size fraction were most abundant at the surface and decreased with depth (**Fig. 3a,b,d**), consistent with the depletion of trace metals in the photic zone due to high-biomass bloom conditions (**Fig. 1c)**. Throughout the water column, ISIPs were predominantly attributed to *Phaeocystis* and to the diatom genera *Fragilariopsis, Chaetoceros,* and *Pseudo-nitzschia* (**Fig. 3i, Supplementary Figure 10b**). ZCRP-A was detected in both 3 and 51 μm filter pore-size fractions (**Fig. 3b**) and was predominantly attributed to *Phaeocystis* (**Supplementary Figure 10c**). ZCRP-A transcripts in the euphotic zone corresponded mainly to *Phaeocystis* and to the diatom genera *Chaetoceros* (**Fig. 3i**). We note that ZCRP-B, a protein also found to be

upregulated in marine diatoms under low Zn/Co and characterized as a putative membrane-tethered Zn/Co protein ligand[41] was most abundant in the 0.2 μm fraction below 100 m (**Fig. 3c**). As ZCRP-B shares ~30% similarity to the bacterial ABC-type nickel transporter component NikA, spectral counts within the bacterial 0.2 μm fraction most likely reflect true bacterial NikA. BLAST analysis of all ZCRP-B contigs confirmed that all ZCRP-B hits (across all size fractions) corresponded to bacteria (**Fig. 3i**).

ZIPs were almost solely found in the 51 μm fraction, likely due to the capture of abundant *Phaeocystis* colonies and chain-forming diatoms (**Fig. 3e; Supplementary Figure 10d**). The assignment of the majority of ISIPs and ZCRP-A proteins to *Phaeocystis* in the upper water column provides additional evidence that *Phaeocystis* was likely Zn/Fe co-limited at the study site, consistent with incubation results (**Fig. 2c, Supplementary Figure 4a**). The enhanced abundance of diatom θ-CA and δ-CA within the water column (**Fig. 3f,g**), as well as transcripts for the diatom Cd carbonic anhydrase CDCA, which can replace Zn^{2+} with Cd^{2+} as the catalytic cofactor[21], in the 3 μm and 51 μm fractions at 200 m (**Fig. 3h**) was indicative of a sinking, prior diatom bloom event[54]. θ-CA and δ-CA were predominantly taxonomically assigned to the diatom genera *Pseudo-nitzschia* and *Chaetoceros*, respectively, while CDCA transcripts belonged to the diatom genera *Chaetoceros* and *Corethron* (**Fig. 3i**). The presence of θ-CA, but lack of δ-CA, assigned to *Chaetoceros* is consistent with proteomic analysis of the polar diatom *Chaetoceros neogracile* RS19 grown in culture under Zn limiting conditions[52].

Analysis of Zn/CO_2 growth limitation thresholds

In this study, we observed multiple independent lines of evidence that phytoplankton within incubation experiments and the field environment were experiencing Zn and Fe

nutritional stress. Coupled with observations of greatly reduced C and Zn availability at the experimental site, which had nearly half the pCO_2 of atmosphere-equilibrated waters (221 μatm compared to ~420 μatm; **Fig. 1b, Fig. 2d**), and the greater demand for Zn as a catalytic cofactor within CAs that are required for CO_2 acquisition, TNB was likely experiencing Zn-C biochemically dependent co-limitation[7], in addition to the expected regional iron limitation. The low pCO_2 waters of the experimental site incubations naturally provided this low CO_2 backdrop, allowing the stimulatory effects of Zn addition described above to be observed. This observation of Zn stimulation within low pCO_2 environments has not been observed previously, and these results imply that other highly productive coastal environments with low pCO_2 are also susceptible to Zn-C limitation, potentially limiting the extent of coastal phytoplankton blooms and carbon export.

Using the available quantitative constraints on Zn and CO_2 co-limitation thresholds available from the literature (see Methods), we estimated that the threshold for Zn-CO_2 limitation in algae occurs at 259 μatm pCO_2. We then compared this laboratory-determined Zn/C limitation threshold to both the *in situ* 221 μatm pCO_2 at our field study site, and to the historical, global trend in surface ocean pCO_2 (**Fig. 4**). It is evident that average, global surface ocean pCO_2 levels are rapidly rising above both the laboratory-estimated 259 μatm pCO_2 Zn/C limitation threshold and our field observation value of 221 μatm[55] (**Fig. 4a,b)** implying that over time, larger amounts of the surface ocean will cease to experience Zn/C limitation. In high-productivity regions, organisms may still experience Zn limitation (as shown in this study in TNB), but the fraction of the ocean that experiences these conditions will continue to shrink, alleviating Zn limitation and potentially increasing overall biological production. Though a fraction of the modern-day surface ocean is currently at ≤ 250 ppm pCO_2 (this fraction is predominantly comprised of polar regions,

Supplementary Figure 11a), this represents a large decrease in oceanic extent compared to only 100 years ago (**Supplementary Figure 11b**). The continued rise in global pCO_2 levels as seen over the last ~100 years is potentially driving a shift away from Zn/C co-limitation, reducing the advantages for algal species with more efficient carbon acquisition capabilities, and also triggering broader changes in the biogeochemical cycling of Zn and other bioavailable trace metals within the oceans. Conversely, during interglacial periods, global atmospheric CO_2 was similar to or below that of this study, implying zinc-carbon co-limiting conditions for phytoplankton would have been prevalent throughout the oceans[56].

This study provides experimental field evidence using multiple independent lines of evidence (chlorophyll, DIC, Zn and Fe biomarker proteins, cellular stoichiometry), combined with contextual biogeochemical (pCO_2, dZn, and Zn uptake) and metaproteomic environmental data to demonstrate the presence of Zn limitation in Terra Nova Bay of the Ross Sea. Given the large Zn requirements of diatoms and other phytoplankton, it is perhaps surprising that more frequent positive observations of Zn nutritional effects have not been seen. We believe this is due to the combined challenges of avoiding Zn contamination and the need to initiate experiments in environments experiencing diminished pCO_2. Low pCO_2 conditions are well known to occur throughout coastal environments globally and could be further examined for Zn effects. While there are elaborate biochemical capabilities available to many marine algae for dealing with Zn scarcity[41], the geographic extent of Zn/C co-limitation will further decrease in the coming decades with rising anthropogenic CO_2 emissions. Despite this, the biochemical demand for Zn in marine organisms remains substantial, with cellular demand rivaling that of Fe. The multitude of metabolic functions requiring Zn, including but not limited to carbonic anhydrase activity, implies the need for further exploration of Zn influences in a changing ocean environment.

