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The influence of lateral mixing on a phytoplankton bloom: Distribution in the Kerguelen Plateau region

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ABSTRACT

A unique phytoplankton bloom appears every year during the austral spring/summer in the northern Kerguelen Plateau region. The Kerguelen Ocean and Plateau compared Study (KEOPS) showed that an increase in subsurface iron coming up from the seafloor through vertical mixing was responsible for the observed increase in chlorophyll-*a* above the plateau. We demonstrate that the bloom pattern is not a simple increase of biomass over shallow water: it is strongly influenced by the bathymetry and its spatial extent controlled by strong currents around the plateau. Here we focus on lateral mixing process to explain the particular shape of the bloom. We use the Smagorinsky [1963. General circulation experiments with the primitive equations. I. The basic experiment. Monthly Weather Review 91 (3), 99–164] formula to estimate and map fields of lateral mixing time scales (τ) due to barotropic tidal currents, barotropic atmospheric forced currents, Ekman velocities and geostrophic velocities. Results show that short time scale mixing is strongly influenced by the tides while the other processes have minor influences. Comparisons of τ and satellite chlorophyll-*a* images show that the spatial pattern of the bloom seems to be delimited by a barrier of high lateral mixing that is essentially due to tides. This emphasises the role played by the tides over the Kerguelen Plateau in supplying iron to the phytoplankton and containing the horizontal shape of the bloom. This is one of the first times such a link has been demonstrated, which has implications for the study of iron advection in the ocean.

1. Introduction

The subantarctic zone in the Southern Ocean is a high nutrient low chlorophyll (HNLC) region with low phytoplankton biomass in spite of high macronutrient concentration. This behaviour has been attributed to micronutrient, such as iron, limitation (Hart, 1934; De Baar et al., 1995; Boyd et al., 2000; Boyd, 2002). Measurements of dissolved iron in the mixed layer showed that iron concentrations were usually low throughout the Southern Ocean and that iron addition enhanced phytoplankton productivity (Martin et al., 1990). While deliberate iron fertilization experiments showed that adding iron increased primary production and possibly export (De Baar et al., 2005; Boyd et al., 2007), little was known about long-term modification in the export fluxes of carbon or changes in the ecosystem itself. The main aim of the KEOPS project, which took place during January and February 2005 around the Kerguelen Islands, was to better understand the mechanisms of naturally occurring iron fertilization.

It is now understood that the occurrence of the large phytoplankton bloom over the Kerguelen Plateau (Fig. 2, Bloom B) is caused by an increase of deep dissolved iron supply due to enhanced vertical mixing over the plateau

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(Blain et al., 2007), and that this increased vertical mixing is due to internal tidal waves (Park et al., 2008a). The net biological community production derived from the cruise showed a threefold increase between the plateau bloom area and the outside plateau area that led to a significant enhancement of the carbon export flux over the plateau. This demonstrated that the carbon sequestration efficiency, which is a measure of the excess of carbon export per unit of iron supplied (De Baar et al., 2005), was much higher than during artificial fertilization. Despite relatively sluggish circulation over the plateau, Mongin et al. (submitted) showed that the Kerguelen Island's plateau and the shelf region could fuel an area much larger than the plateau itself by assuming that iron is transported offshore during winter.

