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Seasonality and scale of the Kerguelen plateau phytoplankton bloom: A remote sensing and modeling analysis of the influence of natural iron fertilization in the Southern Ocean

Mathieu Mongin[a,*], Ernesto Molina[a,b], Thomas W. Trull[a,b,c]

[a]Antarctic Climate and Ecosystems CRC, Hobart 7001, Australia
[b]Institute of Antarctic and Southern Ocean Studies, University of Tasmania, Hobart 7001, Australia
[c]CSIRO Marine and Atmospheric Research, Hobart 7001, Australia

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Abstract

The phytoplankton bloom that develops over the Kerguelen plateau following natural input of iron is analysed on a regional and seasonal scale. The relation between chlorophyll, bathymetry, and surface advection fields is not as obvious as it first appears from large-scale annual mean field. The high chlorophyll biomass does not always correspond with the shallowest water, and there are portions of the plateau, which persistently exhibit low chlorophyll. Despite this complex dynamic, a one-dimensional model calibrated for HNLC (high-nutrient low-chlorophyll) region is able to capture the observed increase in chlorophyll by increasing the deep iron concentration. The elemental budget shows similarity in terms of carbon, nitrogen, and silicon but differences in terms of iron with the budget calculated during the mission. This discrepancy either has its origin in the structure of the iron cycling in the model or in the temporal scarcity of data that could only be collected during the summer months. In the model, flexibility of the Fe/C ratio associated with high Fe export and input fluxes prevents high carbon sequestration efficiency. This first insight with remote sensing data and the model allows the validation of some of the key mechanisms of natural iron fertilization and exposes problems that will need to be solved to have a complete biogeochemical diagnostic of this natural iron fertilization.

Keywords: MODIS; Chlorophyll; KEOPS; Biogeochemical model; Carbon export; Iron fertilization

1. Introduction

Artificial iron-fertilization experiments in HNLC waters have shown that iron addition promotes phytoplankton, and especially large-diatom growth (reviewed in De Baar et al., 2005), but have also revealed that the subsequent development and persistence of the bloom depends strongly on the extent of exchange between fertilized and surrounding waters. For example, during SOIREE (Southern Ocean Iron Release Experiment), the artificial addition of iron in the ocean surface led to a chlorophyll patch that persisted much longer than expected (Boyd et al., 2000) due to a favourable combination of stirring, growth, and diffusion processes (Abraham et al., 2000). In reviewing eight artificial iron experiments, De Baar et al. (2005) also showed that for most of them the dispersion of the phytoplankton bloom was due to horizontal mixing.

The small scale and short duration of these iron fertilization experiments, and thus the enhanced importance of exchange with surrounding waters, have limited their relevance to the assessment of the impact of large scale increased iron availability on Southern Ocean carbon cycling (e.g., Boyd et al., 2002; De Baar et al., 2005). By contrast, KEOPS (Kerguelen Ocean and Plateau compared Study) was designed to address the effects of iron on carbon cycling differently, by examining the area of persistently high phytoplankton biomass that forms over the Kerguelen plateau each year (Fig. 1). Shipboard observations in January–February 2005 revealed that this

*Corresponding author.
E-mail address: Mathieu.Mongin@acecrc.org.au (M. Mongin).

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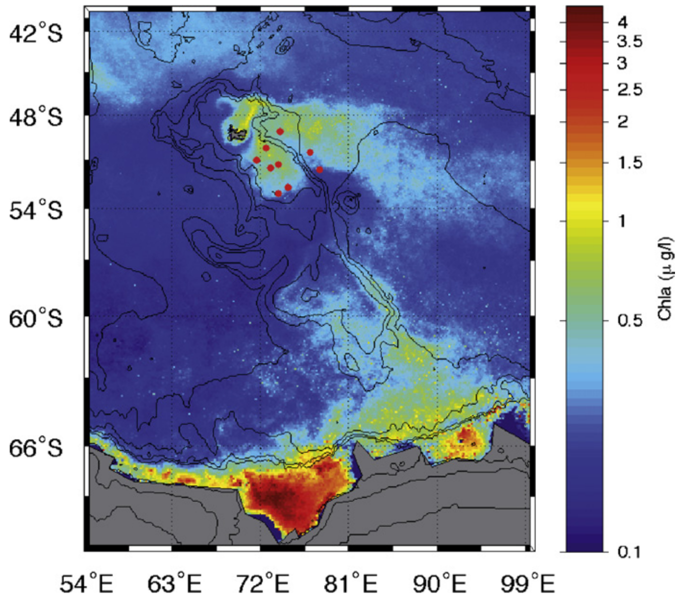