Materials and Methods

Study area and sample collection

Sample collection occurred during the CICLOPS (Cobalamin and Iron Co-limitation of Phytoplankton Species) expedition (NBP18-01) aboard the RVIB *Nathaniel B. Palmer*, December 11, 2017 – March 3, 2018 in the Amundsen Sea and Ross Sea of the Southern Ocean (**Fig. 1a**). Station metadata is provided in **Supplementary Table 2.** All stations were assumed to be representative of TNB during this temporal study (as evident in the total dissolved metal, macronutrient, and chlorophyll *a* datasets). Water samples for dissolved trace metal analyses were collected using trace metal sampling protocols described previously[57]. A trace metal clean rosette suspended on a Kevlar line and equipped with twelve 8L X-Niskin bottles (Ocean Test Equipment) was used to collect seawater at depths ranging from 10 – 600 m. Niskin bottles were transported to a positive-pressure trace metal clean shipboard van for filtration upon surfacing. Total fluorescence on the vertical profiles was measured using an ECO chlorophyll fluorometer (Wet Labs) equipped to the rosette. The rosette also included instrumentation for measuring conductivity and temperature (Sea-Bird Electronics).

Preparation of plasticware

Polyethylene and polycarbonate sampling and incubation bottles were rigorously cleaned to remove trace metal contaminants before use. Bottles were rinsed with 18.2 Ω Milli-Q water (Millipore), soaked for 72h in <1% Citranox detergent, rotated, soaked for an additional 72h, and then rinsed five times with Milli-Q water. Bottles were then filled with 10% HCl (Baker instar-analyzed) by volume and soaked for a minimum of one week, rotated, and soaked for another

week. Bottles were then rinsed five times with dilute acid (HCl, pH 2) and stored double-bagged in plastic zip bags. All cleaning work was conducted in a Class 100 clean room.

Underway seawater pCO_2 partial pressure

Surface water pCO_2 measurements were conducted aboard the RVIB *Nathaniel B. Palmer* using an underway method consisting of an air-water equilibrator and IR CO_2 analyzer developed and operated by the Lamont-Doherty Earth Observatory (LDEO) group[58].

TDIC and POC measurements and calculation of pCO_2

Total alkalinity (TA) and dissolved inorganic carbon (DIC) were measured on CTD and incubations samples in near real-time aboard the NBP. Dissolved inorganic carbon (DIC) and total alkalinity (TA) samples were collected following the protocols of Dickson et. al 2007[59]. DIC analyses were conducted within ~4 h of collection. We acidified 1.25 mL of sample using an automated custom-built injection and bubble stripping system coupled to an infrared gas analyzer (LICOR LI7000) and integrated the infrared absorption signal versus time for each stripped gas sample to yield a total mass of CO_2. Each sample was analyzed in triplicate or greater. Since microbubbles regularly formed as samples warmed between sample acquisition and DIC analysis, every integration curve was visually inspected and those curves that exhibited evidence for bubbles were rejected. Certified reference materials (Dickson CRM batch 169) were analyzed between every 3 to 4 unknowns. The estimated precision based upon unknowns (>860 samples run in triplicate) and CRM replicates (n = 738) was ± 2.0 μmol kg^{-1} (±1 SD). As described by DeJong et al. 2015[60], analyses for TA on filtered samples were completed within ~12 h of collection by using a potentiometric titrator (Metrohm 855 Robotic Titrosampler). The estimated precision based on replicate analyses of CRMs (n = 195) was ± 2.6 μmol kg^{-1} (±1 SD). DIC/TA

pairs were used to calculate pCO_2 values using in situ temperature and salinity. Parameters were input to the MATLAB version of CO2SYS[61], and pCO_2 was calculated using the dissociation constants determined by the Dickson and Millero refit of Mehrbach's data (option 4).

We acknowledge offsets in seawater pCO_2 calculated from TA-DIC pairs and those measured using the ship's underway system. In general, values inferred from TA-DIC pairs are higher than underway measurements, sometimes by up to 70 ppm. Errors in acid dissociation constants due to temperature effects[62] cannot explain this offset, as using these updated constants only exacerbates the offsets rather than reconciling them. While these offsets are beyond the scope of the current manuscript, they hint at oceanographic effects on the carbonate system in very cold seas (e.g. large temperature gradients and their effect on the equilibration of the carbonate system). Nevertheless, both calculated and underway pCO_2 measurements are significantly below atmospheric CO_2 values, suggesting carbon limitation of the microbial community in Terra Nova Bay.

Analysis of historical atmospheric and surface ocean pCO_2 trends

Decadal surface ocean pCO_2 reconstructions from Jiang et al. 2023[55] were downloaded, binned by decade, and plotted using the 'violinplot' in MATLAB. Atmospheric pCO_2 data was assembled from the running Mauna Loa record[63], and from measurements made on Antarctic firn ice[64].

Calculation of Zn-and pCO_2 co-limitation of phytoplankton thresholds

There are few experimental measurements of Zn- and pCO_2-co-limitation, either in the lab or *in situ*. This study represents one of the first demonstrations of Zn- and pCO_2 co-limitation

at a pCO_2 of ~220 ppm (Station 27, **Fig. 2d**). In the literature, several models exist to interpret co-limitation[7,65]. For this study we chose to use the biochemically dependent co-limitation model for growth rate (μ):

$$\mu = V_{max} \frac{[CO_{2(aq)}]}{\varphi K_s + [CO_{2(aq)}]}, \quad (1)$$

where V_{max} is the maximum growth rate, $[CO_{2(aq)}]$ is the aqueous CO_2 concentration of the growth medium in micromoles per kilogram of seawater, K_s is the half-saturation constant in micromoles per kilogram of seawater, and φ is a Zn-dependent growth term:

$$\varphi = \frac{[dZn] + K_{s,Zn}}{[dZn]} \quad (2)$$

Here, the dissolved Zn concentration in the growth medium [dZn] is modified by a Zn-dependent saturation constant ($K_{s,Zn}$). Few studies have enough experimental data to robustly establish a kinetic relationship between [dZn] and $[CO_{2(aq)}]$, so we compiled several estimates for these terms from the literature. Diatom growth rates under pCO_2 limitation were taken from Riebesell et al. (1993) [66]. Reported pH and temperature measurements for each treatment, a total alkalinity of 2300 μmol kg^{-1}, and a salinity of 35 were used to calculate aqueous CO_2 concentrations using CO2SYSv3.2.1.[67]. Reported V_{max} and K_s for *D. brightwellii*, *T. punctigera*, and *R. alata* were 1.46, 1.30, and 0.93 d^{-1}, and 1.4, 1.2, and 2.1 μmol kg^{-1}, respectively. Values for coccolithophore growth (K_s = 0.97 μmol kg^{-1}, V_{max} = 4.7 d^{-1}) were taken from Krumhardt et al. (2017) [68]. A value for $K_{s,Zn}$ of 300 pmol L^{-1} was taken from Buitenhuis et al. (2003). This value is for the coccolithophore *E. huxleyii* generated under varying CO_2 and Zn conditions, and Zn response growth curves under single CO_2 conditions (ambient) are similar to other diatoms like *T. pseudonana*[69]. The value of 300 pmol L^{-1} appears high, but is tied to the functional form of the

