Available online at www.sciencedirect.com
ScienceDirect
Journal of Marine Systems 71 (2008) 112–130
JOURNAL OF MARINE SYSTEMS
www.elsevier.com/locate/jmarsys

The effects of dilution and mixed layer depth on deliberate ocean iron fertilization: 1-D simulations of the southern ocean iron experiment (SOFeX)

Aparna Krishnamurthy [a,*], J. Keith Moore [a], Scott C. Doney [b]

[a] *Earth System Science Department, University of California, Irvine, CA 92697, USA*
[b] *Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA*

Received 14 December 2006; received in revised form 6 July 2007; accepted 12 July 2007
Available online 26 July 2007

Abstract

To better understand the role of iron in driving marine ecosystems, the Southern Ocean Iron Experiment (SOFeX) fertilized two surface water patches with iron north and south of the Antarctic Polar Front Zone (APFZ). Using 1-D coupled biological–physical simulations, we examine the biogeochemical dynamics that occurred both inside and outside of the fertilized patches during and shortly after the SOFeX field campaign. We focus, in particular, on three main issues governing the biological response to deliberate iron fertilization: the interaction among phytoplankton, light, macronutrient and iron limitation; dilution and lateral mixing between the fertilized patch and external, unfertilized waters; and the effect of varying mixed layer depth on the light field. At the patch south of the APFZ, sensitivity simulations with no dilution results in the maximum bloom magnitude, whereas dilution with external water extends the development of the north patch bloom by relieving silicon limitation. In model sensitivity studies for both sites, maximum chlorophyll concentration and dissolved inorganic carbon depletion inside the fertilized patches are inversely related to mixed layer depth, similar to the patterns observed across a number of iron fertilization field experiments. Our results suggest that Southern Ocean phytoplankton blooms resulting from natural or deliberate iron fertilization will tend to become iron-light co-limited unless the mixed layer depth is quite shallow.

Keywords: SOFeX; Southern Ocean; HNLC; Marine ecosystem model; Nutrient limitation; Light limitation; Mixed layer depth; Phytoplankton community; Iron fertilization

1. Introduction

Southern Ocean surface waters contain high levels of macronutrients but relatively modest levels of chlorophyll, in most regions. Theories postulated to explain these high nutrient, low chlorophyll (HNLC) waters include deep mixing along with light limitation (Mitchell et al., 1991; Nelson and Smith, 1991), plankton community structure and strong grazing pressure (Brown and Landry, 2001), and iron limitation (Martin, 1990). Multiple factors impact the seasonal cycle of phytoplankton growth in these regions (Boyd et al., 1999; Abbott et al., 2000; Fennel et al., 2003; Smith and Lancelot, 2004), with light limitation dominating during early spring followed by iron limitation after the onset of water column stratification. During austral summer diatom growth may become silicon limited, particularly in subantarctic waters. Deep mixed layers can

* Corresponding author. Tel.: +1 949 824 2314; fax: +1 949 824 3874.
E-mail address: aparnak@uci.edu (A. Krishnamurthy).

0924-7963/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmarsys.2007.07.002

also result in co-limitation by iron and light, as the phytoplankton cellular requirement for iron increases under light stress (Sunda and Huntsman, 1997; Boyd, 2002).

Among the factors mentioned above, it is now well established that in HNLC areas the limitation of micronutrient iron largely prevents the full consumption of macronutrients by phytoplankton. This has been demonstrated for Southern Ocean HNLC waters in several mesoscale iron fertilization experiments, where artificial additions of iron resulted in increased chlorophyll, primary productivity and phytoplankton biomass (Boyd et al., 2000; Smetacek 2001; Coale et al., 2004).

