PROJECT SUMMARY

Overview:

This project will manage and implement a 60-day research cruise to the Amundsen Sea sector of the Antarctic margin to collect samples for measurements of a broad suite of trace elements and isotopes (TEIs), as part of the US GEOTRACES program. The cruise will comprise essential sampling operations (collection and shipboard processing) and ancillary measurements (hydrography, nutrients, algal pigments) in support of multiple, individual science projects, following the successful model of previous US GEOTRACES cruises in the Atlantic, Pacific and Arctic ocean basins. The cruise will sample the ocean region between 100°W and 135°W, with stations ranging from 67°S in the Antarctic Circumpolar Current southward to the Amundsen Sea continental shelf, including stations adjacent to several rapidly melting ice shelves and in highly-productive shelf polynyas. Water column samples will be collected using conventional and trace-metal clean CTD-rosette systems, in-situ high-volume pumps, and a towed fish sampler or small boat, using established methods. Sampling time will also be provided for collection of sea ice, floating glacial ice, and seafloor sediments. To facilitate access to the study region and capture the imprint of biological processes, the cruise will be carried out in late austral summer (late January-late March), ideally in 2022 following a complementary open-ocean US GEOTRACES cruise (GP17-OCE, supported through a separate, coordinated management proposal).

Intellectual Merit:

TEIs regulate marine primary production and provide tracers of past and present oceanic processes, such as circulation and particle export. The international research program GEOTRACES aims to identify the processes and quantify the fluxes that control the distributions of TEIs in the oceans, and to establish the sensitivity of these distributions to changing environmental conditions. Key TEIs include essential micronutrients (e.g., iron, zinc), tracers of modern and ancient ocean processes (e.g., aluminum, manganese, and isotopes of nitrogen, thorium and neodymium) and of human activities (e.g., lead). In the Southern Ocean, the Antarctic continental margins are important as sources of micronutrient trace elements such as iron, which fuels biological production and carbon export over the Antarctic shelf and in offshore waters of the Antarctic Circumpolar Current. Moreover, these regions are experiencing rapid environmental changes that are expected to impact oceanic circulation and biogeochemical cycles, for which TEIs provide crucial tracers and provide data needed to test and refine numerical models of the Earth system. The Amundsen Sea sector holds particular interest because of the pronounced, decadal-scale increases in the basal melt rates of glacial ice shelves that border the region, driven by intrusions of warm Circumpolar Deep Water (CDW) onto the continental shelf. This melting has potentially major impacts on global sea level, on the formation of Antarctic Bottom Water in the Ross Sea, and on primary production via mobilization of benthic and glacial iron and other TEIs mediated by these processes. We propose to manage and implement a US GEOTRACES cruise to support individual science projects that will exploit measurements of key and additional TEIs (e.g., cobalt, radium isotopes, mercury) to address a wide range of topics such as the sources, fate and impacts of bioactive trace elements; the distribution and transport of glacial melt; the compositional evolution of CDW as it upwells and circulates on the shelf; the rates and elemental stoichiometry of biological and biogeochemical processes; and the veracity of paleoenvironmental proxies and numerical model simulations.

Broader Impacts:

Beyond the disciplinary contributions, the proposed research will contribute knowledge concerning the cryosphere and its impacts on global sea level and ocean circulation, regional ecosystems and biological processes, ocean-atmosphere interactions, and past and future environmental change. The project will contribute to STEM Education and outreach through the participation of an NSF-funded PolarTREC education professional, and a K-12 STEM program for students from underserved and underrepresented schools run by Rutgers University education specialists. To foster public engagement, we will leverage the UCSC Science Communication Program to engage freelance science journalists to profile our research in this spectacular and harsh Antarctic environment. Finally, we anticipate substantial contributions to the training and mentoring of graduate students and early career scientists, as has been the case for previous US GEOTRACES research expeditions.
This proposal requires fieldwork in the Antarctic.

PROJECT DESCRIPTION

1. PREFACE: CONTEXT OF THE PROPOSED RESEARCH

GEOTRACES is an international research program that aims to improve our understanding of the biogeochemical cycles and large-scale distribution of trace elements and their isotopes in the ocean. To this end, over the past decade, the US GEOTRACES program has collected samples for measurements of trace elements and isotopes along a series of ocean sections across the North Atlantic, North and South Pacific, and Arctic Oceans. A remaining basin-scale section proposed for the US GEOTRACES program is the GP17 section, extending from Tahiti south to 67°S, near the WOCE/CLIVAR P16S line, and from there east along the WOCE/CLIVAR SO4P line, including a series of transects across the Amundsen Sea sector of the Antarctic continental margin, before heading northeast to the continental margin of southwest Chile. Logistics constraints dictate that two cruises (Fig. 1) are needed to complete this GP17 section at the lateral sampling resolution required by the GEOTRACES program, with one cruise sampling the deep ocean stations using a global-class research vessel ("GP17-OCE"), and the other cruise sampling the Antarctic continental margin using a research icebreaker ("GP17-ANT"). The NSF Chemical Oceanography Program has requested that separate proposals be submitted, both to the NSF Division of Ocean Sciences, to support the management and implementation of these two cruises; this proposal is for the management and implementation of the GP17-ANT cruise.

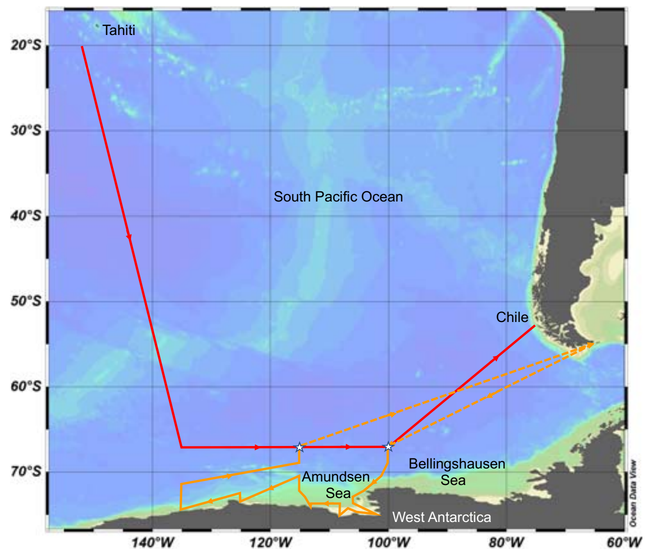

Figure 1. *Proposed tracks for the US GEOTRACES GP17-OCE (red) and GP17-ANT (orange) cruises; stars indicate crossover/intercalibration stations.*

2. INTELLECTUAL MERIT

2.1. Overview of US GEOTRACES Activities and Achievements

During the past twenty years, advances in sampling and analytical methodologies have allowed marine scientists to accurately quantify a wide range of trace elements and isotopes in the ocean at a relatively high spatial resolution. These chemical species are of interest because of their role in regulating marine primary production as essential micronutrients and toxicants, and as tracers of past and present oceanic processes such as circulation, particle export, and atmospheric deposition (Morel et al., 1991; Yu et al., 1996; Chase et al., 2003a; Measures & Vink, 2000). As such, the international research program GEOTRACES was established with the overarching aims of *identifying processes and quantifying fluxes that control the distributions of trace elements and isotopes in the oceans, and establishing the sensitivity of these distributions to changing environmental conditions* (Anderson and Henderson, 2005; Anderson, 2020). A major activity of the international GEOTRACES program has been a series of basin-scale ocean section cruises to collect water column samples at relatively high spatial resolution for the determination of a suite of key trace elements and isotopes (TEIs). With funding from NSF, the US contribution to this effort has comprised cruises in the North Atlantic (GA03, in 2010-2011), North and South Pacific (GP16 in 2013 and GP15 in 2018), and Arctic (GN01 in 2015) Oceans.

The unique combination of measurements of a broad suite of trace elements, radioisotopes and stable isotopes in samples collected during these US GEOTRACES cruises has facilitated major advances in our understanding of oceanic biogeochemistry, including improved constraints on the oceanic residence time of trace elements (Hayes et al., 2018a; Kadko et al., 2019); the composition and associated deposition and dissolution of dust over the ocean surface (Shelley et al., 2015; Anderson et al., 2016); the composition, fluxes and transformations of oceanic particles (Hayes et al., 2018b; Ohnemus et al., 2018; Pavia et al., 2019); the relative importance of different sources of dissolved iron to the ocean (Conway and John, 2014a; Conway et al. 2019); the nature of hydrothermal trace element inputs to the ocean interior (Resing et al., 2015; Roshan et al., 2016; Fitzsimmons et al., 2017); the physicochemical speciation of trace elements in seawater (Fitzsimmons et al., 2015; Boiteau et al., 2016a, 2016b; Bowman et al., 2016); and the assimilation, remineralization and scavenging of bioactive trace elements (Roshan & Wu, 2015; Twining et al., 2015; Roshan et al., 2018; Jensen et al., 2019).

2.2. Rationale for a US GEOTRACES Section Including the Antarctic Continental Margin

The distributions and dynamics of TEIs around the Antarctic continental margins are of particular interest, in terms of their potential biogeochemical impacts and in their utility as tracers of a range of different oceanic processes. The adjacent Southern Ocean comprises the largest high nutrient, low chlorophyll region of the world ocean, where the magnitude of primary production is thought to be regulated by the supply of dissolved iron, and possibly other trace elements (Martin et al., 1990; De Baar et al., 1995; Watson et al., 2000; Moore et al., 2013; Coale et al., 2003; Betrand et al., 2007; Saito et al., 2010). Importantly, primary production in surface waters of the Southern Ocean is thought to regulate the oceanic uptake of carbon dioxide and the supply of nutrients to the lower latitudes, via the biological drawdown of nutrients in surface waters of the so-called "lower-cell" and "upper cell", respectively, of the meridional overturning circulation (Sarmiento et al, 2004; Marinov et al., 2006; Sigman et al., 2010; Resing et al., 2015). Consequently, numerous studies have focused attention on the sources of iron to surface waters of the open Southern Ocean, which are subject to a chronic deficiency in dissolved iron (DFe) relative to macronutrients (Coale et al., 2004; De Baar et al., 2005; Cassar et al., 2007; Boyd et al., 2010), and over the Antarctic shelves, where deep waters are formed and primary production can be seasonally limited by DFe supply (Fitzwater et al., 2000; Sedwick et al., 2000; Alderkamp et al., 2015).

The Antarctic continental margins are likely to provide a number of important inputs of iron and other TEIs to surrounding ocean waters, including sedimentary and benthic inputs that are mobilized by physical circulation processes (Tagliabue et al., 2009; De Jong et al., 2012; Measures et al., 2013; Marsay et al., 2014; Kustka et al., 2015; Ndungu et al., 2016; St-Laurent et al., 2017; Sherrell et al., 2018; Jung et al., 2019); glacial and subglacial meltwaters, including melting icebergs (Raiswell et al., 2006, 2008; Lin et al., 2011; Gerringa et al., 2012; Planquette et al., 2013; McGillicuddy et al., 2015; Sherrell et al., 2015; Duprat et al., 2016); meltwater from sea ice and overlying snow (Sedwick & DiTullio, 1997; Edwards & Sedwick, 2001; Lannuzel et al., 2010, 2016; Van der Merwe et al., 2011), and mineral aerosol deposition (Chewings et al., 2014; Winton et al., 2014, 2016; Bhattachan et al., 2015; Duprat et al., 2019). However, the distributions, relative magnitudes, and potential for future changes in these TEI inputs to the Southern Ocean remain poorly understood. Recent modeling studies have simulated these inputs and associated transport and biological impacts around the Antarctic continent (Death et al., 2014; Mack et al., 2017; St-Laurent et al., 2017, 2019; Laufkoetter et al., 2018; Dinniman et al., 2020), although field observations are required to evaluate the assumptions and fidelity of these model simulations.

The coastal polynyas around the Antarctic continental margin are among the most productive areas in the Southern Ocean (Arrigo et al., 2008a; Smith & Comiso, 2008). It has been suggested that some of these coastal polynyas may serve as oceanic sinks for carbon dioxide (Arrigo et al., 2008b, 2015; Laufkoetter et al., 2018), as a result of biological carbon dioxide drawdown and vertical export of organic matter, combined with the formation of oceanic deep waters over certain areas of the Antarctic shelves (Orsi et al., 1999; Tagliabue & Arrigo, 2005; Heywood et al., 2014; Shadwick et al., 2014). Notably, these processes are expected to change in response to a warming climate: primary production over the Antarctic margins is likely to be modulated by changes in iron supply and in the mixing-irradiance regime (Smith et al., 2014; Boyd et al., 2015), whereas decreased production of Antarctic Bottom Water (AABW), as a result of warming and freshening in AABW source regions on the Antarctic shelves, has already been documented (Jacobs et al., 2002; Rintoul, 2007; Schmidtko et al., 2014; Van Wijk & Rintoul, 2014). The impacts of these changes on ocean biogeochemistry, the global carbon cycle and ocean circulation are clearly important priorities for future research (e.g., Kennicutt et al., 2015).

The broad suite of TEIs measured as part of the GEOTRACES program (see Anderson, 2020), including but not limited to the radioactive isotopes of radium and thorium and the stable isotopes of iron, zinc and cadmium, offer to provide insights into these questions, including quantitative information on sources, transport and removal of micronutrient trace elements, and associated rates of biological production and carbon export, from which the trajectories of future environmental changes may be inferred (e.g., Conway & John, 2014b; Abadie et al., 2017; Sanial et al., 2018; Hayes et al., 2018b; Black et al., 2018). Other chemical tracers such as noble gases and the stable isotopic composition of water can provide information on the meltwater contributions from glacial and sea ice, and their transport, entrainment and impacts on the formation of dense shelf waters that contribute to oceanic bottom waters (e.g., Brown et al., 2014; Loose et al., 2016; Biddle et al., 2019). In addition, information on past and present biogeochemical processes, such as export production and remineralization, scavenging, and water mass formation, may be derived from measurements of nutrient-like (e.g., cadmium, zinc), scavenged (e.g., thorium, protactinium) and quasi-conservative (e.g., neodymium) TEIs, in concert with macronutrients, stable isotopes, oxygen and hydrography (e.g., Chase et al., 2003b; Hendry et al., 2008; Piotrowski et al., 2008; DiFiore et al., 2009; Xue et al., 2013; John & Conway, 2014; Vance et al., 2017; Roy-Barman et al., 2019).

Against this background, we propose to implement and manage a US GEOTRACES cruise that would facilitate the collection of such TEI data along the Amundsen Sea sector of the Antarctic continental margin, in the southeast Pacific sector of the Southern Ocean (Figs. 1, 2). The Amundsen Sea sector was chosen as the focus of this proposed field program because of its importance for key physical and biogeochemical processes that characterize the Antarctic margins and impact the broader Southern Ocean environment, and the rapid environmental changes that have been documented in this region.

2.3. Proposed Study Region: The Amundsen Sea Sector of the Antarctic Margin

Scientific Rationale for the Proposed Study Region

Much of the Antarctic coastline consists of floating glacial ice shelves, some of which terminate in coastal polynyas maintained by offshore winds or upwelling of warm waters (Bromwich 1989; Arrigo et al., 2015). The different sectors of the Antarctic continental shelves can be broadly categorized as either "warm" ("Amundsen-like") or "cold" ("Weddell-like"), depending on the heat content of shelf waters, which is largely determined by the transport of warm Circumpolar Deep Water (CDW) onto the shelf (Petty et al., 2013; Rignot et al., 2013; Dinniman et al., 2020). The cold shelves, such as the Weddell Sea and Ross Sea, are characterized by the formation of dense shelf waters that can contribute to the AABW, and by relatively low basal melt rates of glacial ice shelves, where iceberg calving dominates glacial mass loss. Conversely, warm shelves, such as the Amundsen and Bellingshausen Seas, do not contribute to AABW formation, but border ice shelves with high basal melt rates (Jacobs et al., 1996; Meredith et al., 2000; Orsi et al., 2002; Smethie & Jacobs 2005; Dinniman et al., 2012; Rignot et al., 2013).

