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Introduction

Southern Ocean natural iron fertilization

The surface waters of the Southern Ocean have been widely identified as being replete in macronutrients (nitrogen and phosphorous) that phytoplankton appear unable to use. This makes the Southern Ocean the largest high nutrient low chlorophyll (HNLC) region in the global ocean (e.g. Chisholm and Morel, 1991). Martin (1992) hypothesized that inadequate supplies of iron (Fe) were responsible for HNLC conditions.

John Martin famously joked, “Give me a half tanker of iron, and I will give you an ice age,” suggesting that the addition of iron might stimulate sufficient phytoplankton growth to result in net oceanic uptake of carbon dioxide. Martin's hypothesis motivated a number of field programs that tested how the ocean would respond to artificial addition of iron (de Baar et al., 2005). These included, for example, the Southern Ocean Iron Release Experiment (SOIREE, e.g. Abraham et al., 2000; Boyd et al., 2000) and Southern Ocean Iron Fertilization Experiment (SOFEX, e.g. Coale et al. 2004). Collectively these field experiments showed that iron addition led to immediate localized phytoplankton blooms. They also have stimulated considerable speculation casting doubt on the potential for geoengineering climate via iron fertilization (e.g. Zeebe and Archer, 2005).

However, perhaps the more intriguing question is why some parts of the Southern Ocean appear to have sufficient iron available to support strong biological blooms. Interest in the underlying processes motivated three field programs in 2004–2006. The United Kingdom led the “CROZet natural iron bloom and Export” experiment (CROZEX, e.g. Pollard et al. 2007), which studied mechanisms contributing to biological productivity near the Crozet Islands in the Southern Indian Ocean. The French project “KErguelen: compared study of the Ocean and the Plateau in Surface water” (KEOPS, Blain et al. 2007, 2008) investigated differences in productivity and iron availability in the wake of the Kerguelen Plateau. The United States project explored the mechanisms behind productivity in the Southern Drake Passage region, near the Antarctic Peninsula.

The major feature that unites these regions of high biological productivity is that they are on or near the shelf regions that surround islands or the Antarctic continent, suggesting that the shelves themselves might serve as a source of natural iron fertilization. Understanding the mechanisms behind natural iron fertilization thus depends on developing an interdisciplinary perspective spanning physical, chemical, and biological oceanography in order to identify processes that contribute to transport of iron into surface waters, recycling of nutrients, reactivity of iron, and phytoplankton physiology.

This special volume was motivated in part by an international workshop on natural iron fertilization held in Woods Hole in June 2011 (http://alturl.com/n6yva). It brings together multi-disciplinary results primarily from the US project in the Southern Drake Passage, as well as a few synthesis studies that have attempted to identify key findings from a broader range of Southern Ocean natural iron fertilization regions.

Ocean transport and mixing processes are key in delivering iron-rich shelf/plateau waters to HNLC areas where this micronutrient is needed. Zhou et al. (2013) report that off shelf transport rates into the Drake Passage are two-fold higher in winter compared to summer. Coupled with higher wintertime Fe concentrations over the shelf (Hatta et al., 2013), this process could be key in regulating the timing, intensity and extension of the spring bloom downstream of the Antarctic Peninsula. Frants et al. (2013) used an Optimum Multiparameter analysis of key water column properties to derive the water mass origin of iron-rich shelf waters in this same region. They postulated that the previously observed long residence times of water in the Ona Basin combined with the offshore advection of shelf waters would allow for a build up of iron below the basin's mixed layer.

Three papers set out to identify Fe sources, define seasonal changes in Fe distributions, and quantify Fe fluxes in and around the Antarctic Peninsula. Measures et al. (2013) used the relative concentrations of iron, manganese, and aluminum in austral summer to infer that water column Fe was ultimately derived from sediment diagenesis. Furthermore, ratios of Fe:Mn across a range of water masses were stable, which suggested that physical mixing processes were dominant in controlling their distribution; their distribution was used to explain to relatively large offshelf Fe fluxes compared with biological uptake over the shelf. During austral winter, Hatta et al. (2013) observed high concentrations of Fe, Mn, and Al associated with resuspended sediments over the shelf in regions of intense circulation. They noted that this was further evidence that the dissolved metals in this region are sourced from suboxic or anoxic sediment porewaters entrained into the water column during sediment resuspension. A second paper by Frants et al. (2013) demonstrated that diapycnal mixing at the base of the Ona Basin mixed layer combined with shelf water entrainment could supply sufficient iron to the euphotic zone to sustain the bloom throughout the summer and early fall.

