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Vertical transport in the ocean due to sub-mesoscale structures: Impacts in the Kerguelen region

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ABSTRACT

The summertime phytoplankton bloom near the Kerguelen Plateau is in marked contrast to the low-chlorophyll conditions typical of the Southern Ocean and is thought to arise from natural iron fertilisation. The mechanisms of iron supply to the euphotic zone in this region are poorly understood, and numerical studies of iron transport have until now omitted fine-scale (sub-mesoscale) dynamics which have been shown to significantly increase vertical transport in other parts of the ocean.

We present the first sub-mesoscale-resolving study of the flow and vertical transport in this region. The modelled transport and flow structure agree well with observations. We find that an increase in horizontal resolution from mesoscale-resolving (1/20°) to 1/80° resolves sub-mesoscale filamentary frontal structures in which vertical velocities are dramatically higher and are consistent with available observations. Lagrangian tracking shows that water is advected to the surface from much greater depth in the sub-mesoscale-resolving experiment, and that vertical exchange is far more rapid and frequent. This study of sub-mesoscale vertical velocities sets the foundation for subsequent investigation of iron transport in this environment.

1. Introduction

The Southern Ocean is a prominent example of a high-nutrient low-chlorophyll (HNLC) environment, with summer phytoplankton productivity mainly limited by the availability of iron (Boyd et al., 2000). Phytoplankton blooms are an important component of the earth system, primarily via contributions to the oceanic carbon cycle. In the Southern Ocean, anthropogenic carbon uptake is very high (e.g. Sabine et al., 2004, 2009), yet a complete understanding of the mechanisms controlling air–sea CO_2 fluxes in this environment, and their sensitivity to potential changes in biological productivity, is lacking. Despite the HNLC conditions of the Southern Ocean, elevated chlorophyll concentrations occur in several locations of the Southern Ocean, including the seasonal blooms originating on and downstream of the Kerguelen Plateau (Fig. 1). The Kerguelen Plateau (KP) is a significant feature in the south Indian Ocean basin, with a topography that drives a complex local circulation (Park et al., 2008). In this region, the Antarctic Circumpolar Current (ACC) is constrained by the shallow bathymetry of the plateau and divided into different streams: strong currents occur north of the Kerguelen Islands and through the Fawn Trough (located at 56°S), with a weak flow over the shallow plateau between Kerguelen and Heard Islands.

In particular, while the importance of the Kerguelen bloom has been well documented (Abraham et al., 2000; Blain et al., 2007; Mongin et al., 2008, 2009; Park et al., 2008,; Maraldi et al., 2009), the mechanisms that drive vertical iron fluxes to the euphotic zone, and consequently trigger the bloom, are unclear. Possible mechanisms include lateral (e.g. Mongin et al., 2009; Maraldi et al., 2009; Park et al., 2008) and vertical processes (e.g. Park et al., 2008; Van Beek et al., 2008). These studies have highlighted the intrinsic relation between physical processes and biological

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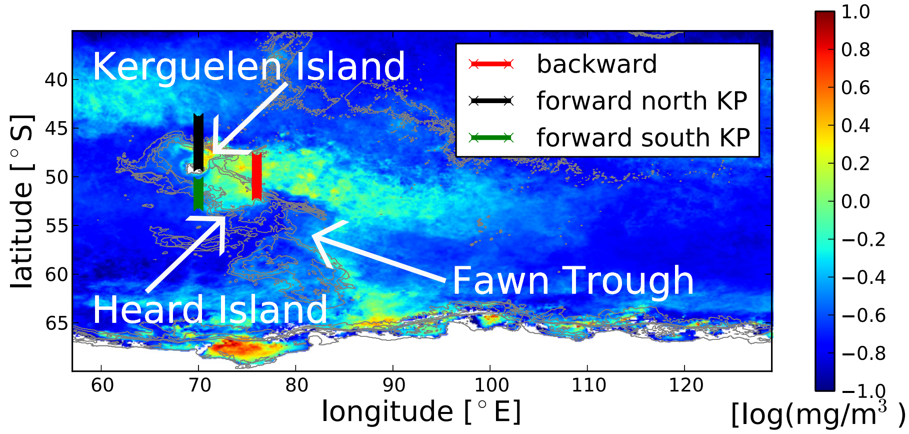

Fig. 1. Monthly climatology (December 2002–2012) of chlorophyll *a* concentration in the south Indian basin (data are taken from Aqua MODIS 9 km and expressed as base 10 logarithms). Also shown are land surface (white), bathymetric contours with a contour interval of 600 m and the initial location of particles for the Lagrangian experiments (see Section 2.3). The bathymetry data are taken from the 1-min SRTM bathymetry.

responses. Yet, an exhaustive analysis of transport mechanisms in this area is lacking. In particular, a numerical model able to fully represent the dynamics in this area has not yet been developed.

