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

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A B S T R A C T

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 CO₂ 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 (Abrahm 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...
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 $\mathcal{O}(10 \text{ km})$ 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 ($1/20^\circ$ and $1/80^\circ$) 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 resolutions ($1/20^\circ$) 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 analysis is performed over an inner area of the domain (69–129$^\circ$E, 43–53$^\circ$S) to avoid unrealistic boundary effects arising in the KP region. We will compare and contrast a pair of regional numerical experiments, run at two different horizontal resolutions ($1/20^\circ$ and $1/80^\circ$) 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 resolutions ($1/20^\circ$) 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 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 $\mathcal{O}(10 \text{ km})$ 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).

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 $\Delta z = 30 \text{ m} - 20 \text{ tanh}(1000 - z)/1500 \text{ m}$. 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 $1/20^\circ$ resolution, denoted KERG20 for the reminder of this paper, and one with $1/80^\circ$ 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$^\circ$E, 43–53$^\circ$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 $1/20^\circ$ resolution

The domain of the KERG20 simulation is 57–129$^\circ$E, 70–35$^\circ$S. With a horizontal resolution of $1/20^\circ$ 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
and 1 has been estimated in the latitudinal direction (Rossby radius derived from Chelton et al., 1998). The 1/20° resolution is therefore considered to be eddy-resolving over most of the domain, including the sub-domain of analysis, with effective resolution degrading close to Antarctica.

Southern Ocean State Estimate (SOSE) annual-averaged climatological fields for the year 2005 (Mazloff et al., 2010) are used to estimate surface fluxes of momentum, heat and freshwater. The circulation is forced at each timestep by a temporally constant wind stress (vectors in Fig. 2), with values taken from SOSE, relaxing to zero at the northern boundary in a layer of 1/14° width (to prevent the development of strong counter-currents along the northern boundary). At the surface, temporally constant freshwater fluxes are applied at each timestep and the climatological SST is used to restore the surface with a timescale of 15 days (Fig. 3). There is no seasonal cycle in the model forcing.

The northern boundary is linearly relaxed to SOSE temperature and salinity climatology over a 1/14° wide sponge layer, with a restoring timescale of 8 days (Fig. 4), while bottom topography of the Antarctic continental slope closes the domain on the southern boundary. The domain is zonally periodic; topography, restoring and forcing fields have been smoothed in a band of approximately 4° wide near the western and eastern boundaries and made periodic.

2.2. MITgcm configuration for 1/80° resolution

The domain for the KERG80 case is a 15° × 12° sub-domain of KERG20, 68–83°E, 42–54°S as represented by the white box in Fig. 2. The resolution in this case gives a zonal grid spacing between 0.8–1.0 km and a constant meridional grid size of 1.4 km. In this case, we estimate a range of approximately 11 to 23 points (longitudinal direction) and of 6 to 17 (latitudinal) points per Rossby radius. The model is nested in KERG20 using one-way open boundary conditions for zonal and meridional velocities, temperature, salinity and sea surface height prescribed by KERG20 daily snapshots. Surface conditions of temperature, salinity, horizontal velocity and sea surface height are also restored to KERG20 daily fields. For the KERG80 bathymetry, the interior points have been interpolated directly from the 1-min SRTM bathymetry and the boundary points from KERG20 for consistency. To reduce reflections from the open boundaries we use relaxation boundary conditions for temperature and salinity, with a relaxation time scale of 2 h and a 20 point linear sponge.

2.3. Connectivity Modelling System

The Connectivity Modelling System is used as an offline tool to study the sensitivity of transport to the horizontal resolution (CMS, Paris et al., 2013). Lagrangian particle-tracking models are techniques used to study the circulation of the ocean and the associated response of ecosystems (e.g. Van Sebille et al., 2009). In this paper we will use the Lagrangian trajectories to focus on the physical properties of the model, highlighting the differences that the KERG20 and KERG80 cases have on the horizontal and vertical transport.

We performed several simulations, driving the CMS with daily snapshot fields of zonal, meridional and vertical velocities. The

Fig. 2. SOSE wind stress field overlying the 1-min SRTM zonally periodic bathymetry. The white contours represent the coastlines and the white box defines the domain of the 1/80° model.

