Goldschmidt 2022 Abstract
https://doi.org/10.46427/gold2022.10268

# Investigating Phytoplankton Manganese Limitation in the Southern Ocean with a Global Biogeochemical Model

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The surface waters of the Southern Ocean have the lowest recorded concentrations of the micronutrient manganese, a necessary component of the photosynthetic apparatus. Alongside the recognized roles for iron and light in driving Southern Ocean productivity, recent experimental studies have shown that manganese can limit or co-limit phytoplankton production in Antarctic waters. Here, we develop parameterizations for phytoplankton manganese requirements and uptake and incorporate them into the global biogeochemical model PISCES-BYONIC to investigate the oceanographic and physiological drivers that lead to phytoplankton manganese stress. The combination of low light, elevated iron, and significant quantities of upwelled zinc - which binds to Mn transporters and blocks Mn uptake - lead to a seasonal maximum in Mn limitation across large areas of the Pacific and Indian sectors during Austral Spring, giving way to predominant iron stress during summer. Our model argues for a substantial role for Mn limitation on the Southern Ocean biological carbon pump, which intensifies when external dust sources of Fe (and Mn) are increased to levels found in the past (e.g. the Last Glacial Maximum period). While more experiments are needed to model phytoplankton adaptations to simultaneously low Mn, Fe and light (as well as high Zn), this work suggests that Mn has been a major player in Southern Ocean biogeochemistry since circumpolar ocean circulation was established after the opening of Antarctic gateways.