biochemically co-limitation equation[7,65]. Based on the same dataset and different models for co-limitation, Buitenhuis et al. (2003) arrived at $K_{s,Zn}$ values of ranging from 38 pmol L^{-1} to 300 pmol L^{-1}. They calculated Zn-limitation alone, at CO_2-replete conditions, of 19 pmol L^{-1}. Thus, the chosen value of $K_{s,Zn}$ is not a reflection of high Zn demand but determined by the functionality of biochemical co-limitation by Zn and C.

To calculate φ, a surface ocean Zn concentration of 50 pmol L^{-1} was assumed [2,70]. While these concentrations reflect total dissolved Zn, the relationship between bioavailable free Zn and dZn, especially in the field, remains unclear. Eq. 1 was then used to calculate effective CO_2 concentrations (and thus pCO_2 values) at which growth is halved, or in other words, $\mu = 0.5V_{max}$. We note that this calculation is distinct from the CO_2 half-saturation constant because of the co-limitation by Zn. The median pCO_2 threshold for 50% growth from the three diatom species was 278 ppm. Including coccolithophores decreases the median to 259 ppm. These values are slightly higher than the *in situ* evidence for Zn limitation at 220 ppm presented in the present study. Our results cannot be considered as an upper bound for Zn-CO_2 limitation, but serve as evidence for growth limitation under those specific environmental conditions.

Analyses of total dissolved metals using isotope dilution

The analysis of total dissolved metals has been described previously [71]. Briefly, seawater collected shipboard by pressure-filtering X-Niskin bottles through an acid-washed 142 mm, 0.2 µM polyethersulfone Supor membrane filter (Pall) within 3 hours of rosette recovery using high purity (99.999%) N_2 gas and stored at 4ºC. All sample collection occurred shipboard within an on-deck trace metal clean van. Samples were acidified to pH 1.7 with high purity HCl (Optima) within 7 months of collection and were stored acidified at room temperature for over 1 year prior to analysis.

Quantification of total dissolved Fe, Mn, Ni, Cu, Zn, and Cd was performed using isotope dilution. Acidified seawater samples were spiked with a stable isotope spike solution artificially enriched in ^{57}Fe, ^{61}Ni, ^{65}Cu, ^{67}Zn, and ^{110}Cd (Oak Ridge National Laboratory). Concentrations and spike ratios were verified by ICP-MS using a multi-element standard curve (SPEX CertiPrep). Preconcentration of spiked seawater samples for total dissolved metal analysis was performed using the automated solid phase extraction system seaFAST-pico (Elemental Scientific) in offline concentration mode with an initial volume of 15mL and elution volume of 500µL [72,73]. Following preconcentration, multielemental quantitative analysis was performed using an iCAP-Q inductively coupled plasma-mass spectrometer (ICP-MS) (Thermo Scientific). Concentrations of Mn, Fe, Ni, Cu, Zn and Cd were determined using a six-point external standard curve of a multi-element standard (SPEX CertiPrep), diluted to range from 1-10 ppb in 5% nitric acid. An indium standard (SPEX CertiPrep) was similarly added to these standard stocks, diluted to range 1-10 ppb. Instrument injection blanks consisted of 5% nitric acid in Milli-Q. Standard curve R^2 values were ≥0.98 for all metals monitored. Method accuracy and precision were assessed using the 2009 GEOTRACES coastal surface seawater (GSC) standard (n = 8; **Supplementary Table 5**), which produced values consistent with consensus results.

Macronutrient, pigment, and Fv/Fm analyses

Seawater for macronutrient (silicate, phosphate, nitrate, and nitrite) analyses were filtered through 0.2 µm pore-size Supor membrane filters and frozen at sea in acid-washed 60-mL high-density polyethylene bottles until analysis. Macronutrient analyses were conducted by nutrient autoanalyzer (Technicon Autoanalyzer II) by Joe Jennings at Oregon State University. The chemotaxonomic distribution of phytoplankton pigments was determined using HPLC as

described previously[74]. Photosynthetic efficiency of photosystem II (Fv/Fm) was measured using a Phyto PAM phytoplankton analyzer (Walz, Effeltrich, Germany) as described previously[75].

Bacterial abundance

One ml samples for heterotrophic prokaryotes abundance (HPA) analysis were fixed for 10 min with a mix of paraformaldehyde and glutaraldehyde (1% and 0.05% final concentration, respectively), frozen in liquid nitrogen and stored at −80°C until analysis. After thawing, samples were stained with SYBR Green (Invitrogen Milan, Italy) using 10^{-3} dilution of stock solution for 15 min at room temperature. Cell concentrations were assessed using a FACSVerse flow cytometer (BD BioSciences Inc., Franklin Lakes, USA) equipped with a 488 nm Ar laser and standard set of optical filters. FCS Express software was used for analyzing the data and HP were discriminated from other particles on the basis of scatter and green fluorescence from SYBR Green [76].

Zn uptake rates using ^{67}Zn

^{67}Zn stable isotope uptake experiments were performed to quantify the movement of dissolved Zn to the particulate phase (in units of pmol L^{-1} d^{-1}). Briefly, raw (unfiltered) seawater was collected using the trace metal rosette over a depth range of 10 – 600 m into 250mL trace metal clean polycarbonate bottles. Bottles were spiked with ^{67}Zn such that the total added (spiked) concentration of Zn was 2 nM. Immediately after spiking, incubation bottles were sealed, inverted to mix, and transferred to flow-through on-deck incubators for 24hr. Biomass was collected after 24hr by vacuum filtering each incubation sample at 34.5 kPa (5 psi) onto an acid-cleaned 3µm pore-size acrylic copolymer Versapore filter (Pall) mounted on an acid-cleaned plastic filtration rig. Sample filters were retrieved from storage at -80°C, removed from