In the context of understanding the inputs and transformations of TEIs along the Antarctic margins, and of utilizing TEIs as tracers of biological, biogeochemical and physical processes in this oceanic region, the Amundsen Sea provides perhaps the best example of the "warm shelf" end member. The glacial ice shelves that border the Amundsen Sea continental shelf (Fig. 2a) exhibit the highest basal melt rates on the Antarctic margin, with the Pine Island, Thwaites, Crosson, Dotson and Getz Ice Shelves accounting for nearly 30% of the estimated total basal melting rate of Antarctic glacial ice as of 2013 (Rignot et al., 2013; Fig 2b). Moreover, there is evidence that these melting rates have markedly accelerated during the past few decades, particularly in the Amundsen Sea sector (Rignot et al., 2019), and will continue to increase in the coming century with a warming climate, with important implications for the stability of the West Antarctic ice sheet and global sea level (Gardner et al., 2018; Naughten et al., 2018; Shepherd et al., 2018; Rignot et al., 2019; Bronselaer et al., 2020). As such, like the Arctic and the West Antarctic Peninsula (Meredith & King, 2005; Walsh et al., 2011; Overland et al., 2014; Cook et al., 2016), the Amundsen Sea is a region experiencing rapid environmental change; hence there is an imperative to document and understand present-day conditions, in order to assess future changes and their impacts.

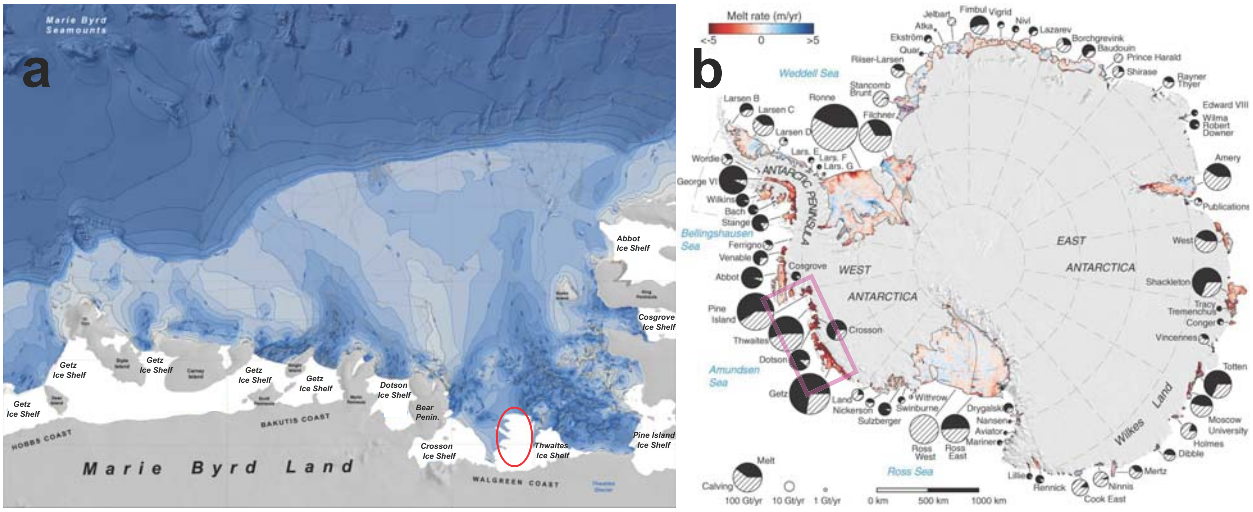

Figure 2. *(a) Bathymetric map of Amundsen Sea showing major ice shelves, modified from Stammerjohn et al. (2015); most of Thwaites Glacier Tongue (red oval) calved away as iceberg B22, now grounded on bank to northeast of Bear Peninsula (see Fig. 5b); (b) Pan-Antarctic estimates of glacial ice shelf basal melt rates (color bar; red = melting, blue = freezing) and glacial ice loss, including proportions due to basal melt vs. iceberg calving (circles), from Rignot et al. (2013). Pink rectangle indicates location of (a).*

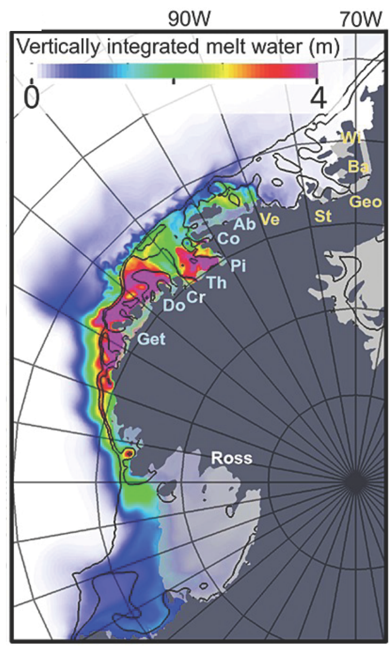

Figure 3. *Modeled distribution of basal meltwater derived from glacial ice shelves in the Amundsen Sea (Getz, Dotson, Crosson, Thwaites, and Pine Island) after 10 y simulation (from Nakayama et al., 2014).*

The high basal melt rates of ice shelves bordering the Amundsen Sea imply that this sector of the Antarctic margin contributes a relatively large flux of glacial meltwater to "downstream" shelf regions, with the meltwater entrained into the CDW that intrudes onto the shelf and under the ice shelf cavities. Indeed, simulations using an ocean/sea-ice/ice-shelf model suggest that glacial meltwater originating from the Amundsen and Bellingshausen Seas, dominated by melt from the Getz Ice Shelf, is a major source of the multi-decadal scale freshening that has been documented in the Ross Sea (Fig. 3), and thus potentially linked to secular changes in AABW production (Nakayama et al., 2014). Meltwaters carry distinctive geochemical signatures in their concentrations of noble gases and stable isotopic composition, such that water-column measurements of these species allow quantification of fresh water inputs from sea ice melt and meteoric water inputs (Brown et al., 2014; Loose & Jenkins, 2014; Biddle et al., 2019), as well as assessment of ice formation and glacial meltwater entrainment in oceanic deep waters (Loose et al., 2016). Incorporation of such measurements as part of a GEOTRACES field program, together with existing data from this region (Hohmann et al., 2002; Randall-Goodwin et al., 2015; Kim et al., 2016), offer to provide information on decadal-scale changes in meltwater inputs to this Southern Ocean sector, as well as the transport of TEIs associated with glacial melting.

The large and increasing melt rates of the ice shelves that surround the Amundsen Sea and other warm Antarctic continental shelves (e.g., in the Bellingshausen Sea and along the West Antarctic Peninsula) are also likely to have **substantial impacts on biogeochemical processes** in adjacent and downstream ocean waters. One example is an elevated supply of "new" DFe to surface waters of the Antarctic margins and perhaps to offshore waters in the Antarctic Circumpolar Current (ACC), relative to the DFe/nitrate ratio of the iron-deficient CDW that ultimately supplies macronutrients

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to the Antarctic continental shelves (Smith et al., 2012; McGillicuddy et al., 2015). This input of new DFe is thought to fuel the high rates of primary production observed in adjacent shelf waters (Gerringa et al., 2012; Alderkamp et al., 2012, 2015; Yager et al., 2012, 2016), and indeed the Amundsen Sea Polynya is distinguished by the highest net primary production per unit area on the Antarctic margin (Arrigo et al., 2015). This interpretation is supported by water column samples collected in the polynyas adjacent to the Pine Island and Dotson Ice Shelves, where relatively high concentrations of DFe (~1 nM) and other bioactive trace elements were observed adjacent to the glacial ice shelves and sea floor (Figs. 4a-4c; Gerringa et al., 2012; Planquette et al., 2013; Sherrell et al., 2015).

Subsequent numerical modeling studies suggest that the elevated DFe concentrations observed near these ice shelves reflect both direct inputs from glacial meltwaters and sedimentary/benthic inputs that are mobilized by buoyancy-driven overturning circulation associated with the melting ice shelves, termed the "meltwater pump" (St-Laurent et al., 2017, 2019; Dinniman et al., 2020; Figs. 4d, 5a). These model simulations imply that (1) westward advection of DFe from "upstream" areas of the inner shelf contributes to the DFe that supports blooms in the Amundsen Sea; (2) elevated production over inner-shelf areas "downstream" (to the west) of the Amundsen Sea shelf is supported by enhanced delivery of DFe associated with ice shelf melting; and (3) there is considerable off-shelf transport of the DFe associated with the ice shelf melting (Fig. 4d). Further empirical data from this region – including data needed to constrain the processes and rates of DFe supply, DFe losses via biological uptake and scavenging, and DFe regeneration, as well as phytoplankton uptake stoichiometry and physiological status, and the boundary conditions for this system – are required to assess the fidelity of these model predictions, and to understand the fate of benthic and glacial iron that is carried westwards and offshore from the Amundsen Sea shelf. The chemical tracers that are routinely measured as part of GEOTRACES section cruises will provide such data.

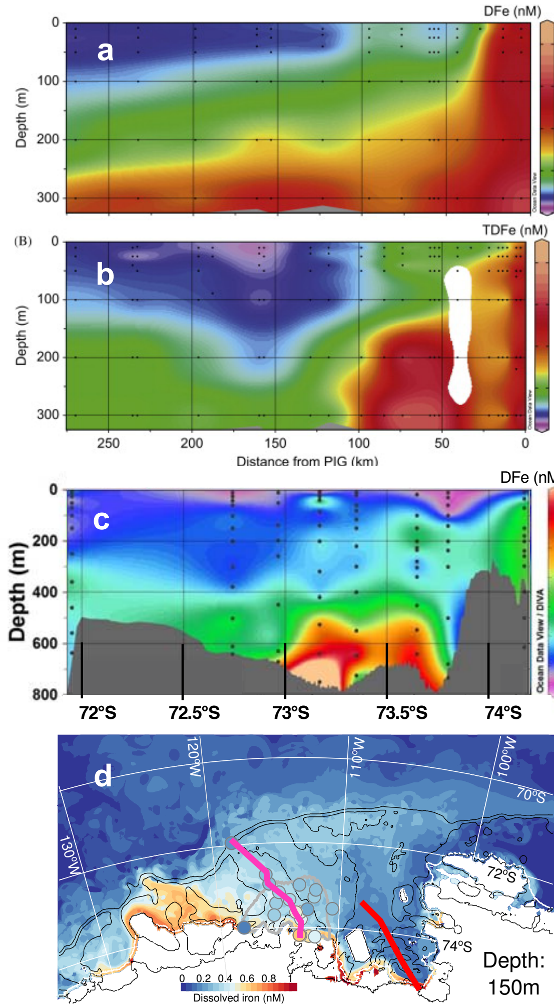

Figure 4. *Vertical sections (~N-S) of (a) DFe and (b) total-dissolvable iron in Pine Island Polynya, with Pine Island Ice Shelf on right (red line in d) from Gerringa et al. (2012); (c) vertical section (~N-S) of DFe in Dotson Trough, Amundsen Sea Polynya, with Dotson Ice Shelf on right (pink line in d) from Sherrell et al. (2015); (d) modeled DFe distribution at 150 m depth in the Amundsen Sea, dominated by input associated with glacial melt processes, modified from St-Laurent et al. (2019).*

In addition to glacial melt, the broad suite of GEOTRACES measurements offers the potential to assess inputs of TEIs to this ocean region from other poorly constrained sources. One of these is meltwater from sea ice, which exhibits considerable spatial and temporal variability in the Amundsen Sea (Arrigo et al., 2012; Stammerjohn et al., 2015), and for which end member TEI concentrations are highly variable and ill constrained (Lannuzel et al., 2010, 2016; Vancoppenolle et al., 2013). Sea ice meltwater is thought to provide a significant and climate-sensitive source of iron and other bioactive TEIs, as well as metal-binding organic ligands, to surface waters around the Antarctic margin (Arrigo et al., 2012;

Vancoppenolle et al., 2013; De Jong et al., 2015; McGillicuddy et al., 2015; Lannuzel et al., 2016; Dinniman et al., 2020). The same tracers that track glacial meltwater also allow quantification of sea ice melt in the water column, which, combined with TEI measurements in sea ice and surface ocean waters, can provide information on end member compositions, input fluxes, and chemical transformations. Another potentially important source of TEIs and fresh water to the Antarctic shelves is subglacial meltwater from the hydrologic system between the glacial ice and the continent, which is exported at the ice margin and is likely to contain biologically available reduced and nanoparticulate iron species and other TEIs, including distinctive lithogenic tracers (e.g., Jeandel et al., 2007). Model simulations (Death et al., 2014) and empirical evidence (Shoenfelt et al., 2017) suggest that this is an important iron source to the Southern Ocean with significant inputs in the Amundsen Sea, although pertinent field observations are lacking. Also of interest are possible TEI inputs associated with volcanism along the West Antarctic Rift System (LeMasurier, 2013; De Vries et al., 2018). In addition to its potential importance for the stability of the West Antarctic Ice Sheet and global sea level (Blankenship et al., 1993; Joughin & Alley, 2011), active subglacial volcanism adjacent to the Amundsen Sea may contribute to the discharge of subglacial meltwaters, as discussed above, or submarine hydrothermal activity beneath ice shelf cavities – both potentially important as sources of TEIs to the adjacent ocean. Indeed, seawater adjacent to the Pine Island Ice Shelf exhibits an elevated helium-3 signature, indicative of volcanic or hydrothermal inputs (Loose et al., 2018). The significance of such inputs for other TEIs, such as iron is not known, but this finding raises exciting questions for GEOTRACES research in this region.

Background: Physical and Biological Characteristics of the Proposed Study Region

The Amundsen Sea is a large embayment that borders Marie Byrd Land in West Antarctica, located roughly halfway between the Antarctic Peninsula and the Ross Sea. Like much of the Antarctic margin, the continental shelf is relatively broad and deep (Jacobs, 1989), with a sill depth at the shelf-slope break of ~300-600 m (Fig. 2a). The shelf deepens toward the continent, as a result of continental ice loading, and is traversed by several large troughs extending from the shelf break to the continent, which are remnants of glacial scouring during the Pleistocene ice ages, when the continental ice sheet extended to the modern shelf break (Nitsche et al., 2007; Fig. 2a). The Amundsen Sea is a major locus for the outflow of glacial ice from the West Antarctic Ice Sheet (Mouginot et al., 2014; Sutterly et al., 2014). Several outlet glaciers terminate in the embayment, forming floating ice shelves up to 100 km long and hundreds of meters thick (Fig. 5b). Glacial ice discharge to the Amundsen Sea is estimated to have nearly doubled since 1973, primarily from melting within the cavities of floating ice shelves that are located over deep troughs on the inner shelf, and contributions from iceberg calving and sub-glacial meltwater discharge (Shepherd et al., 2002; Mouginot et al., 2014; Millan et al., 2017; Rignot et al., 2019).