<table>
<thead>
<tr>
<th>Description</th>
<th>KERG20</th>
<th>KERG80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal resolution</td>
<td>1/20°</td>
<td>1/80°</td>
</tr>
<tr>
<td>Horizontal gridpoints</td>
<td>(1440 × 700)</td>
<td>(1200 × 960)</td>
</tr>
<tr>
<td>Vertical levels</td>
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<td>150</td>
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<td>Coordinates</td>
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<td>Spherical</td>
</tr>
<tr>
<td>Momentum and tracers timestep</td>
<td>120 s</td>
<td>60 s</td>
</tr>
<tr>
<td>Tracers advection scheme</td>
<td>7th Order one-step monotonicity-preserving (Daru and Tenaud, 2004)</td>
<td>Non-linear 3rd order with Flux Limiter</td>
</tr>
<tr>
<td>Vertical mixing of tracers and momentum</td>
<td>K-profile parameterisation (KPP, Large et al., 1994)</td>
<td>K-profile parameterisation (KPP, Large et al., 1994)</td>
</tr>
<tr>
<td>Background vertical viscosity</td>
<td>5.66 × 10^{-4} m² s^{-1}</td>
<td>5.66 × 10^{-6} m² s^{-1}</td>
</tr>
<tr>
<td>Background vertical diffusivity</td>
<td>1 × 10^{-5} m² s^{-1}</td>
<td>1 × 10^{-3} m² s^{-1}</td>
</tr>
<tr>
<td>Harmonic Leith horizontal viscosity coefficient</td>
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<td>1.2</td>
</tr>
<tr>
<td>Biharmonic Leith horizontal viscosity coefficient</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Horizontal salinity and temperature biharmonic diffusivity</td>
<td>1 × 10^6 m^4 s^{-1}</td>
<td>1 × 10^6 m^4 s^{-1}</td>
</tr>
<tr>
<td>Spin-up time</td>
<td>40 years</td>
<td>1 year</td>
</tr>
</tbody>
</table>
advection of the particles is performed with a 60 s timestep, for a maximum integration time of 100 days (or until the particle exits the region of interest). It should be noted that the Lagrangian tracking takes into account purely resolved advective, but not diffusive, contributions to transport (including within the surface mixed layer).

Fig. 3. SOSE climatology surface field from 2005: (a) sea surface temperature and (b) fresh water fluxes (negative values represent fluxes into the ocean). The grey contour lines show topographic depths, with a contour interval of 600 m. The white colour represents land.

Fig. 4. Northern boundary restoring salinity (in colour) and temperature (black lines, units are °C) fields for KERG20.

An advantage of the Lagrangian analysis is that one can track particles either forward or backward in time. We use both of these in our analysis. We track the particles backward in time to study the water sources for particles arriving at the surface in the region of the eastern KP bloom. We integrate particles forward in time to investigate the different patterns of flow from waters upstream of
KP, and their sensitivity to initial location and horizontal resolution. The location of the particle placement for the two different analyses is shown in Fig. 1. For the backward case 800 particles are placed along a line at 76°E, between 48°S and 52°S and at a depth of 5 m (red markers in Fig. 1). Other experiments have been run forward in time, with particles initialised in two different locations: one case north of the plateau and one south. In the first experiment we released particles along a transect at 70°E between 44°S and 49°S (black markers in Fig. 1), in order to track the contribution of the strong stream of the ACC north of KP. For the second case the particles were released south of KP (at 70°E between 50.5°S and 53°S, green markers in Fig. 1) to investigate the possible sources of waters for the bloom occurring over the plateau. In each case, the particles were placed with a spatial step of 0.005° and released simultaneously. We obtained similar patterns using a subset of particles initially spaced 0.5° apart, and in numerous additional Lagrangian experiments (data not shown) confirming the robustness of our results.

We tested the robustness of the daily sampling by temporally sampling the case with initial depth at 200 m, using the model output with a frequency ranging between three hours and two days (not shown). We found that, while the individual paths of the particles were not identical (due to the chaotic nature of the ocean circulation), the vertical displacements presented a strong correlation between the different cases.

3. Model evaluation

The mean circulation (Fig. 5) captures the main features of the Indian sector in the Southern Ocean (e.g. Park et al., 2008). Constrained by the KP bathymetry, two main branches of the ACC are resolved, one flowing north of the KP (evident at both resolutions) and one in the Fawn Trough, which in the KERG80 case is near the edge of the domain (Fig. 5(b)). These flows are very strong and reach mean magnitudes of 1 m s\(^{-1}\), values which are comparable with the near-surface velocities derived from drifters by Park et al. (2008). In the KERG80 case we also found a persistent mean centre at 73°E and 46°S, a feature that has been investigated by the Southern Ocean FINE structure project (SOFINE, Naveira Garabato et al., 2009) and which will be analysed in Section 4.2. Furthermore, the Fawn Trough current presents a local circulation which is also comparable to observations. In particular, the flow
shifts northward at about 78°E, following the bathymetry of the channel, and is then deflected eastward (at 80°E), merging with the northern ACC branch. Finally, a weak cyclonic circulation develops on the plateau, with magnitudes smaller than 0.1 m s⁻¹.

A good indicator of the properties of water masses is represented by oceanic fronts, defined in relation to temperature and salinity fields (Sokolov and Rintoul, 2009). From the temporal mean of the sea surface height (SSH), some main frontal branches can be identified: the black line in Fig. 5 represents the 3°C isoline and in white we show indicative contours of SSH. The SSH contours are not evenly spaced, but they have been chosen because of the resemblance to observed ACC fronts: they align with frontal patterns given by the temporal mean of \( \nabla \alpha \)SSH. Although a detailed analysis of position and properties of the ACC fronts in our simulation is beyond the scope of this paper and a precise identification of fronts, comparable to realistic structures found by Sokolov and Rintoul (2009), is not possible here, we can still identify typical frontal patterns, such as the Subtropical (in the KERG20 case, the northernmost white line) and the Polar front (the closest front to the Kerguelen Island).