cryovials using plastic acid-washed forceps, and transferred into trace metal clean 15 mL PFA vials with 4 mL of 5% HNO_3 (Optima) containing a 1 ppb Indium (In) internal standard. Filters were digested for ~3.5h at 140°C using a HotBlock® heating block (Environmental Express, USA) before they were removed and discarded. After evaporating the remaining solution to just dryness, the residue was resuspended in 2 mL of 5% HNO_3 (Optima) by light vortexing. Process blank filters were digested and processed as sample filters were. This experiment was also carried out using ^{110}Cd as a tracer of Cd uptake in separate incubation bottles (data not shown here). Digests were analyzed in duplicate by ICP-MS using a Thermo ICAP-Q plasma mass spectrometer calibrated to a multi-element standard curve (Spex Certiprep) over a range of 1 – 20 ppb. Natural Cd and Zn isotope abundances of the standards were assumed to calculate concentrations of ^{110}Cd, ^{111}Cd, ^{114}Cd, ^{67}Zn, ^{66}Zn, and ^{68}Zn. Total Zn uptake (pmol L^{-1} d^{-1}) was calculated using particulate ^{67}Zn and total water column dZn measurements as described previously[77]. The particulate metal measurements captured contributions from the active transport of metal into cells, nonspecific metal adsorption to cell surfaces, metal adsorption to non-living particulate organic matter, and metal adsorption to particulate inorganic matter, though we expect active transport into cells to dominate the measured particulate isotopic signal due to the high abundance of actively growing autotrophic cells in the photic zone observed in Southern Ocean during austral summer. Particulate Zn:P measurements presented in Figure 3d,e were calculated using particulate Zn measured on Cd-spiked filters and thus do not include any pZn contribution from Zn tracer addition. Particulate phosphorus concentrations were measured by ICP-MS simultaneously and were calibrated to a standard curve ranging from 100 to 3200 ppb using a 1 ppm certified P stock (Alfa Aesar Specpure). All SPEX and P standard curves had R^2 values > 0.99. The Zn stock solution used in the incubation experiments was similarly

analyzed by ICP-MS to confirm that the stock was not Fe contaminated— this analyses showed that less than 2.3 pM (which was near the instrument blank level for this analysis) of iron was added for every 2 nM of zinc, far less than needed to stimulate phytoplankton to the extent observed in our experiments.

Shipboard incubation experiments

Incubation experiments were conducted at station 27 (-74.9870°N, 165.8898°E). Raw surface seawater was pumped directly into a cleanroom container van, collected into acid-cleaned 50L carboys, and dispensed into acid-washed 1L polycarbonate bottles using a trace metal sampling system with acid-washed polypropylene tubing and a teflon diaphragm pump. Incubation bottles were first rinsed with seawater then filled. Seawater was collected at 16:05 UTC. Triplicate incubation bottles were amended with +Fe (1 nM), +Zn (2 nM) and +Fe+Zn, sealed, and placed into a flow-through on-deck incubator with light screens that shaded the incubator to 20% percent ambient surface irradiance. Incubations were sampled at 0, 48, 96, and 144 hours (corresponding to T0, T2, T4, and T6 timepoints) for analysis by filtering onto GFF filters for chlorophyll (all time points, biological triplicates), pigment analyses (T6, biological triplicates), and proteomic analyses (T6, pooled biological triplicates). Chlorophyll was extracted immediately, otherwise samples were frozen at -80°C until further analyses, with pigment and protein samples kept in -80°C freezers, liquid nitrogen dewars, or dry ice coolers at all times during transport back to the laboratories. All amendments and sampling were conducted in a positive-pressure, clean room van with laminar flow hoods and plastic sheeting to minimize trace-metal contamination.

Metaproteomic analysis

Water column metaproteomic biomass was collected onto 0.2, 3, and 51 µm pore-size filters using in-situ battery operated McLane pumps. Incubation metaproteomic samples were collected on GFF filters as described above. Filters were frozen at -80°C and transported as described above until laboratory extractions. Frozen filters were thawed and extracted as described previously [78]. Briefly, filters were extracted using SDS detergent to solubilize both membrane and soluble proteins and subjected to a 10-min heating incubation at 95 °C. Protein material was subsequently purified, alkylated, reduced and digested with trypsin (mass spectrometry grade; Promega Corporation) at a trypsin:protein ratio of 1:20 and peptides were purified using C18 tips (Pierce C18 Tips, 100-µl bed; Thermo Fisher Scientific). Purified peptides were diluted to 0.1 µg μl^{-1} and 20 µl (2 µg) was injected onto a Dionex UltiMate 3000 RSLCnano LC system (Thermo Fisher Scientific) with an additional RSLCnano pump run in online two-dimensional active modulation mode coupled to a Thermo Fusion Orbitrap mass spectrometer.

A translated metatranscriptome (see below) was used as a reference protein database and peptide spectra matches were performed using the SEQUEST algorithm within Proteome Discoverer v.2.1 (Thermo Fisher Scientific) with a fragment tolerance of 0.6 Da and parent tolerance of 10 ppm. Identification criteria consisted of a peptide threshold of 95% (false discovery rate (FDR) = 0.1%) and protein threshold of 99% (1 peptide minimum, FDR = 0.8%) in Scaffold v.5 (Proteome Software) resulting in 5,387 proteins identified in the incubation experiment and 27,924 proteins identified in the water column. To avoid double-counting mass spectra, exclusive spectral counts were used for the downstream proteomic analysis. Exclusive spectral counts were normalized using the normalized spectral abundance factor (NSAF) calculation [79] to allow for a comparison of protein abundance across samples while remaining

consistent with the metatranscriptomic procedure, see Cohen et al. 2021 for details. Counts associated with redundant ORFs (sharing identical taxonomic and functional assignments) were summed together.

Relative abundances of *Phaeocystis*, cryptophytes, dinoflagellates, and diatoms ("major groups") within the T6 incubation biomass were estimated by summing exclusive total protein spectral counts across all detected proteins that were assigned to the same group (as noted by best hit species; see metatranscriptomic methods below). Protein hits with LPI scores < 0.5, low assigned species identity (< 50%), or no assigned species were excluded.