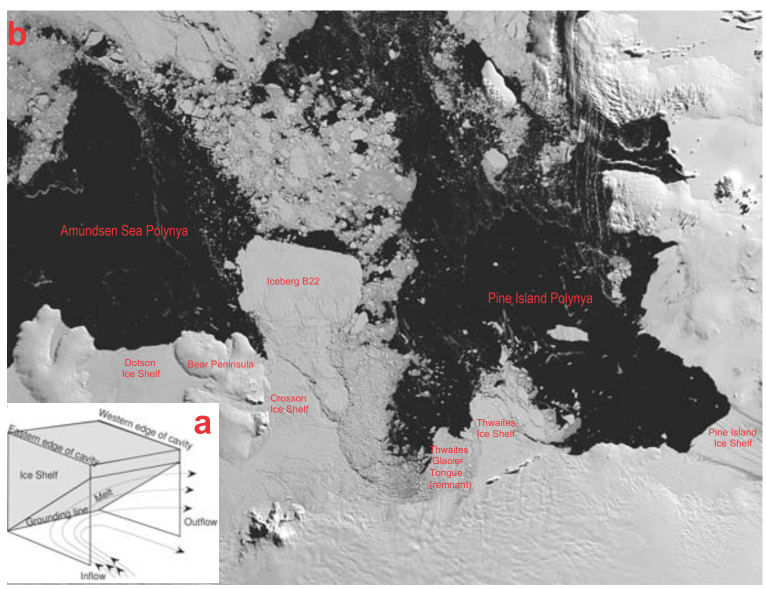

Figure 5. *(a) Schematic of buoyancy-driven circulation under glacial ice shelves in the Amundsen Sea (provided by Pierre St-Laurent); (b) MODIS image of Amundsen Sea (March 2019) showing the two polynyas and adjacent ice shelves (NSIDC).*

These increases in glacial melting are driven mainly by increased intrusion of warm (~2°C) Circumpolar Deep Water (CDW) on to the shelf, in response to changes in the westerly winds as a result of both anthropogenic forcing and variations in the Southern Annular Mode, exacerbated by changes in ice shelf morphology (Jacobs et al., 2011; Steig et al., 2012; Rignot et al., 2014). The CDW intrusions flow south along the eastern flanks of the shelf troughs, and mix with the overlying Winter Water (WW) to form the slightly cooler and fresher modified CDW (mCDW), which eventually flows beneath the floating ice shelves (Arneborg et al., 2012; Ha et al., 2014). Basal melting within the ice shelf cavities cools and adds 1-2% meltwater to the mCDW, which increases in buoyancy and eventually emerges from the ice shelf cavities as a geostrophically-driven northward outflow at depths of ~150-400 m (Jenkins, 1999; Jacobs et al., 2011; Ha et al., 2014; Fig. 5a). This emerging, northward flowing, melt-laden water is entrained in the WW during winter and contributes to the Antarctic Surface Water during summer (Randall-Goodwin et al., 2015); observations and model simulations suggest that it is carried westward on the inner shelf, with some also reaching the outer shelf to be carried eastward and offshore toward the deep ocean and ACC (Nakayama et al,, 2013, 2014; Ha et al., 2014; St-Laurent et al., 2017, 2019; Dinniman et al., 2020).

During spring and summer, southerly winds move sea ice away from the coast and create two adjacent polynyas, the Amundsen Sea Polynya (ASP) and the smaller Pine Island Polynya (PIP), separated by a N-S line of icebergs and fast ice grounded to the east of Bear Peninsula (Fig. 5b). Outside the polynyas, sea ice can extend well beyond the shelf break, often through summer (Stammerjohn et al., 2015). Apparently supported by favorable irradiance and a sufficient supply of macro- and micronutrients nutrients and iron, intense phytoplankton blooms develop in both polynyas commencing in late spring, with maximum surface chlorophyll typically observed in January (Arrigo and Van Dijken, 2003; Arrigo et al., 2012; Alderkamp et al., 2012; Lee et al., 2012; Sherell et al. 2015; Yager et al., 2016). The polynya blooms are dominated by *Phaeocystis antarctica*, whereas *P. antarctica* and diatoms dominate the marginal ice zone outside the polynyas (Alderkamp et al., 2012; Lee et al., 2012; Yager et al., 2016). Iron supply associated with glacial meltwater and melt-driven circulation has been suggested as key in supporting the ASP and PIP blooms (Alderkamp et al., 2012; Gerringa et al., 2012; Sherrell et al., 2015; St-Laurent et al., 2017), although field experiments and recent modeling work suggest that iron and light stress impact phytoplankton during the bloom period (Alderkamp et al., 2015; Oliver et al., 2019), raising questions regarding the nature of iron supply and importance of new versus recycled production. In contrast to other areas of the Antarctic margin and the open Southern Ocean, limited field data suggest a close temporal coupling between the peak phytoplankton bloom and vertical export of organic matter in the ASP (Langone et al., 2003; Ducklow et al., 2015; Lee et al., 2017; Kim et al., 2019; Laws & Maiti, 2019). In addition, despite observations of high algal biomass, net primary production and seasonal biological drawdown of carbon dioxide, the overall efficiency of the biological pump in the Amundsen Sea remains in question (Mu et al., 2014; Yager et al., 2016; Lee et al., 2017).

2.4. Scientific Objective of the US GEOTRACES GP17-ANT Section

Given the importance of the Amundsen Sea for glacial meltwater discharge and associated inputs and mobilization of TEIs, the potential impacts of these inputs, and the rapid pace of environmental changes in this region, we propose to manage and implement US GEOTRACES cruise GP17-ANT, focused on the Amundsen Sea. Our primary objective is to provide a platform for individual, hypothesis-driven projects that address a broad range of topics within the GEOTRACES scientific mission, such as:

(i) the regional distribution and entrainment of glacial, sub-glacial and sea-ice meltwaters derived from the Amundsen Sea sector, as gleaned from measurements of noble gases and the oxygen isotopic composition of seawater, and the associated inputs and transport of dissolved and particulate TEIs;

(ii) the internal cycling of TEIs, including the rates and stoichiometry of biological uptake, vertical and lateral particle export, and remineralization and scavenging, based on measurements of dissolved and particulate TEIs, TEI speciation, thorium isotopes, dissolved oxygen/argon ratios, and macronutrients;

(iii) the sediment-water column exchanges of TEIs, derived from measurements of the concentrations, speciation and isotopic composition of trace elements in the water column, benthic boundary layer and sediment pore fluids, and the integrated fluxes of sediment-derived TEIs into the water column, based on measurements of radiotracers such as radium isotopes;

(iv) the end-member concentrations and speciation of TEIs in sea ice, snow, brines and floating glacial ice, as well as diagnostic meltwater tracers such as noble gases and the oxygen isotopic composition of water, as revealed by the targeted sampling of these phases;

(v) the sources, transport and transformations of particulate TEIs, including their potential biological availability, and the role of different particle types (e.g., biogenic versus lithogenic) in the scavenging of dissolved TEIs and incorporation of paleoproxies from the water column;

(vi) the inputs associated with subglacial continental weathering, volcanic activity or hydrothermal circulation, which may be revealed by measurements of the concentration and isotopic composition of elements such as lead, neodymium, iron and helium;

(vii) the efficiency of biological macro- and micronutrient utilization and associated isotopic fractionation in CDW as it upwells on the shelf and interacts with glacial ice shelves, sediments and shelf waters, as inferred from targeted measurements of carbon, macro- and micronutrients, and hydrography.

Moreover, the cruise data will be used to (1) test and refine numerical models of this ocean region (e.g., Nakayama et al., 2014; St-Laurent et al., 2017, 2019; Laufkoetter et al., 2018; Dinniman et al., 2020), thereby improving projections of future environmental changes, and (2) inform and refine geochemical paleoproxies, such as the isotopic composition of carbon and nitrogen, and uranium-series radioisotopes.

2.5. Scientific Linkages Between the GP17-ANT and GP17-OCE Cruises

Some of the major science questions to be addressed by the GP17 cruises concern the meridional and zonal gradients in TEIs between the Polar Front and the Antarctic continental shelf, and the rates and magnitudes of processes that control these distributions. For example, the potential off-shelf transport of benthic materials and glacial melt waters, and associated TEIs such as iron, may fuel primary production in the ACC (Laufkoetter et al., 2018; Dinniman et al., 2020), although relevant data to test this hypothesis are lacking. Also of interest is the TEI composition of CDW as it upwells south of the Polar Front, and its evolution as it intrudes onto the Antarctic margins and is modified by interaction with the seafloor and glacial ice shelves, and by biological processes, before circulating downstream and northward across the continental shelf. The vast size of our study region renders the task of collecting such data impossible for a single vessel as part of the larger GP17 section. To surmount this obstacle, we propose to carry out two sequential GP17 cruises (see section 1) during a single austral summer growing season. The combined data from these cruises will provide quasi-synoptic information on the regional distribution and offshore transport of TEIs in the Amundsen Sea sector of the Southern Ocean during the growing season (Fig. 1).

3. PROPOSED RESEARCH

Following the model of previous US GEOTRACES cruises that have produced high-quality data sets (Schlitzer et al., 2018; see section 2.1), we are requesting support for essential sampling operations and ancillary measurements for the Antarctic margin portion of the US GEOTRACES South Pacific Ocean section, GP17-ANT, toward the research objectives described in section 2.4, and in coordination with the separate implementation of the open-ocean portion of the section, GP17-OCE. The overall success of the proposed field program relies on the execution of individual, hypothesis-driven science projects that will be proposed once this cruise management program is in place. The last 3 US GEOTRACES expeditions involved, on average, more than 40 PIs from more than 27 institutions, with around one third of the investigators on each expedition serving as PI for the first time.

The main objectives of this proposal are to: (1) coordinate a 60-day research cruise in late January-late March 2022; (2) obtain representative samples for analysis of a broad suite of TEIs from a conventional CTD-rosette system, a GEOTRACES-compliant trace-metal clean CTD-rosette system, a towed surface fish/small boat sampling system, in-situ pumps, and a sediment corer; (3) acquire "conventional" hydrographic data (CTD, transmissometer, fluorometer, dissolved oxygen sensor) and measurements of salinity, dissolved oxygen, dissolved macronutrients and phytoplankton pigments in discrete samples; (4) ensure that acceptable QA/QC protocols are followed and reported and that GEOTRACES intercalibration protocols are followed; (5) prepare and deliver all hydrographic data to the GEOTRACES Data Assembly Centre via the US BCO-DMO data center; and (6) coordinate cruise-related communications between principal investigators, including preparation of a hydrographic cruise report.

3.1. Cruise Track, Timing and Research Vessel

To address scientific questions related to the involvement of TEIs in biological processes, both GP17 cruises will be undertaken during the austral summer bloom season (December-mid January for the GP17-OCE section, and mid January-March for the GP17-ANT section). In the Amundsen Sea region, a cruise conducted during the latter portion of the bloom season should allow us to examine TEI cycling associated with biological uptake, and perhaps export and remineralization (see section 2.3). This cruise sequence and timing also presents logistical advantages in maximizing access to the GP17-ANT study region, based on typical seasonal sea ice extent, and in providing the opportunity for individual science projects to collect samples from both GP17 cruises, with the US Antarctic Program cargo and operations center in Punta Arenas serving as a common port between cruises. This cruise timing also facilitates the use of some major sampling equipment, such as the US GEOTRACES Go-Flo bottles and in-situ pumps, on both cruises. However, given the demands on ship time and availability, particularly for the icebreaker required for GP17-ANT, the cruises could be run in separate years rather than back-to-back, if necessary.

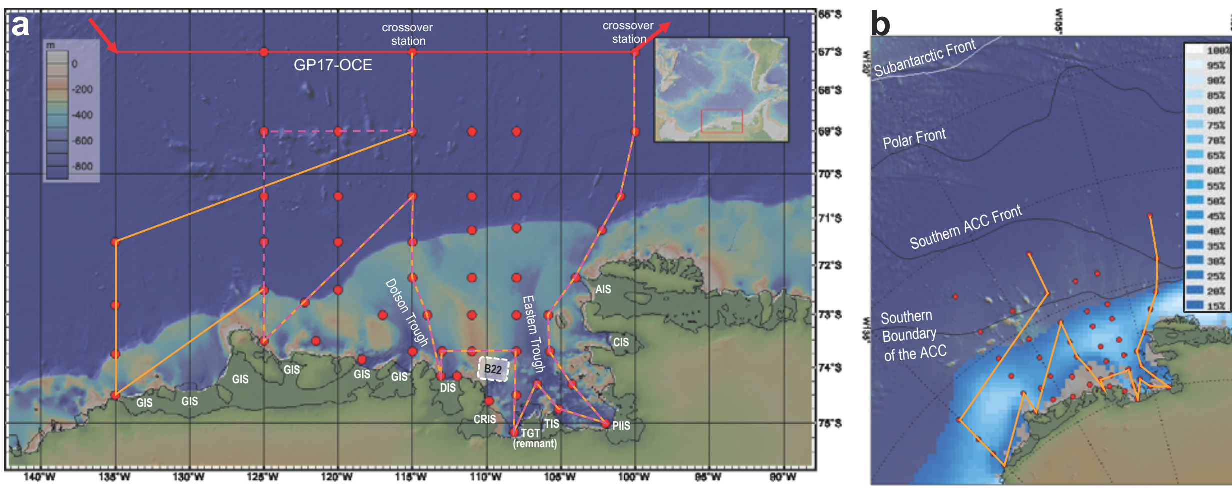

Figure 6. (a). *Proposed full (orange) and abridged (pink) cruise track for GP17-ANT, showing grid of contingency stations (red points), GP17-OCE track (red), major ice shelves – Abbot (AIS), Cosgrove (CIS), Pine Island (PIIS),Thwaites (TIS), Crosson (CRIS), Dotson (DIS) and Getz (GIS) – and the approximate location of iceberg B22 calved from Thwaites Glacial Tongue (TGT); bathymetry from Nitsche et al., (2007); (b) station map (polar projection) and full cruise track as in (a), showing location of major fronts from Orsi et al. (1995) and 1979-2007 average February sea ice concentration (NSIDC)*

Given the icebreaking capability required to access the proposed stations on the Antarctic continental shelf, the anticipated demands for science berths, interior laboratory space and shipboard container laboratories, and the cruise duration, we are requesting use of RVIB *Nathaniel B. Palmer*, which has successfully undertaken water-column TEI sampling in this region during the DynaLiFe (Gerringa et al., 2012) and ASPIRE (Sherrell et al., 2015) field programs. The proposed GP17-ANT cruise track (Figs. 1, 6a) runs from Punta Arenas, around Cape Horn, then southwest toward the eastern Amundsen Sea, with a test deployment of sampling systems and a "bottle-soak" station occupied en-route in the deep ocean, as weather permits. A crossover/intercalibration station (also sampled by GP17-OCE) will be sampled between the Polar Front and the Southern ACC Front at 67°S, 100°W, before heading south to sample stations across the Amundsen Sea shelf between 102°W and 135°W, including deep ocean stations along 135°W and 115°W with a second crossover station south of the Southern ACC Front at 67°S, 115°W

(Fig. 6a). This cruise track and the nominal station locations (orange track in Fig. 6a) aim to delineate TEI distributions and gradients that provide information on the key processes discussed in section 2; they include (1) stations that extend north from the shelf break toward the GP17-OCE zonal section, to define meridional gradients between the continental shelf and the deep ocean, noting that numerical models suggest offshore transport of entrained glacial meltwater near 115°W (St-Laurent et al., 2019; Dinniman et al., 2020), as well as zonal gradients along the outer shelf, continental slope and offshore deep ocean; (2) stations that cross the continental margins at the eastern and western boundaries of the Amundsen Sea shelf, to define zonal inputs and outputs for the shelf region; (3) quasi-meridional sections that follow the Eastern and Dotson Troughs from the shelf break to the Pine Island and Dotson Ice Shelf fronts, to examine shoreward intrusions of CDW; (4) stations near the western ends of the Pine Island, Thwaites, Dotson and Getz Ice Shelf fronts, to examine the outflows from ice shelf cavities and the modification of CDW as it flows westward and interacts with the ice shelves and seafloor; and (4) stations in the highly productive waters of the Amundsen Sea and Pine Island Polynyas, to focus on biological uptake, export, remineralization and scavenging processes.