Chemical speciation plays an important role in determining trace metal bioavailability and residence time. Bundy et al. (2013) reported on the wintertime distribution and concentration of copper and Cu binding ligands surrounding the Antarctic Peninsula. They derived the free Cu concentration (Cu^{2+}), a micronutrient required for phytoplankton growth, and concluded that the low concentrations were such that levels may be limiting for some types of inducible iron acquisition. Jiang et al. (2013) developed and tested a biological-Fe model that incorporated organic ligands.

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The model simulations generally agreed with Antarctic Peninsula field incubation data from 2004 to 2006 that Fe limitation could drive bacterial production of ligands. It also identified some key differences in the Fe cycle between summer and winter. In summer, Fe is consumed and removed by phytoplankton production and export, with dissolved Fe removal partially offset by photoreduction or remineralization of particulate Fe. In winter, lower temperatures, light levels and biological productivity results in much lower rates of exchange between the different iron pools.

While availability of iron clearly regulates primary productivity rates in the Southern Ocean, it can also determine phytoplankton community structure. Selph et al. (2013) used flow cytometry to study austral summer Antarctic Peninsula biomass and distribution between two size classes of phytoplankton. They reported that, while elevated levels of dissolved Fe often led to increases in phytoplankton biomass, light limitation prevented significant biomass accumulation in certain areas where Fe levels remained high. Quéguiner (2013) presents a synthesis of plankton community structure under both artificial and natural iron fertilized conditions. He separates Southern Ocean diatoms into two classes, fast growing/slightly silicified and slow growing/strongly silicified, and describes the physical and biogeochemical conditions under which each can thrive.

Given the potential impacts on climate, the relationship between iron addition and carbon sequestration in the Southern Ocean has been hotly debated. Morris and Charette (2013) review ^{234}Th-derived particulate organic carbon (POC) export among several natural iron fertilization studies. They report that POC export within naturally-Fe fertilized areas was generally ~3-times higher than in control (Fe limited) stations. They also examined the relationship between Fe supply and POC export, which provides a measure of POC export efficiency per unit of iron addition. This analysis resulted in C:Fe export ratios that varied by an order of magnitude between different Southern Ocean regions. In Hopkinson et al. (2013), C:Fe ratios were determined by two independent bottle incubation methods. One used additions of radiolabeled Fe, while the other (‘carrying-capacity’) used only the ambient Fe present in the samples at time of collection. Interestingly, the two methods produced C:Fe ratios that agree within 20% on average despite the very different approaches; these field measurements are essential for models that seek to quantify the impact of C-uptake upon Fe addition in the Southern Ocean (e.g. Tagliabue et al., 2009).

Finally, Jiang et al. (2013) used a high-resolution regional model to study the seasonal circulation and transport in the Antarctic Peninsula shelf region. Both variables were found to be highly seasonally dependent, mostly due to seasonal changes in surface winds and large-scale circulation. A radium isotope, ^{228}Ra–used previously as a conservative tracer of sedimentary Fe input (e.g. Charette et al., 2007), was added to the model and its observed distribution suggested that Fe is derived from shallow sills at the western end of Bransfield Strait and rapidly transported off-shelf into HNLC waters at Elephant Island.

In our June 2011 workshop, it was generally agreed that there is still much to be learned on the factors controlling phytoplankton blooms in naturally Fe-fertilized Southern Ocean regions. While to date the major focus of iron fertilization studies has been on their potential carbon sequestration efficiency, we agreed that future studies need to move beyond this question and strive to better understand the ecosystem processes that control bloom dynamics. Furthermore, no single study has encompassed full seasonal coverage at a one location. To address this shortcoming, we advocated a multi-ship, multi-national process study that would use a suite of standard measurements to capture bloom evolution and collapse as well as seasonal variability in plankton community structure.

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