Metatranscriptomic analysis

RNA sequencing was performed using the Illumina HiSeq platform. Transcriptomic assemblies were generated for biomass collected using McLane pumps filtered through 0.2, 3, and 51 µm pore-size filters. In order to enrich metatranscriptomic libraries derived from 0.2 µm filters in prokaryotic transcripts and libraries derived from 3 µm and 51 µm filters in eukaryotic transcripts, 0.2 µm libraries were generated from total rRNA-depleted mRNA and 3 µm and 51 µm libraries were generated from polyA mRNA. Total RNA was extracted from 0.2 µm, 3 µm, and 51µm filters using Macherey-Nagel a NucleoMag RNA kit (Macherey-Nagel GmbH & Co.KG). Cleared lysate was loaded into a 96 deep-well plate and put on an epMotion 5075 TMX liquid handler to complete the RNA extraction following the Machery-Nagel standard protocol. For 3 µm and 51 µm samples with total RNA greater than 1 ug, 800 ng of total RNA was used for preparing poly A libraries with an Illumina Stranded mRNA Prep Ligation kit (Illumina), following the manufacturer's protocol. For the 3 µm and 51 µm samples with total RNA less than 1 ug, 20 ng of total RNA was used as input for the SMART-Seq v4 Ultra Low Input RNA

kit (Takara Bio USA. Inc), which converts poly(A) RNA to full-length cDNA using a modified oligo (dT) primer with simultaneous cDNA amplification. The resulting double-stranded cDNA was then fragmented using a Covaris E210 system with the target size of 300bp. Libraries were prepared from fragmented double-stranded cDNA using an Illumina Stranded mRNA Prep Ligation kit (Illumina). For RNA obtained from 0.2 μm filters, ribosomal RNA was removed using a riboPOOL Seawater Kit (Galen Laboratory Supplies, North Haven, Connecticut, USA). The riboPOOL Seawater Kit is a customized mixture of Removal Solutions: Pan-Prokaryote riboPOOL, Pan-Plant riboPOOL and Pan-Mammal in a ratio of 6:1:1. The rRNA-depleted total RNA was used for cDNA synthesis by Ovation RNA-Seq System V2 (TECAN, Redwood City, USA). Double stranded cDNA was then prepared for the libraries using an Illumina Stranded mRNA Prep Ligation kit (Illumina). Ampure XP beads (Beckman Coulter) were used for final library purification. Library quality was analyzed on a 2200 TapeStation System with an Agilent High Sensitivity DNA 1000 ScreenTape System (Agilent Technologies, Santa Clara, CA, USA). Resulting libraries were subjected to paired-end Illumina sequencing via NovaSeq S4.

The input paired-end fastq sequences are trimmed of sequencing adapters, primers and low quality bases by using either BLASTN (NCBI, v2.2.25) [80] or trimmomatic, v0.36 [81]. The trimmed paired and unpaired sequences were then depleted of rRNA sequences with riboPicker v0.4.3 [82]. The command-line program clc_assembler, v5.2.1 (Qiagen) was used to assemble processed sequences into contigs and ORFs were identified by FragGeneScan, v1.31 [83]. The trimmed sequences were mapped to the predicted ORFs using the command-line program clc_mapper, v5.2.1 (Qiagen) to generate mapped raw read counts for each ORF. The raw counts were normalized initially to RPKM values, to account for variations in inter-sample sequencing depth and the ORF sequence length [84]. The RPKM values were subsequently converted to TPM

(transcripts per million) units for estimation of the relative RNA abundance among samples [85]. The ORFs were annotated for putative function by several programs in parallel using BLASTP against PhyloDB, hidden Markov models PFAM and TIGRFAM by HMMER, v3.3.2 [86], KEGG Ortholog HMM by kofamscan, v1.3.0 [87], and transmembrane HMM by TMHMM [88]. Additional annotations were generated by similarity searches using BLASTP to transporter (PhyloDB), organelle (PhyloDB) and KOG [89] databases. The ORFs are assigned to the best taxonomic species/group as determined by LPI (Lineage Probability Index) analysis [90]. The final list of curated ORFs was generated by removing ORFs with low mapping coverage (<50 reads total over all samples) and with no BLAST hits and no known domains.

Statistical analysis and data visualization

ANOVA and Dunnett tests were performed using MATLAB 2019a. Statistics are summarized in Supplementary Table 3. The linear regressions shown in Fig. 1h,i are a two-way (type-II) linear regressions, which allows for error in both the x and y parameters and does not assume dependence between the x and y axes. The two-way regression MATLAB function (lsqfitma.m) is available in python at https://github.com/rebecca-chmiel/GP15. Figures were made using matplotlib (version 3.5.0), Ocean Data View (version 5.5.2), Excel (2019), and RStudio (version 1.3.1093).

Data availability

CICLOPS (NBP18-01) total dissolved Zn, Zn uptake rates, macronutrients, and pigment datasets are available through the NSF's Biological and Chemical Oceanography Data Management Office (BCO-DMO) repository under project number 774945 (https://www.bco-

dmo.org/project/774945). The mass spectrometry global proteomics data for CICLOPS bottle incubations and water column analyses have been deposited with the ProteomeXchange Consortium through the PRIDE repository under the project name "Zinc-iron co-limitation of natural marine phytoplankton assemblages in coastal Antarctica" with project accession number PXD037056 (https://www.ebi.ac.uk/pride/archive/projects/PXD037056). This data is accessible for review by using the following login information: username reviewer_pxd037056@ebi.ac.uk, password: lFdOUoEb. The translated transcriptome used for spectrum to peptide matching has been deposited in the National Center for Biotechnology Information sequence read archive under BioProject accession no. PRJNA890306 (https://www.ncbi.nlm.nih.gov/bioproject/?term=PRJNA890306) and RNA-Seq BioSample accession nos. SAMN31286421-SAMN31286522 (https://www.ncbi.nlm.nih.gov/biosample/?term=SAMN31286421).

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Author contributions statement

All authors contributed to data acquisition and analysis. RMK, NLS, LEL, RJC, DR, DMM, MRM, FB, RBD, GRD and MAS implemented the shipboard incubation study. RMK, MMB, RJC, DR, TJH, and AVS contributed to the formal analysis. NLS, LEL, FB, OM, RF, and GRD contributed to pigment datasets and interpretations. CB provided bacterial abundance data. RBD contributed DIC and *in situ* pCO_2 data. AVS contributed analyses and discussion regarding historical pCO_2 data. AEA contributed the metatranscriptome reference database used for proteomic analyses. RMK and MAS wrote the original draft. RMK, MAS, GRD, AVS, TJH, and RBD contributed to review and editing. All authors approved the final submitted manuscript.

Competing interests statement

The authors declare no competing interests.