We have requested 60 days of ship time, which includes 2 weather days, based on estimated steaming and sampling times to occupy approximately 30 stations, plus test and soak stations en-route to the study region. Final station locations (except for the crossover stations) will be decided at a pre-cruise PI meeting (see section 4, below). Noting that access to some stations or track legs may be impeded by sea ice cover (Fig 6b), which exhibits considerable year-to-year variability (Stammerjohn et al., 2015), we have identified both an abridged cruise track and a grid of "contingency stations" (see Fig. 6a) that can be used to define alternate stations/track legs in such situations, while still providing data from locations that are germane to our science goals. The mixture of station types will be modified pending sampling needs and sea ice conditions, but as an example, our time estimate leaves time for 8 full stations, 11 shelf stations, 6 super stations, and 5 demi stations, as defined in section 3.2, below.

3.2. Sampling Methods

We will generally use the water sampling systems and protocols used on previous US GEOTRACES cruises, following the *Sampling and Sample-Handling Protocols for GEOTRACES Cruises* "cookbook" (Cutter et al., 2014). For sampling contamination-prone TEIs in the water column, we will use a SeaBird trace-metal clean rosette fitted with a titanium SeaBird SBE 911plus CTD, SeaBird SBE 43 dissolved oxygen sensor, WetLabs fluorometer (US Antarctic Program), and 12 x 12-L Go-Flo sampling bottles (US GEOTRACES program). This rosette has a dedicated winch and 3000 m of non-metal conducting cable, and been successfully used for TEI sampling on several previous Antarctic cruises (e.g., Sherrell et al., 2015, 2018). This system will also include a Benthos altimeter and SeaBird bottom-contact switch alarm, to facilitate near-bottom sampling on the continental shelf. Given the anticipated importance and sharp gradients of particulate trace elements in this study region, particles will be collected by membrane filtration from dedicated Go-Flo bottles at all depths, hence the trace metal casts will sample 6 depths at a time using paired Go-Flo bottles, requiring two casts to sample 12 depths. For near-surface water sampling we will use a trace-metal clean towed fish system (Cutter et al., 2014) where sea ice conditions allow, as used successfully on previous Antarctic cruises in austral summer (Sedwick et al., 2011; Annett et al., 2017), or, where there is significant sea ice cover, by using a clean pump system or individual Go-Flo bottles deployed from a small boat (Jensen et al., 2019). Water samples collected for contamination-prone TEIs will be processed (filtered, subsampled) in a shipboard clean laboratory van (US Antarctic Program) by a single team of "Super Techs", following protocols described by Cutter et al. (2014), to ensure the consistency and efficiency for these critical processes.

For collection of non-contamination-prone TEIs and ancillary parameters such as phytoplankton pigments, we will use a conventional CTD rosette system with 36 x 12 L Niskin bottles supplied by the Oceanographic Data Facility (ODF, see section 3.3). Water-column hydrographic data (CTD, transmissometer, fluorometer, dissolved oxygen sensor) and discrete samples for measurements of salinity, dissolved oxygen and dissolved macronutrients, will be collected from both the trace metal and conventional rosettes. In addition to high resolution samples collected by filtration from the Go-Flo bottles for particulate trace elements, McLane high-volume in-situ pumps will be deployed at lower vertical and horizontal resolution for sampling size-fractionated particulate TEIs and major phases for multi-PI distribution, as well as short-lived radioactive tracers such as radium that require large volumes, as on previous US GEOTRACES cruises (Lam et al., 2015, 2018; Ohnemus and Lam, 2015). Finally, given the importance of sediments as a source of TEIs on the Antarctic shelf, we anticipate that individual science projects may require samples of sediments and pore fluids, and thus propose to collect sediments from selected shelf stations using a Bowers and Connelly Mega multiple corer (US Antarctic Program). Station time estimates also allow for collection of sea ice and associated snow, brines and surface water, floating glacial ice, and aerosols and precipitation, for which sampling equipment would be provided by individual project investigators (Marsay et al., 2018a; Buck et al., 2019; Kadko et al., 2019).

Four types of stations will be occupied along the cruise track shown in Figure 6a: (1) "*full stations*" of up to 24 depths will include water-column sampling at stations >1000 m depth to 3000 m maximum depth, using four casts of the trace metal rosette, three casts of the conventional rosette, and two casts of McLane in situ pumps with up to 8 pumps per cast; (2) "*shelf stations*" will include water-column sampling at stations <1000 m depth, using two casts of the trace metal rosette, two casts of the conventional rosette, and one cast of McLane in situ pumps with up to 8 pumps per cast; (3) "*super stations*" will be like shelf stations, but with an additional cast for each of the trace metal and conventional rosettes to accommodate additional demand, as well as multicorer deployment for sediment collection; and (4) "*demi stations*" will include water-column sampling at stations <1000 m depth, using two casts of the trace metal rosette and one cast of the conventional rosette, with no McLane in situ pumps or multicorer sampling. All stations will include near-surface water sampling using either towed fish or small boat, and full, shelf and super stations will include sea ice sampling if suitable ice is readily accessible using a small boat or personnel basket. We anticipate that near-bottom casts of the conventional rosette will include a small "monocore" gravity corer (PI provided), as used on previous GEOTRACES cruises, to complement the multicorer sampling. Based on experience from previous US GEOTRACES cruises, we estimate that 30 hours, 11 hours, 16 hours and 5 hours are required to complete sampling at full-, shelf-, super- and demi stations, respectively. For all stations, sampled depths will not be fixed, but rather targeted in response to observed hydrography, desired sampling features (e.g., chlorophyll and particle maxima, nepheloid layers, salinity anomalies) and shipboard ADCP data to identify outflows from ice-shelf cavities or along troughs. This method for selecting sample depths has proven successful on previous US GEOTRACES cruises.

3.3. Analytical Methods

Hydrography and Nutrients. High-quality hydrographic and nutrient data are crucial for characterizing water masses as well as for verifying the performance of Go-Flo bottles (Cutter and Bruland, 2012). These measurements will be made by the ODF group overseen by Todd Martz, who will perform measurements fully compliant with GO-SHIP/Repeat Hydrography protocols, including determinations of salinity, dissolved oxygen, phosphate, nitrate, nitrite, and silicate on discrete samples from the conventional rosette, trace-metal clean rosette, and clean surface water sampling systems; details are provided in the subcontract to Lam (UCSC Budget).

Zinc Contamination. Samples from the trace-metal clean rosette Go-Flo bottles will be analyzed onboard for dissolved zinc, which is an excellent indicator of potential sampling contamination (Cutter and Bruland, 2012). For these analyses we will employ the solid phase extraction/fluorescence detection lab-on-valve system described by Grand et al. (2016) with a detection limit of ~0.02 nM. These measurements will be made at all stations and for all Go-Flo bottles during the first week of sampling, and subsequently if Go-Flos are replaced with backup bottles or repaired.

Pigments. Samples will be collected for phytoplankton pigment analysis from the uppermost 5 depths sampled at full, shelf and super stations. Water collected from the conventional rosette will be sampled into dark 2 L polyethylene bottles and gently filtered through 25 mm GF/F filters. Samples will be frozen at -80°C and shipped to Oregon State University (Letelier laboratory) for HPLC pigment analyses.

4. MANAGEMENT TEAM AND RESPONSIBILITIES

The management team comprises the four PIs on this proposal, who will oversee implementation of the US GEOTRACES GP17-ANT cruise, including all aspects of logistics, interaction with the Antarctic Support Contractor and ship operator, communication with the science community, and data management including synthesis of the combined results of the GP17 cruises (see Data Management Plan). This team has considerable past experience with field work as part of the US Antarctic and US GEOTRACES programs, including science cruises aboard RVIB *Nathaniel B. Palmer*. Prior to the cruise, we will follow the precedent of previous US GEOTRACES cruises and host a combined GP17-OCE and GP17-ANT workshop on 6-8 May 2020, where interested PIs can learn about the background science, rationale, and logistics of the two cruises, present their statements of interest, and explore potential collaborations well before their science proposal deadline in August 2020; funding for this workshop will come from the US GEOTRACES Project Office. In addition, statements of interest from individual PIs will be posted on the US GEOTRACES web site, to facilitate coordination of logistics and encourage scientific collaborations. Participation on this cruise will be open to any US PI who proposes high quality research that supports the GEOTRACES goals; as of 4 February 2020, 66 investigators (21 not previously funded for US GEOTRACES) from 38 separate institutions have expressed interest in attending this workshop, reflecting the strong level of scientific interest in this cruise from the US chemical oceanography community. After funding decisions on individual science proposals are known, we will coordinate a pre-cruise PI meeting in early 2021, to determine shipboard requirements and operations, including the number, type and exact locations of stations to be occupied during the cruise.

At sea, we will provide for all sample acquisition, quality control and archiving of appropriate operational metadata (navigation, event and sampling logs, and hydrographic data) following established US GEOTRACES and GO-SHIP protocols. The ODF team will be in charge of hydrographic and nutrient data acquisition, and will work with the management team on shipboard data management (see Data Management Plan and ODF subcontract in UCSC Budget). Sampling and sample handling will follow the methods detailed in sections 3.2 and 3.3. We anticipate that individual PIs will provide the equipment for sampling ice, snow, brines, aerosols and precipitation, as well as for the processing of sediment samples and pore fluid extraction. The management team will coordinate all on-board water sampling, ensure smooth and efficient operation of all station-related activities, and be responsible for acquisition of all essential hydrographic data (CTD, salinity, nutrients, oxygen, and pigments). Working with the ODF team, the management team will also be responsible for establishing and monitoring both Go-Flo and Niskin sampler integrity using shipboard hydrographic measurements and dissolved zinc determinations. The management team will be responsible for the quality control and archiving of all shipboard measurement data and for making all data and metadata available to shipboard science participants. Post cruise, the management team will be responsible for ensuring the timely transmission of all data and metadata acquired during the cruise to the US GEOTRACES data archive at BCO-DMO, who will in turn be responsible for transferring all such data and metadata to the International GEOTRACES Data Assembly Centre (GDAC; see Data Management Plan). The management team will also be responsible for creating a final cruise report and hydrographic synthesis, describing the basic context (water mass structure, major current flows, etc.) to assist in the interpretation of all TEI data. With funding from the US GEOTRACES project office, the management team will host a post-cruise synthesis meeting around 1.5 years after the cruise, to promote collaboration and manuscript preparation among GP17 participants.

Peter Sedwick will serve as chief scientist on the cruise and lead investigator of the management team. He will oversee sampling from the conventional rosette water sampling system, including supervision of the two Super Techs contracted to sample from that system, in close consultation with the ODF shipboard team. Sedwick will supervise senior laboratory supervisor Bettina Sohst, who will manage cruise logging in collaboration with the ODF data manager; Sohst will also measure zinc concentrations from Go-Flo samples during the first portion of the cruise, and train the three Super Techs who will be contracted for shipboard sampling from the trace-metal clean water sampling system. He will also be the primary point of contact with the ship schedulers and US Antarctic Program contractors. **Robert Anderson** will leverage his position as director of the NSF-funded US GEOTRACES project office to coordinate the implementation of the GP17-ANT and GP17-OCE cruises, and to manage the post-cruise synthesis activities within the US GEOTRACES community. He will not sail on the cruise, and no salary is budgeted in this proposal for his participation in the cruise management. **Phoebe Lam** will sail as co-leader on the expedition, with primary responsibility for coordinating McLane pump sampling activities, including supervision of the two Super Techs for the pump operations. She will also act as the primary interface with the ODF group, subcontracted by UCSC, for acquisition of hydrographic and nutrient data. **Robert Sherrell** will sail as co-leader of the expedition, with primary responsibility for coordinating the water sampling for dissolved and particulate TEIs using the trace-metal clean rosette, towed fish, and small boat systems, including supervision of the Super Techs who will be contracted to perform these sampling operations. He will also oversee collection and analysis of samples for phytoplankton pigments (see details in Rutgers budget), and the collection of sediment samples using the multicorer system.

5. BROADER IMPACTS

The dramatic recent acceleration in the melting of the West Antarctic Ice Sheet, particularly that associated with the glacial ice shelves that border the Amundsen Sea, has captured the attention of both the scientific community and the public at large, given its implications for global sea level rise and other impacts. In this context, the research that will be facilitated by the GP17-ANT cruise will have a range of broader impacts, including (1) advancing knowledge within and beyond the disciplinary focus; (2) making significant contributions to education and outreach at the K-12 levels; (3) contributing to the education and training of graduate students, early career scientists and education professionals; and (4) increasing public scientific literacy and public engagement with science and technology.

Research Community. Beyond the disciplinary contributions in chemical oceanography and marine biogeochemistry described in proposal section 2, the proposed research will contribute knowledge relevant to understanding of the cryosphere and its impacts on global sea level and ocean circulation, regional ecosystems and biological processes, ocean-atmosphere interactions and exchange, and past and future environmental changes on regional to global scales. Moreover, the proposed research is expected to provide qualitative and quantitative information that is required to test and develop mechanistically-accurate numerical models with the capacity to predict how this oceanic region will be affected by and modulate future climate change. Beyond the GEOTRACES program, results from the GP17 cruises are expected to complement a number of ongoing research efforts, including the ongoing NSF/NERC-funded International Thwaites Glacier Collaboration, which examines the mechanisms behind the massive and accelerating ice loss from the Thwaites glacier, but includes no research focused on the biogeochemical implications of this ocean-ice interaction; the NSF-funded Southern Ocean Carbon and Climate Observations and Modeling project (SOCCOM), which uses observational data, primarily from instrumented floats that are typically restricted to the offshore Southern Ocean (Riser et al., 2018), to analyze and improve high resolution earth system models. Data from the GP17 cruises are also expected to contribute to the goals of the Amundsen and Bellingshausen Sector Working Group of the Southern Ocean Observing System (SOOS), an international initiative that aims to coordinate and expand international efforts to collect and disseminate sustained observations from the Southern Ocean.

STEM Education and Outreach. The GP17-ANT research context and setting provides a compelling platform to promote science literacy and develop STEM-related teaching resources at the K-12 level. To this end, PI Sedwick will apply for a grade 7-12 teacher to participate in the GP17-ANT cruise through the NSF-funded PolarTREC program (See letter of commitment from Janet Warburton, PolarTREC Project Manager). The teacher will interact with several US schools and general public using educational tools such as blogs, photos, videos, and email or radio Q&A sessions, and develop course curricula. Sedwick has budgeted funds for the PolarTREC teacher to present results of their cruise-related work at a national scientific meeting. At Rutgers, co-PI Sherrell will work with Janice McDonnell (STEM Agent, Department of Youth Development) and Christine Bean (STEM Coordinator, Department of Marine and Coastal Sciences) to create meaningful out-of-school-time science experiences for middle and high school students through the Rutgers 4-H STEM Ambassador program (McDonnell et al., 2019). This program recruits 60 high-achieving rising 9th graders from underserved and underrepresented schools to participate in a 5-day program designed to enrich students' interest and competency in STEM. The students visit the Rutgers campus to engage with science faculty and graduate students to learn about scientific research and career paths. The program trains and supports 4-H STEM Ambassadors, who share their experience and understanding of STEM topics with student peers, and has proven highly successful, with 59% of program alumni who attended college being enrolled in a STEM major or pursuing a STEM career. Sherrell has previously participated in this program, working with a group of 10 female minority students from Newark inner-city schools. As part of the GP17-ANT project, he will create an experience focused on Antarctic marine biogeochemistry, glacial melting, and climate change.

