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Long term trend of increasing iron stress in Southern Ocean phytoplankton

Sandy Thomalla[1,2], Thomas Ryan-Keogh[1], Alessandro Tagliabue[3], and Pedro Monteiro[1,2]
[1]CSIR, Southern Ocean Carbon and Climate Observatory (SOCCO), Cape Town, South Africa
[2]University of Cape Town, Marine Research Institute (Ma-Re), Cape Town, South Africa
[3]University of Liverpool, Department of Earth, Ocean and Ecological Sciences, Liverpool, United Kingdom

Net primary production is a major contributor to carbon export in the Southern Ocean and supports rich marine ecosystems [Henley et al., 2020], driven in part by high macronutrient availability and summertime light levels, but ultimately constrained by seasonal changes in light and scarce supply of the essential micronutrient iron [Martin et al., 1990; Boyd, 2002; Tagliabue et al., 2016]. Although changing iron stress is a component of climate-driven trends in model projections of net primary production [Bopp et al., 2013; Laufkotter et al., 2015; Kwiatkowski et al., 2020], our confidence in the accuracy of their predictions is undermined by a lack of *in situ* constraints at appropriate spatial and temporal scales [Tagliabue et al., 2016; Tagliabue et al., 2020]. Earth System Models tend to predict increased Southern Ocean net primary production by the end of the 21st century, but are characterized by significant inter-model disagreement [Bopp et al., 2013; Kwiatkowski et al., 2020 Biogeosciences]. We show a significant multi-decadal increase in *in situ* iron stress from 1996 to 2020 that is positively correlated to the Southern Annular Mode and reflected by diminishing *in situ* net primary production over the last five years. It is not possible to directly infer Fe stress from observed concentrations, which necessitate experimental approaches (*in situ* open ocean fertilization / bottle nutrient addition experiments or proteomics). These experimental methods cannot be easily applied at appropriate spatial and temporal scales across the Southern Ocean that are required to assess trends in ecosystem status linked to climate drivers. Our novel proxy for *in situ* iron stress is based on the degree of non-photochemical quenching in relation to available light as a measurable photophysiological response to iron availability [Alderkamp et al., 2019; Schuback & Tortell, 2019; Schallenberg et al., 2020; Ryan-Keogh & Thomalla, 2020]. The proxy was able to reproduce expected variations in iron stress that occur seasonally [Boyd, 2002] and from natural and artificial fertilization [Boyd et al., 2000; Coale et al., 2004; Blain et al., 2008]. A particular strength of this iron stress proxy is that it can be retrospectively applied to data from ships and autonomous platforms with coincident measurements of fluorescence, photosynthetically active radiation and backscatter or beam attenuation to deliver a long-term time series. An iron stress trend of this magnitude in the Southern Ocean, where the primary constraint on net primary production is known to be iron limitation, is likely to have significant implications for the effectiveness of the biological carbon pump globally and may impact the trajectory of climate. The progressive *in situ* trend of increasing iron stress is however much stronger than net primary production trends from a suite

of remote sensing and earth system models, indicating hitherto potential underestimation of ongoing Southern Ocean change.