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Figures

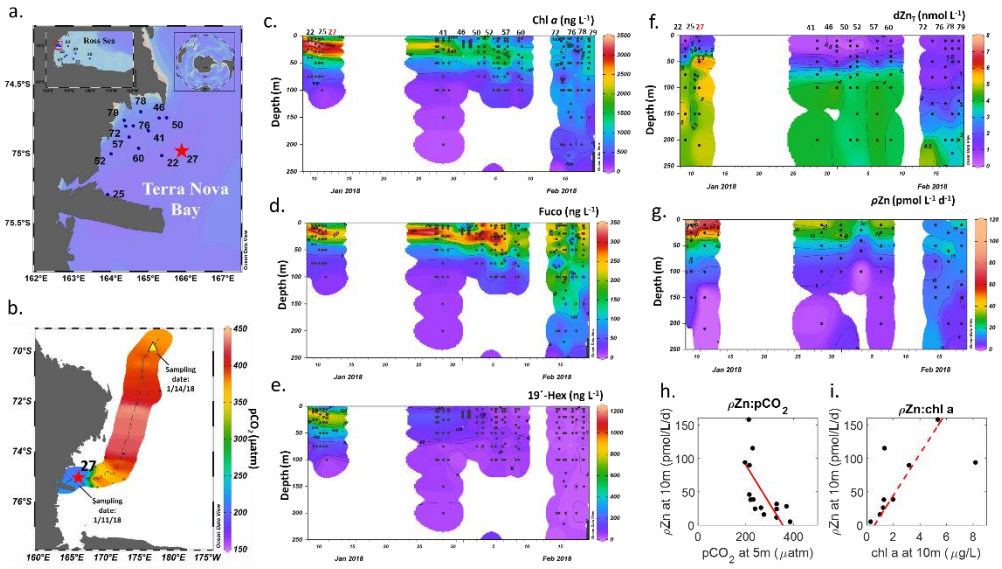
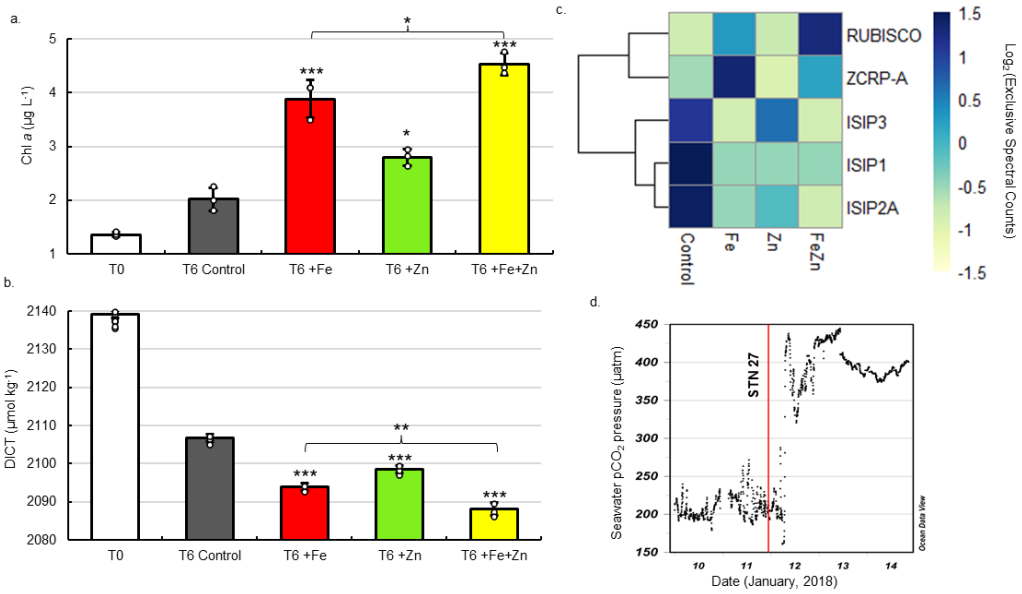


Figure 1. **Temporal biogeochemistry of Terra Nova Bay, Jan-Feb 2018.** (**a**) Sampling locations over the Ross Sea shelf in Terra Nova Bay, Antarctica. (**b**) Location of station 27 and surrounding seawater pCO_2 measured over a three-day transit northwards represented in color scale. Locations sampled on January 11, 2018 and on January 14, 2018 are indicated. (**c**) chlorophyll *a* (chl *a*), (**d**) fucoxanthin (fuco), (**e**) 19' hexanoyloxyfucoxanthin (19'-hex), (**f**) total dissolved Zn (dZn_T), and (**g**) total Zn uptake rates for all Terra Nova Bay stations over time measured in the upper 250m. Station numbers are given at the top of (c) and (f). Station data is presented in order of sampling date, from the earliest (Stn 22, early January) to the latest (Stn 79, late February). (**h**) negative linear relationship between seawater CO_2 partial pressure (pCO_2) at 5 m depth and Zn uptake rates (ρZn) measured at surface (≤10m) depths for 15 stations of the CICLOPS cruise (n = 15, R^2 = 0.63). (**i**) positive linear relationship between chlorophyll *a* at 10 m depth and Zn uptake rates (ρZn) measured at 10 m depth for 9 stations of the CICLOPS cruise (n = 9, R^2 = 0.65). The data gap between January 13-23 occurred when the ship was unable to sample due to icebreaking duties for the McMurdo Station resupply ship. Stations indicated in (a) are those where the trace metal rosette (TMR) was deployed; pigment data was supplemented with additional stations using a CTD.