Public Engagement. Co-PI Lam will work with the highly regarded UCSC Science Communication Program to identify freelance science journalists who will profile our research in written, audio, or video reports aimed at national media outlets. Given the high-profile nature of rapid glacial melting in the Amundsen Sea, our field project will provide an exciting opportunity to demonstrate to a wide audience the importance of geochemistry as a tool for understanding global change. Lam has previously worked with this program to engage a science writer for the US GEOTRACES GP15 cruise.

Training and Mentoring. The US GEOTRACES program has an impressive record of involving and training graduate students, postdoctoral fellows and early career scientists in its core research work; indeed, in the 2015-19 period, at least 18 PhD dissertations included US GEOTRACES data. This has produced numerous, high-profile scientific journal publications led by these researchers, some cited in this proposal, and propelled a number of these junior scientists to academic or research faculty positions, in which they are training the next generation of chemical oceanographers and marine biogeochemists. We anticipate that numerous graduate students and early career scientists will be involved in GP17-ANT.

6. RESULTS FROM PRIOR NSF SUPPORT

P. N Sedwick. *Collaborative Research: US GEOTRACES Pacific Section - Shipboard Al, Mn and Fe* (OCE-1237034, 2012-2017, $172,982 to PNS). Under this award, Sedwick and co-PI Resing made shipboard and post-cruise measurements of dissolved Fe (DFe), Mn (DMn) and Al (DAl) in water-column samples collected during the US GEOTRACES GP16 cruise. Intellectual Merit and Products: The major result from this award was the identification of mid-depth hydrothermal plumes of DAl, DFe and DMn that extended several thousand kilometers westward from the East Pacific Rise into the South Pacific basin. These results, combined with numerical modeling, suggest that ridge-axis hydrothermal emissions are an important source of DFe to the iron-deficient surface waters of Southern Ocean. Project results were published in Resing et al. (2016) and in publications by Boiteau et al. (2016a), Hawco et al. (2016), Tagliabue and Resing (2016), Sanial et al. (2017), Buck et al. (2018) and Ho et al. (2019). Sedwick and Resing participated in multi-lab intercomparison exercises and their data contributed to the 2017 GEOTRACES intermediate data product (Schlitzer et al., 2018). Broader Impacts: Our shipboard data informed the cruise sampling strategy and was made available to the GP16 PIs immediately after the cruise to assist with analyses and data interpretation, facilitating publications led by PIs, graduate students and junior scientists. The award provided support for female PhD students P. Barrett and S. Michael.

R. F. Anderson. *Support for the U.S. GEOTRACES Project Office* (OCE-1536294, 2015-2020, $1,281,746.00). This award supports US GEOTRACES community-related activities, from planning of future expeditions to synthesis of recent findings. Among other roles, PI Anderson has served as an organizer of GEOTRACES synthesis efforts, a role that he anticipates will continue following completion of Southern Ocean GEOTRACES expeditions. He served on the organizing committee for the first GEOTRACES synthesis workshop on the supply and removal of trace elements at ocean boundaries

(London, UK, December 2015), hosted a second GEOTRACES synthesis workshop on internal cycling of trace elements within the ocean (Lamont-Doherty, August 2016), and co-organized the GEOTRACES synthesis workshop on geochemical proxies used in paleoceanography (Aix, France, December 2018). Intellectual Merit and Products: Anderson led the first GEOTRACES synthesis effort to combine results from multiple trace elements and isotopes to quantify dust fluxes to the ocean (Anderson et al., 2016). Building on the principles developed in that pioneering study, follow-up efforts placed new constraints on the residence time of trace elements in the ocean (Hayes et al., 2018a) and on their fluxes (Hayes et al., 2018b). Encompassing a greater body of GEOTRACES data has expanded these synthesis efforts to include full water column fluxes of particulate organic carbon (Pavia et al., 2019). Broader Impacts: Motivated by the initiatives described above, a rapidly growing body of GEOTRACES synthesis efforts are providing unprecedented insight into the processes that regulate TEI distributions in the ocean as well as the rates of these processes. Concurrently, we are seeing new developments in understanding the bioavailability and speciation of trace elements, all of which are pursued under GEOTRACES synthesis efforts. Synthesis products such as these represent the true value of a large program like GEOTRACES to the broader oceanographic community.

P. J. Lam. *Collaborative Research: GEOTRACES Pacific Section: The Geochemistry of Size-fractionated Suspended Particles Collected by In-situ Filtration* (OCE-1233272, 2013-2017, $551K to PJL). Intellectual Merit and Products: Lam and co-PI Toner provided the first zonal full-depth section of size-fractionated particle composition and concentration in the Pacific (Lam et al., 2018; Lee et al., 2018). These data are part of the publicly available GEOTRACES Intermediate Data Product 2017 (Schlitzer et al., 2018). We demonstrated that non-oxygen dependent oxidation of iron occurs in the Peru oxygen deficient zone (Heller et al., 2017). More than 10 manuscripts have so far emerged from collaborations with other GEOTRACES PIs on topics including: ^{234}Th-based particle export (Black et al., 2018), Co scavenging (Hawco et al., 2018), hydrothermal C and Fe (Hoffman et al., 2018), Fe isotopes and cycling (John et al., 2018; Marsay et al., 2018b), optics (Ohnemus et al., 2017), Th and Pa scavenging by hydrothermal particles (Pavia et al., 2018), shallow regeneration of carbon (Pavia et al., 2019), Mo and V cycling (Ho et al., 2018), particulate trace metal flux (Black et al., 2019). Broader Impacts: This project supported two early career female scientists (M. Heller, J.-M. Lee), two undergraduate interns from underrepresented groups (U. Kakou, S. Mehic), one graduate student (Y. Xiang), and two high school students (M. Abrams, L. Repeta). PI Lam helped develop and participated in a live webinar on the GEOTRACES program coordinated and archived by COSEE-Maine.

R. M. Sherrell. *Collaborative Research: Investigating the Role of Mesoscale Processes and Ice Dynamics in Carbon and Iron Fluxes in a Changing Amundsen Sea (INSPIRE)* **(**ANT-1443315, 2015-2018, $49,996 to RMS). Intellectual Merit and Products: With co-PIs St-Laurent, Yager, and Stammerjohn, this modeling project followed ASPIRE to explore mechanistically how the injection of iron into the upper water column from the Dotson Ice Shelf and neighboring ice shelves contributes to the extreme productivity of the ASP (St-Laurent et al. 2017; St-Laurent et al. 2019; Oliver et al. 2019). We simulated the ASPIRE bloom by developing a new high resolution (1.5 km) physical-biogeochemical model of the ASP system, including iron pools and exchanges. The model predicted basal melt rate for the Thwaites Glacier to within 10% of observations (Rignot et al., 2013), and traced pathways and relative contributions of potential iron sources (St-Laurent et al., 2017). The full 3-D version of the model (St-Laurent et al. 2019) informed by a station-specific 1-D model (Oliver et al., 2019) pointed to the importance of the "meltwater pump" within ice shelf cavities in delivering sediment-sourced iron to the upper water column through the buoyancy added by basal melting. Overall, the model suggests that shelf-sediment iron sources are more important to the productivity of the polynya than iron from basal melting of glacial ice. Broader Impacts: Educational materials for elementary students; a *Research Features* article; 3 sets of model results publicly archived; a website; and numerous invited lectures and outreach presentations. Model output movies are used in K-12 and college classes to illustrate glacial ice shelf melting in Antarctica. Sherrell helped mentor University of Georgia PhD student Hilde Oliver (currently a WHOI postdoctoral scholar), whose dissertation focused on this project.

REFERENCES CITED

Abadie, C., Lacan, F., Radic, A., Pradoux, C., & Poitrasson, F. (2017). Iron isotopes reveal distinct dissolved iron sources and pathways in the intermediate versus deep Southern Ocean. *Proceedings of the National Academy of Sciences*, *114*(5), 858-863.

Alderkamp, A. C., Mills, M. M., van Dijken, G. L., Laan, P., Thuróczy, C. E., Gerringa, L. J., ... & Arrigo, K. R. (2012). Iron from melting glaciers fuels phytoplankton blooms in the Amundsen Sea (Southern Ocean): Phytoplankton characteristics and productivity. *Deep Sea Research Part II: Topical Studies in Oceanography*, *71*, 32-48.

Alderkamp, A. C., Van Dijken, G. L., Lowry, K. E., Connelly, T. L., Lagerström, M., Sherrell, R. M., ... & Yager, P. L. (2015). Fe availability drives phytoplankton photosynthesis rates during spring bloom in the Amundsen Sea Polynya, Antarctica. *Elementa Science of the Anthropocene*, *3*.

Anderson, R. F., & Henderson, G. M. (2005). GEOTRACES. *Oceanography*, *18*(3), 76.

Anderson, R. F. (2020). GEOTRACES: Accelerating research on the marine biogeochemical cycles of trace elements and their isotopes. *Annual Review of Marine Science*, *12*.

Anderson, R. F., Cheng, H., Edwards, R. L., Fleisher, M. Q., Hayes, C. T., Huang, K. F., ... & Lu, Y. (2016). How well can we quantify dust deposition to the ocean? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *374*(2081), 20150285.

Annett, A. L., Fitzsimmons, J. N., Séguret, M. J., Lagerström, M., Meredith, M. P., Schofield, O., & Sherrell, R. M. (2017). Controls on dissolved and particulate iron distributions in surface waters of the Western Antarctic Peninsula shelf. *Marine Chemistry*, *196*, 81-97.

Arneborg, L., Wåhlin, A. K., Björk, G., Liljebladh, B., & Orsi, A. H. (2012). Persistent inflow of warm water onto the central Amundsen shelf. *Nature Geoscience*, *5*(12), 876-880.

Arrigo, K. R., & Van Dijken, G. L. (2003). Phytoplankton dynamics within 37 Antarctic coastal polynya systems. *Journal of Geophysical Research: Oceans*, *108*(C8).

Arrigo, K. R., van Dijken, G. L., & Bushinsky, S. (2008a). Primary production in the Southern Ocean, 1997–2006, *Journal of Geophysical Research*, *113*, C08004, doi:10.1029/2007JC004551.

Arrigo K. R., van Dijken, G. L., & Long, M. (2008b). Coastal Southern Ocean: A strong anthropogenic CO_2 sink, *Geophysical Research Letters*, *35*, L21602, doi:10.1029/2008GL035624.

Arrigo, K. R., Lowry, K. E., & van Dijken, G. L. (2012). Annual changes in sea ice and phytoplankton in polynyas of the Amundsen Sea, Antarctica. *Deep Sea Research Part II: Topical Studies in Oceanography*, *71*, 5-15.

Arrigo, K. R., van Dijken, G. L., & Strong, A. L. (2015). Environmental controls of marine productivity hot spots around A ntarctica. *Journal of Geophysical Research: Oceans*, *120*(8), 5545-5565.

Bertrand, E. M., Saito, M. A., Rose, J. M., Riesselman, C. R., Lohan, M. C., Noble, A. E., ... & DiTullio, G. R. (2007). Vitamin B12 and iron colimitation of phytoplankton growth in the Ross Sea. *Limnology and Oceanography*, *52*(3), 1079-1093.

Bhattachan, A., Wang, L., Miller, M. F., Licht, K. J., & D'Odorico, P. (2015). Antarctica's Dry Valleys: A potential source of soluble iron to the Southern Ocean? *Geophysical Research Letters*, *42*(6), 1912-1918.

Biddle, L. C., Loose, B., & Heywood, K. J. (2019). Upper ocean distribution of glacial meltwater in the Amundsen Sea, Antarctica. *Journal of Geophysical Research: Oceans*.

Black, E. E., Buesseler, K. O., Pike, S. M., & Lam, P. J. (2018). 234Th as a tracer of particulate export and remineralization in the southeastern tropical Pacific. *Marine Chemistry*, *201*, 35-50.

Black, E. E., Lam, P. J., Lee, J. M., & Buesseler, K. O. (2019). Insights from the ^{238}U-^{234}Th method into the coupling of biological export and the cycling of cadmium, cobalt, and manganese in the Southeast Pacific Ocean. *Global Biogeochemical Cycles*, *33*(1), 15-36.

Blankenship, D. D., Bell, R. E., Hodge, S. M., Brozena, J. M., Behrendt, J. C., & Finn, C. A. (1993). Active volcanism beneath the West Antarctic ice sheet and implications for ice-sheet stability. *Nature*, *361*(6412), 526-529.

Boiteau, R. M., Mende, D. R., Hawco, N. J., McIlvin, M. R., Fitzsimmons, J. N., Saito, M. A., ... & Repeta, D. J. (2016a). Siderophore-based microbial adaptations to iron scarcity across the eastern Pacific Ocean. *Proceedings of the National Academy of Sciences*, *113*(50), 14237-14242.

Boiteau, R. M., Till, C. P., Ruacho, A., Bundy, R. M., Hawco, N. J., McKenna, A. M., ... & Repeta, D. J. (2016b). Structural characterization of natural nickel and copper binding ligands along the US GEOTRACES Eastern Pacific Zonal Transect. *Frontiers in Marine Science*, *3*, 243.

Bowman, K. L., Hammerschmidt, C. R., Lamborg, C. H., Swarr, G. J., & Agather, A. M. (2016). Distribution of mercury species across a zonal section of the eastern tropical South Pacific Ocean (US GEOTRACES GP16). *Marine Chemistry*, *186*, 156-166.

Boyd, P. W., Strzepek, R., Fu, F., & Hutchins, D. A. (2010). Environmental control of open-ocean phytoplankton groups: Now and in the future. *Limnology and Oceanography*, *55*(3), 1353-1376.

Boyd, P. W., Lennartz, S. T., Glover, D. M., & Doney, S. C. (2015). Biological ramifications of climate-change-mediated oceanic multi-stressors. *Nature Climate Change*, *5*(1), 71.

Bromwich, D. H. (1989). Satellite analyses of Antarctic katabatic wind behavior. *Bulletin of the American Meteorological Society*, *70*(7), 738-749.

Bronselaer, B., Russell, J. L., Winton, M., Williams, N. L., Key, R. M., Dunne, J. P., ... & Sarmiento, J. L. (2020). Importance of wind and meltwater for observed chemical and physical changes in the Southern Ocean. *Nature Geoscience*, *13*(1), 35-42.

Brown, P. J., Meredith, M. P., Jullion, L., Naveira Garabato, A., Torres-Valdés, S., Holland, P., ... & Venables, H. (2014). Freshwater fluxes in the Weddell Gyre: results from δ 18O. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *372*(2019), 20130298.

Buck, C. S., Aguilar-Islas, A., Marsay, C., Kadko, D., & Landing, W. M. (2019). Trace element concentrations, elemental ratios, and enrichment factors observed in aerosol samples collected during the US GEOTRACES eastern Pacific Ocean transect (GP16). *Chemical Geology*, *511*, 212-224.

Buck, K. N., Sedwick, P. N., Sohst, B., & Carlson, C. A. (2018). Organic complexation of iron in the eastern tropical South Pacific: results from US GEOTRACES Eastern Pacific Zonal Transect (GEOTRACES cruise GP16). *Marine Chemistry*, *201*, 229-241.

Cassar, N., Bender, M. L., Barnett, B. A., Fan, S., Moxim, W. J., Levy, H., & Tilbrook, B. (2007). The Southern Ocean biological response to aeolian iron deposition. *Science*, *317*(5841), 1067-1070.

Chase, Z., Anderson, R. F., Fleisher, M. Q., & Kubik, P. W. (2003a). Accumulation of biogenic and lithogenic material in the Pacific sector of the Southern Ocean during the past 40,000 years. *Deep Sea Research Part II: Topical Studies in Oceanography*, *50*(3-4), 799-832.