The Southern Ocean Iron Experiment (SOFeX) was conducted during austral summer of 2002 in the Pacific sector of the Southern Ocean (Coale et al., 2004). It involved fertilizing two patches, one north of the Antarctic Polar Front Zone (APFZ) characterized in austral spring by low-silicate, high nitrate waters (North Patch) and one south of the APFZ characterized by high-silicate, high-nitrate waters (South Patch). These two regions were selected such that the hydrography, nutrients and the biogeochemical provinces could represent larger areas of the Southern Ocean. Apart from testing the iron hypothesis, the experiment was also intended to test whether low silicate ($Si(OH)_4$) conditions north of the APFZ would diminish the fertilization response because of diatom Si limitation.

The North Patch was created on 12th January, 2002 at 56.23° S, 172° W, and the South Patch was created on 24th January, 2002 at 66.45° S, 171.8° W. Successive iron additions were done by injecting acidified iron sulfate into the ship's wake such that mixed layer iron concentrations were raised to 1.2 nM, 1.2 nM, 1.5 nM at the North Patch, and four additions were done at the South Patch such that iron concentrations were 0.7 nM after each addition. Sulfur hexafluoride (SF_6) was added along with iron during the first infusion to track the patches. The enriched patches were studied by three research vessels, *R/V* Revelle, *R/V* Melville and *R/V* Polar Star for a period of 40 and 28 days for the north and south sites, respectively (supplemental material, Coale et al., 2004). Particulate organic carbon (POC), temperature and salinity in the upper 1000 m were measured using three free-profiling Lagrangian Carbon Explorers at 55° S and one at 66° S deployed from the *R/V* Revelle (Bishop et al., 2004). These Explorers also estimated carbon export at 100 m using an optically derived carbon flux index.

Satellite remote sensing indicates that the unfertilized waters in the region of the SOFeX South Patch sometimes exhibit a natural seasonal chlorophyll bloom, while natural blooms are absent for the North Patch region (Moore and Doney, 2006). During the period of SOFeX, background surface chlorophyll levels at the South Patch were low compared to climatological conditions at that site and to nearby locations to the east and west of the study location. Moore and Doney (2006) hypothesize that these differences could have arisen from variable iron supply from melting sea ice and icebergs along with increased stratification at the southern site. Their study concluded that there was a delay in the melting of sea-ice during the growing season of 2001–2002 compared to other years. This led to a delay in the naturally occurring modest spring bloom from December to January–February in this region.

Our purpose here is to examine, using 1-D coupled biological–physical numerical simulations, the biogeochemical dynamics that occurred both inside and outside of the fertilized patches during and shortly after the SOFeX field campaign. We focus, in particular, on three main issues governing the biological response to iron fertilization: the interaction among phytoplankton, light, macronutrient and iron limitation; the effects of dilution and lateral mixing between the fertilized and unfertilized waters; and variations in mixed layer depth and mixed layer light field.

Like all deliberate ocean fertilization studies, the SOFeX fertilized patches were finite in horizontal extent and underwent lateral mixing with the surrounding unfertilized waters. The North Patch was located at the subantarctic frontal zone, a region of fronts that elongated the patch from a square into a long, thin filament (~7 km × 340 km) by day 38. The South Patch extended more slowly in all directions (Coale et al., 2004; Moore and Doney, 2006). Dilution rates can be estimated in two ways. One is to find the amount of physical strain of tracer filament when the patch stretches. During the Southern Ocean iron release experiment (SOIREE), for example, the dispersal of the tracer due to dilution was estimated by locally resolving the tracer flow into pure strain and rotation (Abraham et al., 2000). The extent of this stretching can be obtained also from satellite ocean color observations. During the SOFeX, a dilution rate of 0.11 per day at the North Patch and 0.086 per day at the South Patch was obtained using this technique (Coale et al., 2004). A second way is to estimate dilution rates by calculating the loss of SF_6, accounting for outgassing. Dilution rate estimates during the SOFeX using this method were 0.1 per day at the North Patch and 0.03 to 0.07 per day at the South Patch (Coale et al., 2004). There was a variation in SF_6 derived estimates because of inhomonogeneities within the patch and analytical variability. Coale et al. (2004) used dilution rates 0.08 per day for South Patch and 0.11 per day for North Patch as a best estimate. We adopted these values of dilution in our baseline simulations.