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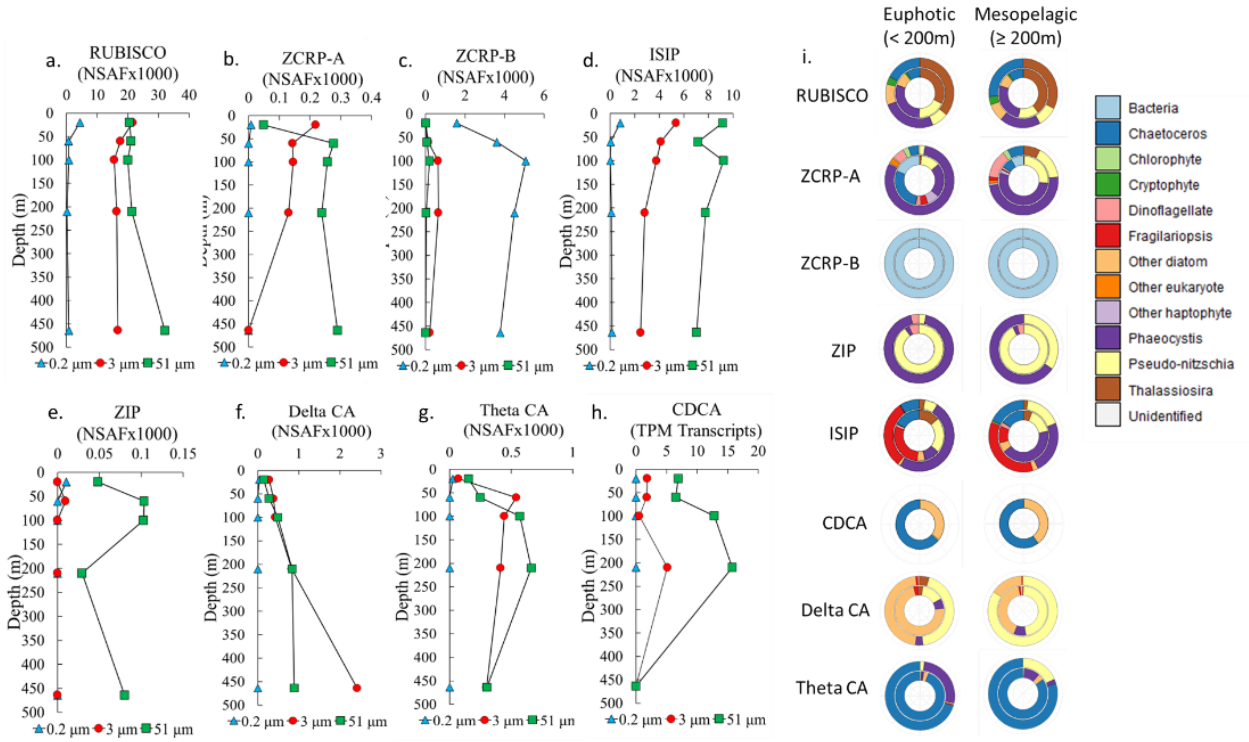

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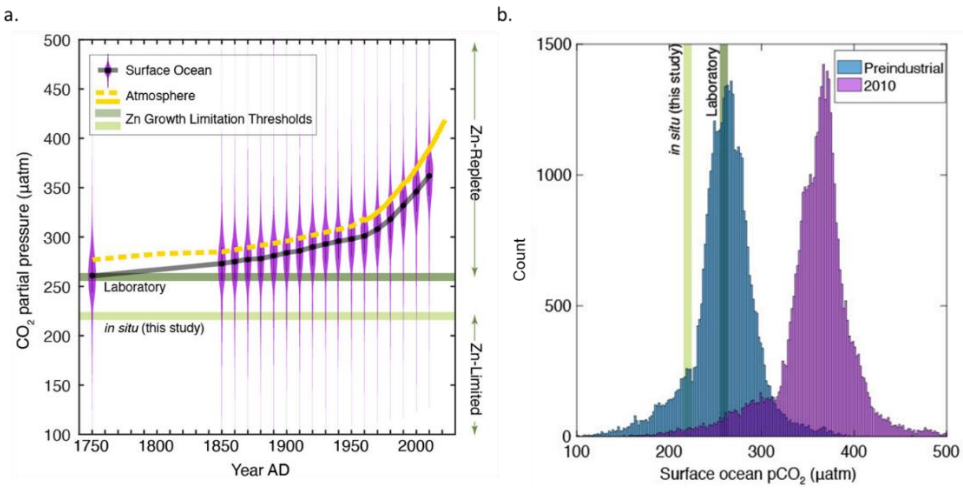

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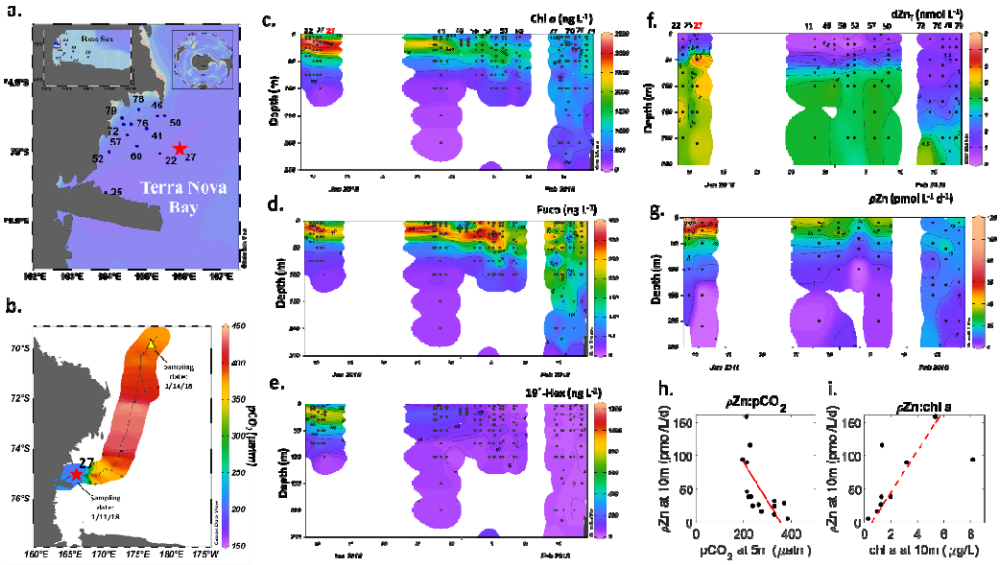
Main Text Figures



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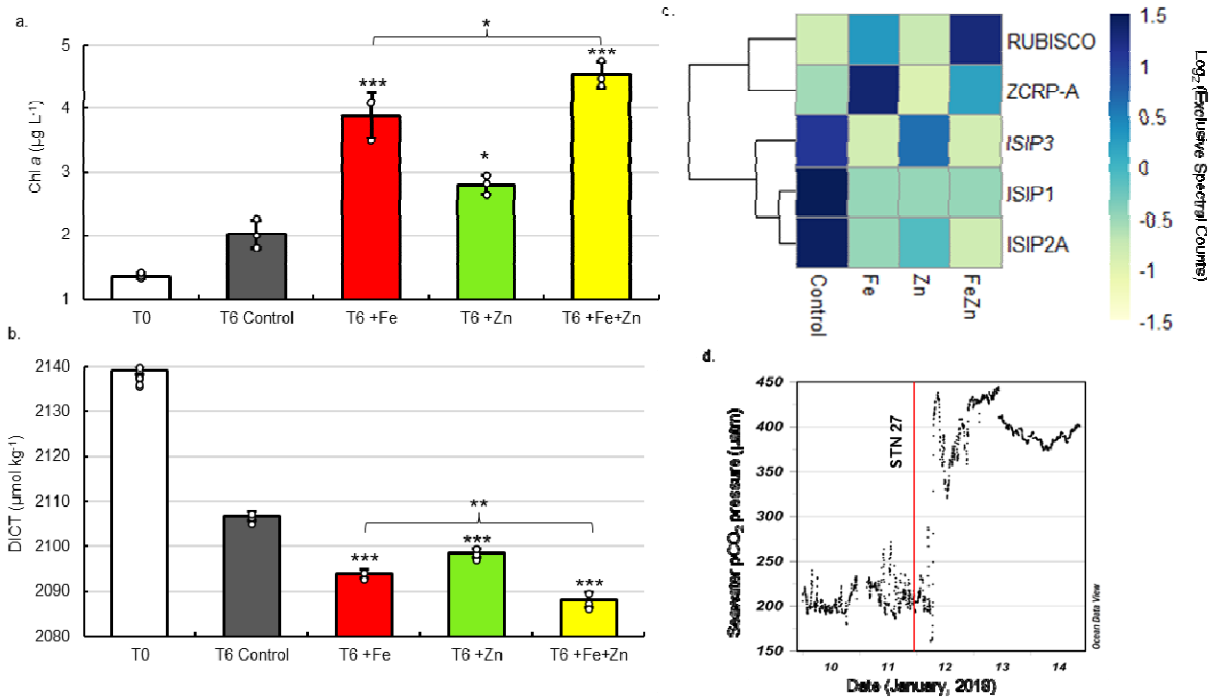