Chase, Z., Anderson, R. F., Fleisher, M. Q., & Kubik, P. W. (2003b). Scavenging of 230Th, 231Pa and 10Be in the Southern Ocean (SW Pacific sector): The importance of particle flux, particle composition and advection. *Deep Sea Research Part II: Topical Studies in Oceanography*, *50*(3-4), 739-768.

Chewings, J. M., Atkins, C. B., Dunbar, G. B., & Golledge, N. R. (2014). Aeolian sediment transport and deposition in a modern high-latitude glacial marine environment. *Sedimentology*, *61*(6), 1535-1557.

Coale, K. H., Wang, X., Tanner, S. J., & Johnson, K. S. (2003). Phytoplankton growth and biological response to iron and zinc addition in the Ross Sea and Antarctic Circumpolar Current along 170 W. *Deep Sea Research Part II: Topical Studies in Oceanography*, *50*(3-4), 635-653.

Coale, K. H., Johnson, K. S., Chavez, F. P., Buesseler, K. O., Barber, R. T., Brzezinski, M. A., ... & Wanninkhof, R. H. (2004). Southern Ocean iron enrichment experiment: carbon cycling in high-and low-Si waters. *science*, *304*(5669), 408-414.

Conway, T. M., & John, S. G. (2014a). Quantification of dissolved iron sources to the North Atlantic Ocean. *Nature*, *511*(7508), 212.

Conway, T. M., & John, S. G. (2014b). The biogeochemical cycling of zinc and zinc isotopes in the North Atlantic Ocean. *Global Biogeochemical Cycles*, *28*(10), 1111-1128.

Conway, T. M., Hamilton, D. S., Shelley, R. U., Aguilar-Islas, A. M., Landing, W. M., Mahowald, N. M., & John, S. G. (2019). Tracing and constraining anthropogenic aerosol iron fluxes to the North Atlantic Ocean using iron isotopes. *Nature communications*, *10*.

Cook, A. J., Holland, P. R., Meredith, M. P., Murray, T., Luckman, A., & Vaughan, D. G. (2016). Ocean forcing of glacier retreat in the western Antarctic Peninsula. *Science*, *353*(6296), 283-286.

Cutter, G. A., & Bruland, K. W. (2012). Rapid and noncontaminating sampling system for trace elements in global ocean surveys. *Limnology and Oceanography: Methods*, *10*(6), 425-436.

Cutter, G.A., Andersson, P., Codispoti, L., Croot, P., Francois, R. Lohan, M., Obata, H, &. van der Loeff, M. R. (2014). *Sampling and Sample-handling Protocols for GEOTRACES Cruises*, Version 2.0, http://www.geotraces.org/images/stories/documents/intercalibration/Cookbook.pdf.

Death, R., Wadham, J. L., Monteiro, F., Le Brocq, A. M., Tranter, M., Ridgwell, A., ... & Raiswell, R. (2014). Antarctic ice sheet fertilises the Southern Ocean.

De Baar, H. J., De Jong, J. T., Bakker, D. C., Löscher, B. M., Veth, C., Bathmann, U., & Smetacek, V. (1995). Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean. *Nature*, *373*(6513), 412.

De Baar, H. J., Boyd, P. W., Coale, K. H., Landry, M. R., Tsuda, A., Assmy, P., ... & Buesseler, K. O. (2005). Synthesis of iron fertilization experiments: from the iron age in the age of enlightenment. *Journal of Geophysical Research: Oceans*, *110*(C9).

De Jong, J., Schoemann, V., Lannuzel, D., Croot, P., de Baar, H., & Tison, J. L. (2012). Natural iron fertilization of the Atlantic sector of the Southern Ocean by continental shelf sources of the Antarctic Peninsula. *Journal of Geophysical Research: Biogeosciences*, *117*(G1).

De Jong, J. T. M., Stammerjohn, S. E., Ackley, S. F., Tison, J. L., Mattielli, N., & Schoemann, V. (2015). Sources and fluxes of dissolved iron in the Bellingshausen Sea (West Antarctica): The importance of sea ice, icebergs and the continental margin. *Marine chemistry*, *177*, 518-535.

De Vries, M. V. W., Bingham, R. G., & Hein, A. S. (2018). A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. *Geological Society, London, Special Publications*, *461*(1), 231-248.

DiFiore, P. J., Sigman, D. M., & Dunbar, R. B. (2009). Upper ocean nitrogen fluxes in the Polar Antarctic Zone: Constraints from the nitrogen and oxygen isotopes of nitrate. *Geochemistry, Geophysics, Geosystems*, *10*(11).

Dinniman, M. S., Klinck, J. M., & Hofmann, E. E. (2012). Sensitivity of Circumpolar Deep Water transport and ice shelf basal melt along the west Antarctic Peninsula to changes in the winds. *Journal of Climate*, *25*(14), 4799-4816.

Dinniman, M. S., St-Laurent, P, Arrigo, K. R, Hofmann, E. E., & van Dijken, G. L. (2020), Analysis of iron sources in Antarctic continental shelf waters, revised manuscript submitted to *Journal of Geophysical Research: Oceans*.

Ducklow, H. W., Yager, P. L., Sherrell, R. M., Lowry, K. E., Lee, S. H., Erickson, M., ... & Wilson, S. E. (2015). Particle flux on the continental shelf in the Amundsen Sea Polynya and Western Antarctic Peninsula.

Duprat, L. P., Bigg, G. R., & Wilton, D. J. (2016). Enhanced Southern Ocean marine productivity due to fertilization by giant icebergs. *Nature Geoscience*, *9*(3), 219.

Duprat, L., Kanna, N., Janssens, J., Roukaerts, A., Deman, F., Townsend, A. T., ... & Lannuzel, D. (2019). Enhanced iron flux to Antarctic sea ice via dust deposition from ice-free coastal areas. *Journal of Geophysical Research: Oceans*, 1-19.

Edwards, R., & Sedwick, P. (2001). Iron in East Antarctic snow: Implications for atmospheric iron deposition and algal production in Antarctic waters. *Geophysical Research Letters*, *28*(20), 3907-3910.

Fitzsimmons, J. N., Bundy, R. M., Al-Subiai, S. N., Barbeau, K. A., & Boyle, E. A. (2015). The composition of dissolved iron in the dusty surface ocean: an exploration using size-fractionated iron-binding ligands. *Marine Chemistry*, *173*, 125-135.

Fitzsimmons, J. N., John, S. G., Marsay, C. M., Hoffman, C. L., Nicholas, S. L., Toner, B. M., ... & Sherrell, R. M. (2017). Iron persistence in a distal hydrothermal plume supported by dissolved–particulate exchange. *Nature Geoscience*, *10*(3), 195.

Fitzwater, S. E., Johnson, K. S., Gordon, R. M., Coale, K. H., & Smith Jr, W. O. (2000). Trace metal concentrations in the Ross Sea and their relationship with nutrients and phytoplankton growth. *Deep Sea Research Part II: Topical Studies in Oceanography*, *47*(15-16), 3159-3179.

Gardner, A. S., Moholdt, G., Scambos, T., Fahnstock, M., Ligtenberg, S., van den Broeke, M., & Nilsson, J. (2018). Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years. *Cryosphere*, *12*(2), 521-547.

Gerringa, L. J., Alderkamp, A. C., Laan, P., Thuroczy, C. E., De Baar, H. J., Mills, M. M., ... & Arrigo, K. R. (2012). Iron from melting glaciers fuels the phytoplankton blooms in Amundsen Sea (Southern Ocean): Iron biogeochemistry. *Deep Sea Research Part II: Topical Studies in Oceanography*, *71*, 16-31.

Grand, M. M., Chocholouš, P., Růžička, J., Solich, P., & Measures, C. I. (2016). Determination of trace zinc in seawater by coupling solid phase extraction and fluorescence detection in the Lab-On-Valve format. *Analytica chimica acta*, *923*, 45-54.

Ha, H. K., Wåhlin, A. K., Kim, T. W., Lee, S. H., Lee, J. H., Lee, H. J., ... & Kalén, O. (2014). Circulation and modification of warm deep water on the central Amundsen Shelf. *Journal of Physical Oceanography*, *44*(5), 1493-1501.

Hawco, N. J., Ohnemus, D. C., Resing, J. A., Twining, B. S., & Saito, M. A. (2016). A dissolved cobalt plume in the oxygen minimum zone of the eastern tropical South Pacific. *Biogeosciences*, *13*(20), 5697-5717.

Hayes, C. T., Anderson, R. F., Cheng, H., Conway, T. M., Edwards, R. L., Fleisher, M. Q., ... & Little, S. H. (2018a). Replacement times of a spectrum of elements in the North Atlantic based on thorium supply. *Global Biogeochemical Cycles*, *32*(9), 1294-1311.

Hayes, C. T., Black, E. E., Anderson, R. F., Baskaran, M., Buesseler, K. O., Charette, M. A., ... & Lam, P. J. (2018b). Flux of particulate elements in the North Atlantic Ocean constrained by multiple radionuclides. *Global Biogeochemical Cycles*, *32*(12), 1738-1758.

Heller, M. I., Lam, P. J., Moffett, J. W., Till, C. P., Lee, J. M., Toner, B. M., & Marcus, M. A. (2017). Accumulation of Fe oxyhydroxides in the Peruvian oxygen deficient zone implies non-oxygen dependent Fe oxidation. *Geochimica et Cosmochimica Acta*, *211*, 174-193.

Hendry, K. R., Rickaby, R. E., de Hoog, J. C., Weston, K., & Rehkämper, M. (2008). Cadmium and phosphate in coastal Antarctic seawater: implications for Southern Ocean nutrient cycling. *Marine Chemistry*, *112*(3-4), 149-157.

Heywood, K. J., Schmidtko, S., Heuzé, C., Kaiser, J., Jickells, T. D., Queste, B. Y., ... & Guihen, D. (2014). Ocean processes at the Antarctic continental slope. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *372*(2019), 20130047.

Ho, P., Lee, J. M., Heller, M. I., Lam, P. J., & Shiller, A. M. (2018). The distribution of dissolved and particulate Mo and V along the US GEOTRACES East Pacific Zonal Transect (GP16): The roles of oxides and biogenic particles in their distributions in the oxygen deficient zone and the hydrothermal plume. *Marine Chemistry*, *201*, 242-255.

Ho, P., Resing, J. A., & Shiller, A. M. (2019). Processes controlling the distribution of dissolved Al and Ga along the US GEOTRACES East Pacific Zonal Transect (GP16). *Deep Sea Research Part I: Oceanographic Research Papers*, *147*, 128-145.

Hoffman, C. L., Nicholas, S. L., Ohnemus, D. C., Fitzsimmons, J. N., Sherrell, R. M., German, C. R., ... & Toner, B. M. (2018). Near-field iron and carbon chemistry of non-buoyant hydrothermal plume particles, Southern East Pacific Rise 15 S. *Marine Chemistry*, *201*, 183-197.

Hohmann, R., Schlosser, P., Jacobs, S., Ludin, A., & Weppernig, R. (2002). Excess helium and neon in the southeast Pacific: Tracers for glacial meltwater. *Journal of Geophysical Research: Oceans*, *107*(C11), 19-1.

Jacobs, S. S. (1989). Marine controls on modern sedimentation on the Antarctic continental shelf. *Marine Geology*, *85*(2-4), 121-153.

Jacobs, S. S., Hellmer, H. H., & Jenkins, A. (1996). Antarctic ice sheet melting in the Southeast Pacific. *Geophysical Research Letters*, *23*(9), 957-960.

Jacobs, S. S., Giulivi, C. F., & Mele, P. A. (2002). Freshening of the Ross Sea during the late 20th century. *Science*, *297*(5580), 386-389.

Jacobs, S. S., Jenkins, A., Giulivi, C. F., & Dutrieux, P. (2011). Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nature Geoscience*, *4*(8), 519.

Jeandel, C., Arsouze, T., Lacan, F., Techine, P., & Dutay, J. C. (2007). Isotopic Nd compositions and concentrations of the lithogenic inputs into the ocean: A compilation, with an emphasis on the margins. *Chemical Geology*, *239*(1-2), 156-164.

Jenkins, A. (1999). The impact of melting ice on ocean waters. *Journal of physical oceanography*, *29*(9), 2370-2381.

Jensen, L. T., Wyatt, N. J., Twining, B. S., Rauschenberg, S., Landing, W. M., Sherrell, R. M., & Fitzsimmons, J. N. (2019). Biogeochemical cycling of dissolved zinc in the Western Arctic (Arctic GEOTRACES GN01). *Global Biogeochemical Cycles*, *33*(3), 343-369.

Joughin, I., & Alley, R. B. (2011). Stability of the West Antarctic ice sheet in a warming world. *Nature Geoscience*, *4*(8), 506.

John, S. G., & Conway, T. M. (2014). A role for scavenging in the marine biogeochemical cycling of zinc and zinc isotopes. *Earth and Planetary Science Letters*, *394*, 159-167.

John, S. G., Helgoe, J., Townsend, E., Weber, T., DeVries, T., Tagliabue, A., ... & Till, C. (2018). Biogeochemical cycling of Fe and Fe stable isotopes in the Eastern Tropical South Pacific. *Marine Chemistry*, *201*, 66-76.

Jung, J., Yoo, K. C., Rosenheim, B. E., Conway, T. M., Lee, J. I., Yoon, H. I., ... & Kim, J. (2019). Microbial Fe (III) reduction as a potential iron source from Holocene sediments beneath Larsen Ice Shelf. *Nature Communications*, *10*(1), 1-10.

Kadko, D., Aguilar-Islas, A., Bolt, C., Buck, C. S., Fitzsimmons, J. N., Jensen, L. T., ... & Whitmore, L. M. (2019). The residence times of trace elements determined in the surface Arctic Ocean during the 2015 US Arctic GEOTRACES expedition. *Marine Chemistry*, *208*, 56-69.

Kennicutt, M. C., Chown, S. L., Cassano, J. J., Liggett, D., Peck, L. S., Massom, R., ... & Allison, I. (2015). A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. *Antarctic Science*, *27*(1), 3-18.

Kim, I., Hahm, D., Rhee, T. S., Kim, T. W., Kim, C. S., & Lee, S. (2016). The distribution of glacial meltwater in the Amundsen Sea, Antarctica, revealed by dissolved helium and neon. *Journal of Geophysical Research: Oceans*, *121*(3), 1654-1666.

Kim, M., Yang, E. J., Kim, D., Jeong, J. H., Kim, H. J., Park, J., ... & Hwang, J. (2019). Sinking particle flux and composition at three sites of different annual sea ice cover in the Amundsen Sea, Antarctica. *Journal of Marine Systems*, *192*, 42-50.

Kustka, A. B., Kohut, J. T., White, A. E., Lam, P. J., Milligan, A. J., Dinniman, M. S., ... & Measures, C. I. (2015). The roles of MCDW and deep water iron supply in sustaining a recurrent phytoplankton bloom on central Pennell Bank (Ross Sea). *Deep Sea Research Part I: Oceanographic Research Papers*, *105*, 171-185.

Lam, P. J., Ohnemus, D. C., & Auro, M. E. (2015). Size-fractionated major particle composition and concentrations from the US GEOTRACES North Atlantic Zonal Transect. *Deep Sea Research Part II: Topical Studies in Oceanography*, *116*, 303-320.

Lam, P. J., Lee, J. M., Heller, M. I., Mehic, S., Xiang, Y., & Bates, N. R. (2018). Size-fractionated distributions of suspended particle concentration and major phase composition from the US GEOTRACES Eastern Pacific Zonal Transect (GP16). *Marine Chemistry*, *201*, 90-107.

Langone, L., Dunbar, R. B., Mucciarone, D. A., Ravaioli, M., Meloni, R., & Nittrouer, C. A. (2003). Rapid sinking of biogenic material during the late austral summer in the Ross Sea, Antarctica. *Biogeochemistry of the Ross Sea. AGU Antarctic Research Series Monograph*, *78*, 221-234.