The objective of our study is to link the spatial distribution of the KEOPS plankton bloom to geophysical surface characteristics. Tyrrell et al. (2005) found some correlations between seafloor depth and chlorophyll-*a* concentration in HNLC regions. Statistical comparisons revealed that, in general, shallow water regions have higher peaks in chlorophyll concentration than deep water areas. Some studies have used the derivation of Lagrangian diagnostics to reconstruct the specific effect of horizontal mixing on bloom patterns. Abraham et al. (2000) used a Lagrangian method to highlight the efficiency of the deformation field associated with mesoscale circulation to reproduce surface chlorophyll filaments observed in satellite imagery of the Southern Ocean. Lehahn et al. (2007) computed Lagrangian diagnostics from geostrophic fields and compared the results with satellite-derived plankton patches. Similarly, there are results that explain the KEOPS bloom pattern. Mongin et al. (2008) concluded that the phytoplankton bloom shape was clearly related to bathymetry and surface advection fields, and Park et al. (2008b) suggested it was strongly influenced by the strong currents binding it. These results explain the principal features of the bloom; in particular, they support the observation that the bloom is concentrated over the northern Kerguelen Plateau and is not advected away from the Plateau shelf break. However, other characteristics are still not explained, such as the low chlorophyll tongue that appears regularly north of Heard Island. There are probably other physical processes that explain those characteristics. In particular, Martin (2003) discussed the way lateral stirring and mixing could influence the spatial structure in phytoplankton distribution. Abraham et al. (2000) showed that horizontal stirring acted as an important control on the SOIREE iron-fertilized chlorophyll bloom development and diffusion in the Southern Ocean. More recently, Lehahn et al. (2007) studied the effect of geostrophic stirring on the Northern Atlantic spring bloom variability.

In this study, we focus on the lateral mixing process to find explanations of the northern Kerguelen Plateau bloom pattern. We use the Smagorinsky (1963) formula that relates mixing to the strain deformation of the velocity field. The eastward and northward velocity components were computed using barotropic tidal currents, barotropic currents in response to atmospheric forcing, geostrophic currents and surface Ekman currents.

2. Data and model

2.1. Velocity field

The barotropic tidal and wind forcing current components were computed using the MOG2D/T-UGOm barotropic, time-stepping and non-linear model. This model, derived from Lynch and Gray (1979), computes the sea level variations and the mean currents by solving the shallow water and momentum equations on a finite element mesh. This space discretization method allowed the mesh to be larger in the deep ocean and the resolution to be increased in coastal areas and regions with strong topographic gradients, like the Kerguelen Plateau shelf break, enabling good resolution of gravity waves. The mesh covers the southern part of the Indian Ocean with a grid size ranging from a few kilometers or less along the coast and the shelf break to about 100 km in the deep ocean. The regional tidal model used here has been validated using sea surface elevation data (Maraldi et al., 2007). The eight main tidal constituents were computed, and the elevations from the FES2004 global solution (Lyard et al., 2006) were used to force the model along the open boundaries.

The atmospheric forced model is driven using pressure and 10-m altitude wind speeds from the European Centre for Medium-range Weather Forecasting (ECWMF) analysis fields. These forcing fields were interpolated onto a $1/4^\circ \times 1/4^\circ$ regular grid, and the temporal resolution is 3 h; they are bilinearly interpolated to the model 1-h time step. At the open boundaries, we use the currents from the global MOG2D/T-UGOm simulation of the response to atmospheric forcing (Carrère and Lyard, 2003) driven by the same ECMWF fields as the regional model. The global simulation uses the GEBCO 1-min lobal bathymetric grid and the regional simulation uses the GEBCO bathymetry improved with updated topographic data around the Kerguelen Islands (Maraldi et al., 2007).

The regional simulation ran from November 2004 to February 2005, with sea surface elevations and currents being recorded hourly. The horizontal tidal and atmospheric forced velocities are interpolated onto the same regular grid.

We used geostrophic ocean currents developed by the CTOH (Centre de Topographie des Océans et de l'Hydrosphère) at LEGOS (Sudre and Morrow, 2008). The geostrophic currents are calculated from sea surface height (SSH) fields and are distributed over a global $1/4^\circ$ Mercator grid. The SSHs are computed using the mapped sea level anomalies from the Data Unification and Altimeter Combination System and the mean dynamic topography RIO05 (Rio and Hernandez, 2004). Ekman surface currents are derived from the same ECMWF wind and pressure fields used to force the model.

2.2. In situ current measurements

We used measured current profiles from two sites to validate the model velocity fields, one situated on the northern Plateau (P2, Fig. 1) and the other one on its