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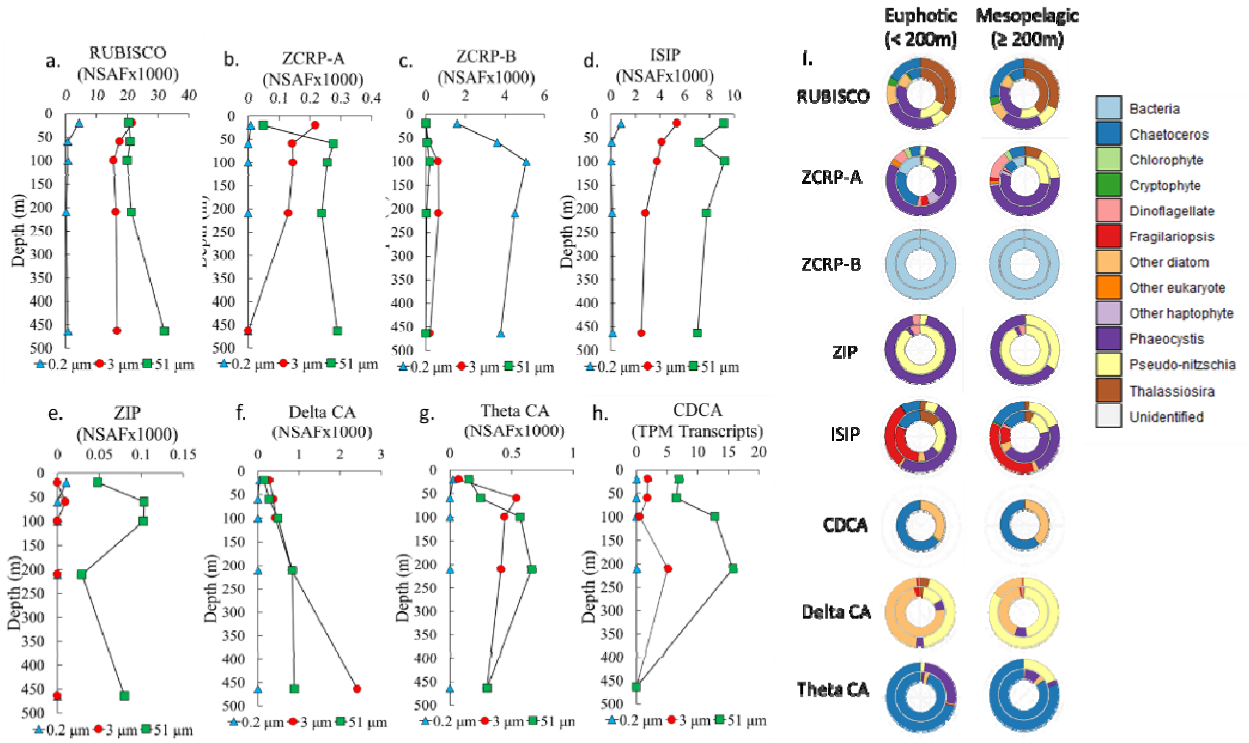

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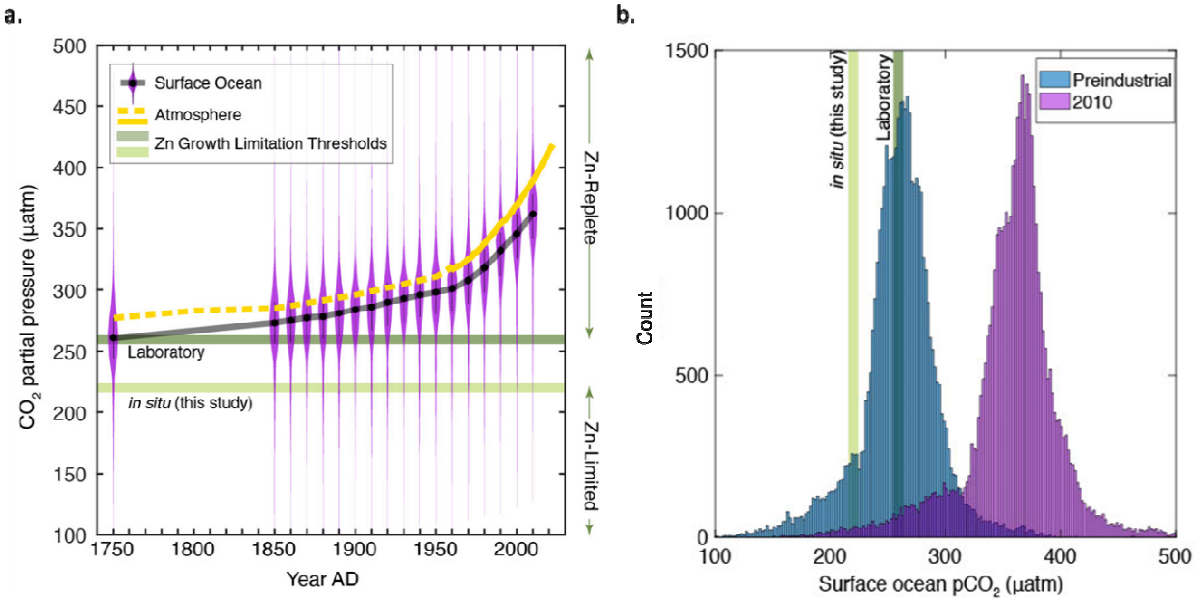

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