Lannuzel, D., Schoemann, V., De Jong, J., Pasquer, B., Van der Merwe, P., Masson, F., ... & Bowie, A. (2010). Distribution of dissolved iron in Antarctic sea ice: Spatial, seasonal, and inter-annual variability. *Journal of Geophysical Research: Biogeosciences*, *115*(G3).

Lannuzel, D., Vancoppenolle, M., Van der Merwe, P., De Jong, J., Meiners, K. M., Grotti, M., ... & Schoemann, V. (2016). Iron in sea ice: Review and new insights. *Elem Sci Anth*, *4*.

Laufkoetter, C., Stern, A. A., John, J. G., Stock, C. A., & Dunne, J. P. (2018). Glacial iron sources stimulate the southern ocean carbon cycle. *Geophysical Research Letters*, *45*(24), 13-377.

Laws, E. A., & Maiti, K. (2019). The relationship between primary production and export production in the ocean: Effects of time lags and temporal variability. *Deep Sea Research Part I: Oceanographic Research Papers*, *148*, 100-107.

Lee, S. H., Kim, B. K., Yun, M. S., Joo, H., Yang, E. J., Kim, Y. N., ... & Lee, S. (2012). Spatial distribution of phytoplankton productivity in the Amundsen Sea, Antarctica. *Polar Biology*, *35*(11), 1721-1733.

Lee, S., Hwang, J., Ducklow, H. W., Hahm, D., Lee, S. H., Kim, D., ... & Yang, E. J. (2017). Evidence of minimal carbon sequestration in the productive Amundsen Sea polynya. *Geophysical Research Letters*, *44*(15), 7892-7899.

Lee, J. M., Heller, M. I., & Lam, P. J. (2018). Size distribution of particulate trace elements in the US GEOTRACES Eastern Pacific Zonal Transect (GP16). *Marine Chemistry*, *201*, 108-123.

LeMasurier, W. (2013). Shield volcanoes of Marie Byrd Land, West Antarctic rift: oceanic island similarities, continental signature, and tectonic controls. *Bulletin of volcanology*, *75*(6), 726.

Lin, H., Rauschenberg, S., Hexel, C. R., Shaw, T. J., & Twining, B. S. (2011). Free-drifting icebergs as sources of iron to the Weddell Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, *58*(11-12), 1392-1406.

Loose, B., & Jenkins, W. J. (2014). The five stable noble gases are sensitive unambiguous tracers of glacial meltwater. *Geophysical Research Letters*, *41*(8), 2835-2841.

Loose, B., Jenkins, W. J., Moriarty, R., Brown, P., Jullion, L., Garabato, A. C. N., ... & Meredith, M. P. (2016). Estimating the recharge properties of the deep ocean using noble gases and helium isotopes. *Journal of Geophysical Research: Oceans*, *121*(8), 5959-5979.

Loose, B., Garabato, A. C. N., Schlosser, P., Jenkins, W. J., Vaughan, D., & Heywood, K. J. (2018). Evidence of an active volcanic heat source beneath the Pine Island Glacier. *Nature Communications*, *9*(1), 2431.

Mack, S. L., Dinniman, M. S., McGillicuddy Jr, D. J., Sedwick, P. N., & Klinck, J. M. (2017). Dissolved iron transport pathways in the Ross Sea: Influence of tides and horizontal resolution in a regional ocean model. *Journal of Marine Systems*, *166*, 73-86.

Marinov, I., Gnanadesikan, A., Toggweiler, J. R., & Sarmiento, J. L. (2006). The Southern Ocean biogeochemical divide. *Nature*, *441*(7096), 964.

Marsay, C. M., Sedwick, P. N., Dinniman, M. S., Barrett, P. M., Mack, S. L., & McGillicuddy Jr, D. J. (2014). Estimating the benthic efflux of dissolved iron on the Ross Sea continental shelf. *Geophysical Research Letters*, *41*(21), 7576-7583.

Marsay, C. M., Aguilar-Islas, A., Fitzsimmons, J. N., Hatta, M., Jensen, L. T., John, S. G., ... & Pasqualini, A. (2018a). Dissolved and particulate trace elements in late summer Arctic melt ponds. *Marine Chemistry*, *204*, 70-85.

Marsay, C. M., Lam, P. J., Heller, M. I., Lee, J. M., & John, S. G. (2018b). Distribution and isotopic signature of ligand-leachable particulate iron along the GEOTRACES GP16 East Pacific Zonal Transect. *Marine Chemistry*, *201*, 198-211.

Martin, J. H., Fitzwater, S. E., & Gordon, R. M. (1990). Iron deficiency limits phytoplankton growth in Antarctic waters. *Global Biogeochemical Cycles*, *4*(1), 5-12.

McDonnell, J., Staffenova, M., Ripberger, C., Shernoff, D., Kunicki, M., Bressler, D., & Bean, C. (2019). Promoting STEM interest and identity through the 4-H STEM Ambassador program. *Connected Science Learning, 9*.

McGillicuddy Jr, D. J., Sedwick, P. N., Dinniman, M. S., Arrigo, K. R., Bibby, T. S., Greenan, B. J., ... & Marsay, C. M. (2015). Iron supply and demand in an Antarctic shelf ecosystem. *Geophysical Research Letters*, *42*(19), 8088-8097.

Measures, C. I., & Vink, S. (2000). On the use of dissolved aluminum in surface waters to estimate dust deposition to the ocean. *Global Biogeochemical Cycles*, *14*(1), 317-327.

Measures, C. I., Brown, M. T., Selph, K. E., Apprill, A., Zhou, M., Hatta, M., & Hiscock, W. T. (2013). The influence of shelf processes in delivering dissolved iron to the HNLC waters of the Drake Passage, Antarctica. *Deep Sea Research Part II: Topical Studies in Oceanography*, *90*, 77-88.

Meredith, M. P., Locarnini, R. A., Van Scoy, K. A., Watson, A. J., Heywood, K. J., & King, B. A. (2000). On the sources of Weddell Gyre Antarctic bottom water. *Journal of Geophysical Research: Oceans*, *105*(C1), 1093-1104.

Meredith, M. P., & King, J. C. (2005). Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. *Geophysical Research Letters*, *32*(19).

Millan, R., Rignot, E., Bernier, V., Morlighem, M., & Dutrieux, P. (2017). Bathymetry of the Amundsen Sea Embayment sector of West Antarctica from Operation IceBridge gravity and other data. *Geophysical Research Letters*, *44*(3), 1360-1368.

Moore, C. M., Mills, M. M., Arrigo, K. R., Berman-Frank, I., Bopp, L., Boyd, P. W., ... & Jickells, T. D. (2013). Processes and patterns of oceanic nutrient limitation. *Nature Geoscience*, *6*(9), 701-710.

Morel, F. M., Hudson, R. J., & Price, N. M. (1991). Limitation of productivity by trace metals in the sea. *Limnology and Oceanography*, *36*(8), 1742-1755.

Mouginot, J., Rignot, E., & Scheuchl, B. (2014). Sustained increase in ice discharge from the Amundsen Sea Embayment, West Antarctica, from 1973 to 2013. *Geophysical Research Letters*, *41*(5), 1576-1584.

Mu, L., Stammerjohn, S. E., Lowry, K. E., & Yager, P. L. (2014). Spatial variability of surface pCO_2 and air-sea CO_2 flux in the Amundsen Sea Polynya, Antarctica. *Elementa-Science Of The Anthropocene*, *3*.

Nakayama, Y., Schröder, M., & Hellmer, H. H. (2013). From circumpolar deep water to the glacial meltwater plume on the eastern Amundsen Shelf. *Deep Sea Research Part I: Oceanographic Research Papers*, *77*, 50-62.

Nakayama, Y., Timmermann, R., Rodehacke, C. B., Schröder, M., & Hellmer, H. H. (2014). Modeling the spreading of glacial meltwater from the Amundsen and Bellingshausen Seas. *Geophysical Research Letters*, *41*(22), 7942-7949.

Naughten, K. A., Meissner, K. J., Galton-Fenzi, B. K., England, M. H., Timmermann, R., & Hellmer, H. H. (2018). Future projections of Antarctic ice shelf melting based on CMIP5 scenarios. *Journal of Climate*, *31*(13), 5243-5261.

Ndungu, K., Zurbrick, C. M., Stammerjohn, S., Severmann, S., Sherrell, R. M., & Flegal, A. R. (2016). Lead sources to the Amundsen Sea, West Antarctica. *Environmental Science & Technology*, *50*(12), 6233-6239.

Nitsche, F. O., Jacobs, S. S., Larter, R. D., & Gohl, K. (2007). Bathymetry of the Amundsen Sea continental shelf: Implications for geology, oceanography, and glaciology. *Geochemistry, Geophysics, Geosystems*, *8*(10).

Ohnemus, D. C., & Lam, P. J. (2015). Cycling of lithogenic marine particles in the US GEOTRACES North Atlantic transect. *Deep Sea Research Part II: Topical Studies in Oceanography*, *116*, 283-302.

Ohnemus, D. C., Rauschenberg, S., Cutter, G. A., Fitzsimmons, J. N., Sherrell, R. M., & Twining, B. S. (2017). Elevated trace metal content of prokaryotic communities associated with marine oxygen deficient zones. *Limnology and Oceanography*, *62*(1), 3-25.

Ohnemus, D. C., Lam, P. J., & Twining, B. S. (2018). Optical observation of particles and responses to particle composition in the GEOTRACES GP16 section. *Marine Chemistry*, *201*, 124-136.

Oliver, H., St-Laurent, P., Sherrell, R. M., & Yager, P. L. (2019). Modeling Iron and Light Controls on the Summer *Phaeocystis antarctica* Bloom in the Amundsen Sea Polynya. *Global Biogeochemical Cycles*, *33*(5), 570-596.

Orsi, A. H., Whitworth III, T., & Nowlin Jr, W. D. (1995). On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep Sea Research Part I: Oceanographic Research Papers*, *42*(5), 641-673.

Orsi, A. H., Johnson, G. C., & Bullister, J. L. (1999). Circulation, mixing, and production of Antarctic Bottom Water. *Progress in Oceanography*, *43*(1), 55-109.

Orsi, A. H., Smethie Jr, W. M., & Bullister, J. L. (2002). On the total input of Antarctic waters to the deep ocean: A preliminary estimate from chlorofluorocarbon measurements. *Journal of Geophysical Research: Oceans*, *107*(C8), 31-1.

Overland, J. E., Wang, M., Walsh, J. E., & Stroeve, J. C. (2014). Future Arctic climate changes: Adaptation and mitigation time scales. *Earth's Future*, *2*(2), 68-74.

Pavia, F., Anderson, R., Vivancos, S., Fleisher, M., Lam, P., Lu, Y., ... & Edwards, R. L. (2018). Intense hydrothermal scavenging of 230Th and 231Pa in the deep Southeast Pacific. *Marine Chemistry*, *201*, 212-228.

Pavia, F. J., Anderson, R. F., Lam, P. J., Cael, B. B., Vivancos, S. M., Fleisher, M. Q., ... & Edwards, R. L. (2019). Shallow particulate organic carbon regeneration in the South Pacific Ocean. *Proceedings of the National Academy of Sciences*, *116*(20), 9753-9758.

Petty, A. A., Feltham, D. L., & Holland, P. R. (2013). Impact of atmospheric forcing on Antarctic continental shelf water masses. *Journal of physical oceanography*, *43*(5), 920-940.

Piotrowski, A. M., Goldstein, S. L., Sidney, R. H., Fairbanks, R. G., & Zylberberg, D. R. (2008). Oscillating glacial northern and southern deep water formation from combined neodymium and carbon isotopes. *Earth and Planetary Science Letters*, *272*(1-2), 394-405.

Planquette, H., Sherrell, R. M., Stammerjohn, S., & Field, M. P. (2013). Particulate iron delivery to the water column of the Amundsen Sea, Antarctica. *Marine Chemistry*, *153*, 15-30.

Raiswell, R., Tranter, M., Benning, L. G., Siegert, M., De'ath, R., Huybrechts, P., & Payne, T. (2006). Contributions from glacially derived sediment to the global iron (oxyhydr) oxide cycle: Implications for iron delivery to the oceans. *Geochimica et Cosmochimica Acta*, *70*(11), 2765-2780.

Raiswell, R., Benning, L. G., Tranter, M., & Tulaczyk, S. (2008). Bioavailable iron in the Southern Ocean: the significance of the iceberg conveyor belt. *Geochemical Transactions*, *9*(1), 7.

Randall-Goodwin, E., Meredith, M. P., Jenkins, A., Yager, P. L., Sherrell, R. M., Abrahamsen, E. P., ... & Alderkamp, A. C. (2015). Freshwater distributions and water mass structure in the Amundsen Sea Polynya region, Antarctica. *Elementa: Science of the Anthropocene*, *3*.

Resing, J. A., Sedwick, P. N., German, C. R., Jenkins, W. J., Moffett, J. W., Sohst, B. M., & Tagliabue, A. (2015). Basin-scale transport of hydrothermal dissolved metals across the South Pacific Ocean. *Nature*, *523*(7559), 200-203.

Rignot, E., Jacobs, S., Mouginot, J., & Scheuchl, B. (2013). Ice-shelf melting around Antarctica. *Science*, *341*(6143), 266-270.

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., & Scheuchl, B. (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters*, *41*(10), 3502-3509.

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M. J., & Morlighem, M. (2019). Four decades of Antarctic Ice Sheet mass balance from 1979–2017. *Proceedings of the National Academy of Sciences*, *116*(4), 1095-1103.

Rintoul, S. R. (2007). Rapid freshening of Antarctic Bottom Water formed in the Indian and Pacific oceans. *Geophysical Research Letters*, *34*(6).

Riser, S. C., Swift, D., & Drucker, R. (2018). Profiling floats in SOCCOM: Technical capabilities for studying the Southern Ocean. *Journal of Geophysical Research: Oceans*, *123*(6), 4055-4073.

Roshan, S., & Wu, J. (2015). Cadmium regeneration within the North Atlantic. *Global Biogeochemical Cycles*, *29*(12), 2082-2094.

Roshan, S., Wu, J., & Jenkins, W. J. (2016). Long-range transport of hydrothermal dissolved Zn in the tropical South Pacific. *Marine Chemistry*, *183*, 25-32.

Roshan, S., DeVries, T., Wu, J., & Chen, G. (2018). The internal cycling of zinc in the ocean. *Global Biogeochemical Cycles*, *32*(12), 1833-1849.

Roy-Barman, M., Thil, F., Bordier, L., Dapoigny, A., Foliot, L., Ayrault, S., ... & Garcia-Solsona, E. (2019). Thorium isotopes in the Southeast Atlantic Ocean: Tracking scavenging during water mass mixing along neutral density surfaces. *Deep Sea Research Part I: Oceanographic Research Papers*.

Saito, M. A., Goepfert, T. J., Noble, A. E., Bertrand, E. M., Sedwick, P. N., & DiTullio, G. R. (2010). A Seasonal Study of Dissolved Cobalt in the Ross Sea, Antarctica: Micronutrient Behavior, Absence of Scavenging, and Relationships with Zd, Cd, and P. *Biogeosciences*, *7*(12).

Sanial, V., Kipp, L. E., Henderson, P. B., Van Beek, P., Reyss, J. L., Hammond, D. E., ... & Moore, W. S. (2018). Radium-228 as a tracer of dissolved trace element inputs from the Peruvian continental margin. *Marine Chemistry*, *201*, 20-34.

Sarmiento, J. L., Gruber, N., Brzezinski, M. A., & Dunne, J. P. (2004). High-latitude controls of thermocline nutrients and low latitude biological productivity. *Nature*, *427*(6969), 56-60.