Fig. 1. Map of the Kerguelen plateau area, showing major topography and chlorophyll-*a* climatology (1997–2007) from the MODIS AQUA sensor.

phytoplankton bloom was triggered by enhanced natural iron input from subsurface waters (Blain et al., 2007). The other articles in this special issue use these shipboard observations to examine the distribution and sources of this iron (Blain et al., 2008; Zhang et al., 2008; Van Beek et al., 2008), its availability and uptake by the microbial community (Gerringa et al., 2008; Sarthou et al., 2008) and the subsequent biological response (Mosseri et al., 2008; Obernosterer et al., 2008; Trull et al., 2008; Carlotti et al., 2008; Armand et al., 2008), including the magnitude of carbon dioxide drawdown (Jouandet et al., 2008) and carbon export (Savoye et al., 2008).

In this study we take a larger view, and examine the regional scale and seasonal evolution of the phytoplankton bloom based on satellite images. We then combine this perspective to build a simple model and investigate its response to the observed enhanced iron input. Specifically we:

- Develop a comprehensive description of the Kerguelen plateau bathymetry, chlorophyll-*a* distributions (as estimated from ocean-colour measurements), and surface horizontal advection field (as estimated from satellite altimetry).
- Modify an existing model that has been applied at the nearby KERFIX site in HNLC waters (Mongin et al., 2006; Mongin et al., 2007) to simulate the microbial ecosystem response to increased iron supply.
- Use this model to investigate the seasonal cycle of the bloom, to calculate carbon and iron budgets, and to assess carbon sequestration efficiency, including its dependence on the plasticity of phytoplankton Fe uptake and horizontal dispersion strength.

1.1. Context of the KEOPS project

The KEOPS survey during January–February 2005 examined the phytoplankton bloom that forms annually in the vicinity of the Kerguelen plateau. In brief, the Kerguelen plateau is a large area of relatively shallow sea floor in the Indian sector of the Southern Ocean that extends for more than 2200 km southeast from the Kerguelen Islands (49°S, 70°E). Its full extent reaches as far south as the Princess Elizabeth Trough near 63°S, but our interest is focused on the portion of the plateau north of the Fawn Trough, between and to the east of the Kerguelen and Heard Islands (Fig. 1). From here on we refer to this region as "the plateau".

High-energy internal tidal waves that interact with the bathymetry enhance the vertical eddy diffusivity above the plateau, and hence the supply of subsurface iron and other nutrients (Park et al., 2008a). This supply from below appears to be the main source of iron to fuel the phytoplankton bloom, with negligible aeolian iron dust fluxes from the Kerguelen desert (Blain et al., 2007).

Despite the high primary production and standing stock of chlorophyll in the Kerguelen bloom, surface-water nitrate depletion was insufficient to limit phytoplankton production, although near complete depletion of silicic acid did occur (Blain et al., 2007; Mosseri et al., 2008). Similar decoupling of the Si and N cycles was observed during experimental iron-fertilization experiments (Boyd et al., 2004), and also resembles the general much larger depletion of silicic acid than nitrate in surfaces waters from south to north across the Southern Ocean (Trull et al., 2001a).

Both on and off the plateau, the planktonic ecosystem structure was dominated by large diatoms and large copepods (Armand et al., 2008; Carlotti et al., 2008). Bacterial activity was elevated over the plateau (Obernosterer et al., 2008) and the utilisation of new nitrogen by phytoplankton also appeared to be greater (Mosseri et al., 2008; Trull et al., 2008). At the time of the KEOPS survey, particulate carbon export over the plateau was approximately twice that of surrounding waters (Blain et al., 2007; Savoye et al., 2008). Based on surface dissolved inorganic carbon concentrations a similar enhancement seems to persist over the full season (Blain et al., 2007; Jouandet et al., 2008).

1.2. Regional description

Based on mean annual ocean colour (Fig. 1) and animations of the seasonal cycle (available at http://staff.acecrc.org.au/~mmongin/), the satellite-derived surface chlorophyll-*a* (SCHL) distribution over the region can be separated into four regimes:

(i) North of the SAF (subantarctic front), in subtropical waters (40°S–45°S) the SCHL is usually low (max of 1.5 mg Chl*a* m^{-3}) and develops late in the season (January).