The present study investigates the transport of tracers by small-scale processes, which may control local circulation and be important for the iron supply to the KP region. We build on a series of recent studies which have found that sub-mesoscale structures of scale $O(10\text{ km})$ may generate a strong vertical transport, upwelling nutrient rich waters from the base of the mixed layer and downwelling depleted waters from the surface (Martin et al., 2002; Mahadevan, 2006; Capet et al., 2008a; Klein and Lapeyre, 2009; Lévy et al., 2001, 2012). The sub-mesoscales arise from the interaction between larger scale structures and are mainly related to frontogenetic processes (Capet et al., 2008b; Ferrari and Wunsch, 2009). High values of simulated surface pCO_2, vertical velocity and vorticity are found close to sub-mesoscale fronts (e.g. Resplandy et al., 2009; Lévy et al., 2001), which act as preferential paths for the exchange of gases between the atmosphere and ocean interior. Frontal instabilities can explain this enhancement by driving an ageostrophic secondary circulation (ASC) occurring in the cross-front plane, upwelling of waters on the light side of the front and downwelling on the dense side (e.g. Capet et al., 2008b).

The aim of this paper is to demonstrate the impact that changing the horizontal resolution has on the vertical motion in numerical simulations of the KP region. We will compare and contrast a pair of regional numerical experiments, run at two different horizontal resolutions (1/20° and 1/80°) to investigate the relative importance of mesoscale and sub-mesoscale processes to the vertical circulation. A Lagrangian tracking tool is used to quantify the transport due to these fields. We highlight that the use of high horizontal resolution and realistic topography in our model is a significant advance on the series of numerical models previously used to investigate the dynamics of the area. In particular, this is the first comparative study of differences between mesoscales and sub-mesoscales under Southern Ocean conditions. Finally, motivated by the necessity of studying ocean processes in a high productivity area such as the Kerguelen Plateau, this work lays the foundation for a future study into iron transport.

The paper is organised as follows: Section 2 is divided into three parts, where Sections 2.1 and 2.2 describe the ocean numerical models used to simulate the circulation and Section 2.3 the Lagrangian particle tool used to study the transport of particles. The validation of the model through a comparison of the mean circulation with observations is given in Section 3. Section 4 shows the results of the different experiments, while Section 5 gives a discussion of the results.

2. Method

The circulation in the area of KP is simulated using the primitive equation model MITgcm (Marshall et al., 1997). We use realistic bathymetry from the 1 min resolution Shuttle Radar Topographic Mission dataset (Smith and Sandwell, 1997, SRTM,) and we set the maximum depth at 5000 m (Fig. 2). To capture the dynamics at the surface while resolving the topographic features, we use 150 vertical levels with a variable vertical resolution (10 m thickness at the surface, increasing to 50 m at roughly 2000 m depth) via the profile $\Delta z = 30\text{ m} - 20\tanh[(1000 + z)\pi/1500]$ m. The vertical grid has z-coordinates and uses partially filled cells for the bathymetry (Adcroft et al., 1997), to reduce the vertical velocities arising close to the topography (which were found to otherwise dominate the deep velocity field when using a step topography). The model uses the non-linear free surface algorithm (Adcroft and Campin, 2004), with a free-slip condition at the northern and southern boundaries (zero-stress at the boundaries) and bottom drag with a typical quadratic drag coefficient of 0.0025. Furthermore, the model uses the Jackett and McDougall (1995) equation of state for seawater. We have implemented different experiments using two horizontal resolutions: one with 1/20° resolution, denoted KERG20 for the reminder of this paper, and one with 1/80° resolution (KERG80). In Section 2.1 we present the configuration for KERG20 and in Section 2.2 the KERG80 implementation. An outline of the physical parameters used for the two models is given in Table 1.

The data, in the form of instantaneous fields, are stored daily and the analysis is performed over 200 days for both resolutions. The analysis is performed over an inner area of the domain (69–82°E, 43–53°S) to avoid unrealistic boundary effects arising in KERG80. Analyses include standard surface flow metrics and the statistics of interior vertical velocity. However, the primary mode of analysis is a Lagrangian tracking system which is described in Section 2.3.

2.1. MITgcm configuration for 1/20° resolution

The domain of the KERG20 simulation is 57–129°E, 70–35°S. With a horizontal resolution of 1/20° the zonal grid spacing ranges between approximately 4.5 km on the northern boundary and 1.9 km to the south, while along the meridional direction the resolution is approximately 5.6 km. At this resolution, the number of points per Rossby radius, in the longitudinal direction, ranges between 12 (northern boundary) and 2, while a range between 5