Schlitzer, R., Anderson, R. F., Dodas, E. M., Lohan, M., Geibert, W., Tagliabue, A., ... & Cockwell, D. (2018). The GEOTRACES intermediate data product 2017. *Chemical Geology*, *493*, 210-223.

Schmidtko, S., Heywood, K. J., Thompson, A. F., & Aoki, S. (2014). Multidecadal warming of Antarctic waters. *Science*, *346*(6214), 1227-1231.

Sedwick, P. N., & DiTullio, G. R. (1997). Regulation of algal blooms in Antarctic shelf waters by the release of iron from melting sea ice. *Geophysical Research Letters*, *24*(20), 2515-2518.

Sedwick, P. N., DiTullio, G. R., & Mackey, D. J. (2000). Iron and manganese in the Ross Sea, Antarctica: seasonal iron limitation in Antarctic shelf waters. *Journal of Geophysical Research: Oceans*, *105*(C5), 11321-11336.

Sedwick, P. N., Marsay, C. M., Sohst, B. M., Aguilar-Islas, A. M., Lohan, M. C., Long, M. C., ... & DiTullio, G. R. (2011). Early season depletion of dissolved iron in the Ross Sea polynya: Implications for iron dynamics on the Antarctic continental shelf. *Journal of Geophysical Research: Oceans*, *116*(C12).

Shadwick, E. H., Tilbrook, B., & Williams, G. D. (2014). Carbonate chemistry in the Mertz Polynya (East Antarctica): Biological and physical modification of dense water outflows and the export of anthropogenic CO2. *Journal of Geophysical Research: Oceans*, *119*(1), 1-14.

Shelley, R. U., Morton, P. L., & Landing, W. M. (2015). Elemental ratios and enrichment factors in aerosols from the US-GEOTRACES North Atlantic transects. *Deep Sea Research Part II: Topical Studies in Oceanography*, *116*, 262-272.

Shepherd, A., Wingham, D. J., & Mansley, J. A. (2002). Inland thinning of the Amundsen Sea sector, West Antarctica. *Geophysical Research Letters*, *29*(10), 2-1.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., Van Den Broeke, M., Velicogna, I., ... & Nowicki, S. (2018). Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature*, *558*, 219-222.

Sherrell, R. M., Lagerström, M. E., Forsch, K. O., Stammerjohn, S. E., & Yager, P. L. (2015). Dynamics of dissolved iron and other bioactive trace metals (Mn, Ni, Cu, Zn) in the Amundsen Sea Polynya, Antarctica. *Elementa Science of the Anthropocene*, *3*.

Sherrell, R. M., Annett, A. L., Fitzsimmons, J. N., Roccanova, V. J., & Meredith, M. P. (2018). A 'shallow bathtub ring'of local sedimentary iron input maintains the Palmer Deep biological hotspot on the West Antarctic Peninsula shelf. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2122), 20170171.

Shoenfelt, E. M., Sun, J., Winckler, G., Kaplan, M. R., Borunda, A. L., Farrell, K. R., ... & Bostick, B. C. (2017). High particulate iron (II) content in glacially sourced dusts enhances productivity of a model diatom. *Science advances*, *3*(6), e1700314.

Sigman, D. M., Hain, M. P., & Haug, G. H. (2010). The polar ocean and glacial cycles in atmospheric CO_2 concentration. *Nature*, *466*(7302), 47.

Smethie Jr, W. M., & Jacobs, S. S. (2005). Circulation and melting under the Ross Ice Shelf: estimates from evolving CFC, salinity and temperature fields in the Ross Sea. *Deep Sea Research Part I: Oceanographic Research Papers*, *52*(6), 959-978.

Smith, W. O., & Comiso, J. C. (2008). Influence of sea ice on primary production in the Southern Ocean: A satellite perspective. *Journal of Geophysical Research: Oceans*, *113*(C5).

Smith Jr, W. O., Sedwick, P. N., Arrigo, K. R., Ainley, D. G., & Orsi, A. H. (2012). The Ross Sea in a sea of change. *Oceanography*, *25*(3), 90-103.

Smith Jr, W. O., Dinniman, M. S., Hofmann, E. E., & Klinck, J. M. (2014). The effects of changing winds and temperatures on the oceanography of the Ross Sea in the 21st century. *Geophysical Research Letters*, *41*(5), 1624-1631.

Stammerjohn, S. E., Maksym, T., Massom, R. A., Lowry, K. E., Arrigo, K. R., Yuan, X., ... & Yager, P. L. (2015). Seasonal sea ice changes in the Amundsen Sea, Antarctica, over the period of 1979–2014. *Elem Sci Anth*, *3*.

Steig, E. J., Ding, Q., Battisti, D. S., & Jenkins, A. (2012). Tropical forcing of Circumpolar Deep Water inflow and outlet glacier thinning in the Amundsen Sea Embayment, West Antarctica. *Annals of Glaciology*, *53*(60), 19-28.

St-Laurent, P., Yager, P. L., Sherrell, R. M., Stammerjohn, S. E., & Dinniman, M. S. (2017). Pathways and supply of dissolved iron in the A mundsen S ea (A ntarctica). *Journal of Geophysical Research: Oceans*, *122*(9), 7135-7162.

St-Laurent, P., Yager, P. L., Sherrell, R. M., Oliver, H., Dinniman, M. S., & Stammerjohn, S. E. (2019). Modeling the seasonal cycle of iron and carbon fluxes in the Amundsen Sea Polynya, Antarctica. *Journal of Geophysical Research: Oceans*, *124*(3), 1544-1565.

Sutterley, T. C., Velicogna, I., Rignot, E., Mouginot, J., Flament, T., Van Den Broeke, M. R., ... & Reijmer, C. H. (2014). Mass loss of the Amundsen Sea Embayment of West Antarctica from four independent techniques. *Geophysical Research Letters*, *41*(23), 8421-8428.

Tagliabue, A., & Arrigo, K. R. (2005). Iron in the Ross Sea: 1. Impact on CO2 fluxes via variation in phytoplankton functional group and non-Redfield stoichiometry. *Journal of Geophysical Research: Oceans*, *110*(C3).

Tagliabue, A., Bopp, L., & Aumont, O. (2009). Evaluating the importance of atmospheric and sedimentary iron sources to Southern Ocean biogeochemistry. *Geophysical Research Letters*, *36*(13).

Tagliabue, A., & Resing, J. (2016). Impact of hydrothermalism on the ocean iron cycle. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *374*(2081), 20150291.

Twining, B. S., Rauschenberg, S., Morton, P. L., & Vogt, S. (2015). Metal contents of phytoplankton and labile particulate material in the North Atlantic Ocean. *Progress in Oceanography*, *137*, 261-283.

Vancoppenolle, M., Meiners, K. M., Michel, C., Bopp, L., Brabant, F., Carnat, G., ... & Tison, J. L. (2013). Role of sea ice in global biogeochemical cycles: emerging views and challenges. *Quaternary science reviews*, *79*, 207-230.

Van der Merwe, P., Lannuzel, D., Bowie, A. R., Nichols, C. M., & Meiners, K. M. (2011). Iron fractionation in pack and fast ice in East Antarctica: Temporal decoupling between the release of dissolved and particulate iron during spring melt. *Deep Sea Research Part II: Topical Studies in Oceanography*, *58*(9-10), 1222-1236.

Van Wijk, E. M., & Rintoul, S. R. (2014). Freshening drives contraction of Antarctic bottom water in the Australian Antarctic Basin. *Geophysical Research Letters*, *41*(5), 1657-1664.

Vance, D., Little, S. H., de Souza, G. F., Khatiwala, S., Lohan, M. C., & Middag, R. (2017). Silicon and zinc biogeochemical cycles coupled through the Southern Ocean. *Nature Geoscience*, *10*(3), 202.

Walsh, J. E., Overland, J. E., Groisman, P. Y., & Rudolf, B. (2011). Ongoing climate change in the Arctic. *Ambio*, *40*(1), 6-16.

Watson, A. J., Bakker, D. C. E., Ridgwell, A. J., Boyd, P. W., & Law, C. S. (2000). Effect of iron supply on Southern Ocean CO 2 uptake and implications for glacial atmospheric CO 2. *Nature*, *407*(6805), 730-733.

Winton, V. H. L., Dunbar, G. B., Bertler, N. A. N., Millet, M. A., Delmonte, B., Atkins, C. B., ... & Andersson, P. (2014). The contribution of aeolian sand and dust to iron fertilization of phytoplankton blooms in southwestern Ross Sea, Antarctica. *Global Biogeochemical Cycles*, *28*(4), 423-436.

Winton, V. H. L., Edwards, R., Delmonte, B., Ellis, A., Andersson, P. S., Bowie, A., ... & Tuohy, A. (2016). Multiple sources of soluble atmospheric iron to Antarctic waters. *Global Biogeochemical Cycles*, *30*(3), 421-437.

Xue, Z., Rehkämper, M., Horner, T. J., Abouchami, W., Middag, R., van de Flierd, T., & de Baar, H. J. (2013). Cadmium isotope variations in the Southern Ocean. *Earth and Planetary Science Letters*, *382*, 161-172.

Yager, P. L., Sherrell, R. M., Stammerjohn, S. E., Alderkamp, A. C., Schofield, O., Abrahamsen, E. P., ... & Lowry, K. E. (2012). ASPIRE: the Amundsen Sea Polynya international research expedition. *Oceanography*, *25*(3), 40-53.

Yager, P. L., Sherrell, R. M., & Sipler, R. E. (2016). A carbon budget for the Amundsen Sea Polynya, Antarctica: Estimating net community production and export in a highly productive polar ecosystem. *Elementa-Science Of The Anthropocene*, *4*(140).

Yu, E. F., Francois, R., & Bacon, M. P. (1996). Similar rates of modern and last-glacial ocean thermohaline circulation inferred from radiochemical data. *Nature*, *379*(6567), 689.

LOGISTICAL REQUIREMENTS AND FIELD PLAN

Collaborative Research: Management and Implementation of US GEOTRACES GP17 Section: Amundsen Sea Sector of the Antarctic Continental Margin (GP17-ANT)

1. Research objective: This project aims to manage and implement a 60-day research cruise to collect samples and field data from the Amundsen Sea sector of the Southern Ocean, as part of the US GEOTRACES program, focusing on measurements of a broad suite of trace elements and isotopes (TEIs). Specifically, this work comprises the essential sampling operations (collection, processing) and ancillary measurements (hydrography, nutrients, algal pigments) in support of multiple, TEI-focused science projects that will be proposed by individual PIs, following the successful model of four previous US GEOTRACES cruises completed in the Atlantic, Pacific and Arctic Oceans.

2. Geographic region: The proposed research will support the collection of water-column and surface-water samples and data, as well as ice, snow, aerosols and seafloor sediments, from the Amundsen Sea sector of the Southern Ocean between 100°W and 135°W. The cruise would occupy stations ranging from the 67°S in the Antarctic Circumpolar Current on to the Amundsen Sea continental shelf, sampling as far south as the fronts of the Pine Island, Thwaites, Dotson and Getz Ice Shelves. The proposed cruise track and sampling stations are shown in Figure 1. The cruise track has been chosen so as to minimize ice breaking, based on the long-term average sea ice extent in the February-March target period.

3. Field activities and logistical resources: We anticipate that RV *Nathaniel B. Palmer* will be required for its ice breaking capability, endurance and laboratory/berthing space. Primary field activities will be water-column sampling using (i) a conventional CTD-rosette system (ODF 36-bottle rosette); (ii) a trace-metal clean CTD rosette (USAP 12-bottle rosette); and (iii) in-situ McLane high volume pumps (PI-supplied). We will also sample surface waters using a towed 'fish' sampler in open waters (PI-supplied) or a small boat (USAP supplied) where sea ice is present, and collect samples of sea ice and floating glacial ice using either a small boat to access isolated ice floes, or a man basket on larger floes, using PI-supplied sampling gear. In addition, a multicorer (USAP) will be used to collect sediment samples from stations on the continental shelf. We also request use of the USAP trace-metal lab van and trace-metal winch and conducting cable, and anticipate need for other laboratory vans, including a radioisotope lab van, general purpose lab van, and cold lab van.

4. Desired deployment schedule and proposed field sampling: We request a 60-day cruise departing Punta Arenas in late January 2022, arriving in the Amundsen Sea study region in early February, with ca. 45 days to occupy 30 stations (Fig. 1) with the sampling activities detailed above, then returning to arrive in Punta Arenas in late March 2022.

5. Justification for requested number of field team members: Based on experience from previous US GEOTRACES ocean section cruises, we anticipate that the number of individual science proposals funded will require use of all available science berthing and lab space aboard RV *Nathaniel B. Palmer*.

6. Description of facility construction, modification, or installation requirements: Nothing major anticipated for the proposed project.

7. Description of instrumentation to be deployed on aircraft, autonomous platforms, scientific instruments, equipment with special support requirements, or scientific diving: None anticipated for the proposed project.

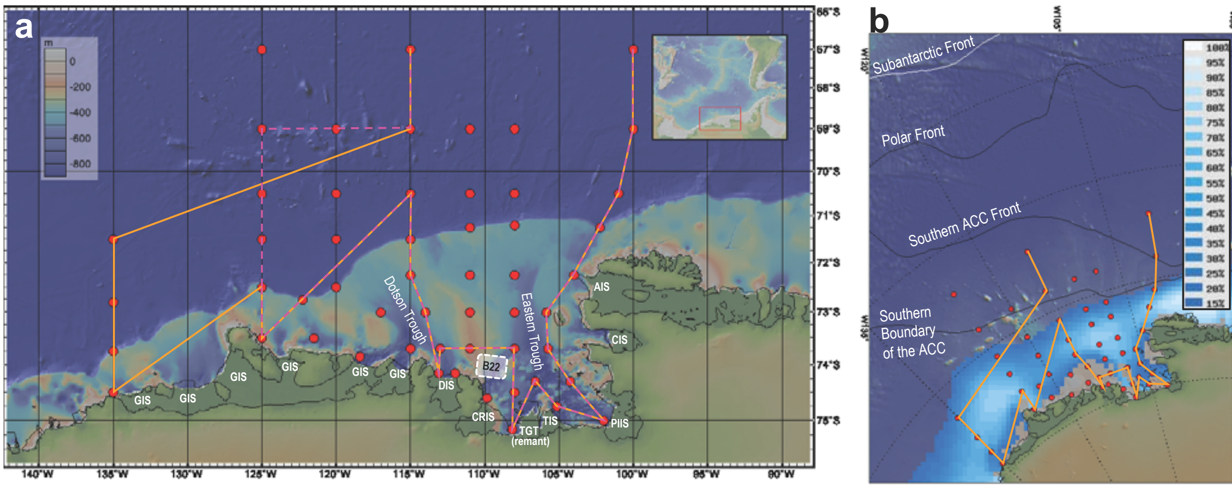

Figure 1. (a). *Proposed cruise track (in orange) and station locations for the proposed US GEOTRACES GP17-ANT cruise. Also shown is an abridged track (in pink), as a contingency plan in case of delays due to above-average sea ice extent, and a grid of additional contingency stations (shown as red points not located along cruise tracks) that will be occupied if nominal stations are not accessible (bathymetry from Nitsche et al., 2007); ice shelves shown are Abbot (AIS), Cosgrove (CIS), Pine Island (PIIS), Thwaites (TIS), Crosson (CRIS), Dotson (DIS) and Getz (GIS); approximate location of iceberg B22 calved from Thwaites Glacial Tongue (TGT) also shown;* (b) *Proposed full cruise track and contingency stations (polar projection) shown over 1979-2007 average of sea ice concentration in February (from NSIDC).*