A quantitative assessment of the model was conducted by computing the cumulative ACC transport across a path as shown by the coloured line in Fig. 6. For the choice of the integration path, we took into account the different contributions to the eastward

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**Fig. 6.** Cumulative transport for the KERG20 experiment, following the path drawn on the picture. Numbers are transports in Sv and the dotted bars report transports from Park et al. (2009).

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**Fig. 7.** (a) 9-Month average (05/2011 to 02/2012) of the eddy kinetic energy (resolution of 1/8°), computed from a regional high-resolution altimetry product around the Kerguelen Plateau (data from AVISO); the white box indicates the area in panels (b) and (c). The 200-day average of surface eddy kinetic energy for (b) KERG20 and (c) KERG80 (the colourmap is saturated and peak values are 0.4 m² s⁻²). Contours are bathymetry levels with 600 m steps.
transport from the Kerguelen Plateau. This diagnostic is in good agreement with transports evaluated by Park et al. (2009), especially in the area north of the Kerguelen Island and in the Fawn Trough, red and blue branches in the figure, respectively. On the Plateau, between the Kerguelen and Heard Islands (green line) and between Heard Island and the Fawn Trough (magenta line), we found a total transport of 2 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3\text{ s}^{-1}$), which is 6 Sv less than in Park et al. (2009). Given the large range of modelled and observed transports across the subsections (1 to 120 Sv), we feel that this discrepancy is minor.

The surface 9-month average of the eddy kinetic energy (EKE) from a regional high-resolution altimetry product of the Kerguelen Plateau (Regional-Kerguelen experimental product from AVISO) was compared with the model 200-day temporal mean, shown in Fig. 7(a). The three datasets show that the EKE is much larger in the area east of the plateau, away from the topography, and weaker over the plateau. Compared with the AVISO dataset, the magnitude of EKE in the region east of the Kerguelen Plateau is approximately a factor of 2 larger in KERG20; this discrepancy is largely eliminated when spatial filtering on scales similar to that used in satellite data processing is applied. The difference between observed and modelled EKE increases to be a factor of 4 larger in KERG80, which is most likely due to the additional fine scale variability at high resolution. We also calculated total kinetic energy spectra in the KERG80 region, at different depths, by averaging zonally and modelled EKE increases to be a factor of 4 larger in KERG80, compared with previous findings (e.g. Capet et al., 2008a.; Klein et al., 2008).

We conclude that, despite the idealised nature of our simulations, the dynamics of the Kerguelen area are well captured. In the following sections, we will present our results and discuss how the two resolutions impact the ocean circulation.

4. Results

We examine the differences in the circulation between the two experiments and the impacts that the small-scale features in the KERG80 case have on the vertical velocity (Section 4.1) and transport of Lagrangian particles (Section 4.2). In the following, horizontal spatial averages are denoted by $\langle \cdot \rangle$ and 200-day temporal averages by an overbar ($\bar{\cdot}$). A video of the surface temperature, velocity and relative vorticity at the two resolutions can be found in Supplementary material.

4.1. Frontal structures

We begin our analysis by comparing the surface velocity and vorticity fields from both resolutions. Fig. 9 shows the emergence of transient localised fronts and fine-scale structures when increasing the resolution. The patterns that emerge in the KERG80 vorticity field are characteristic of features captured by resolutions of $O(1 \text{ km})$ (Capet et al., 2008a). These structures have high values of vertical relative vorticity, $\zeta_z = v_z - u_z$, localised in stretched filaments and at the edges of the mesoscale eddies (not shown). There, $\zeta_z$ is comparable with the Coriolis frequency $f$, as measured by the Rossby number $Ro = |\zeta_z/f|$. A common feature observed at both resolutions is the absence of strong patterns over the plateau. Here, a weaker velocity field is present (Fig. 9(a) and (b)), because the plateau acts as a natural barrier to the strong ACC fronts coming from the west. In the region east of the KP, the ACC flow, interacting with topography, generates instabilities and filaments.

The strength of frontal structures increases with horizontal resolution. Fig. 10(a) and (b) show the surface density gradient, $|\nabla_H \rho(x,y)|$, at 50 m depth (where $\nabla_H$ is the horizontal gradient and $\rho$ the local density). A field of strong fronts emerges at high resolution, whose structures are connected to strong vertical motions (Fig. 10(d) and (f)). We have compared the magnitude of the vertical velocity ($w$) with observations from the SOFINE experiment (Phillips and Bindoff, submitted for publication). We found that vertical velocities in excess of 100 m day$^{-1}$ are routinely observed in this region, implying that the magnitude of velocities...
seen in our KERG80 experiment are realistic. However, $w$ is weaker in the KERG20 case which indicates that at this resolution the vertical motion (and its contribution to transport) may be underestimated (note the different scales in Fig. 10(c)–(f) between KERG20 and KERG80). The location of $w$ in relation to fronts is also shown in panels (c)–(f). In the KERG80 case, the colocation of these features is consistent with an ageostrophic secondary circulation mechanism, which arises in connection to frontogenesis (Capet et al., 2008b; Taylor and Ferrari, 2011). In fact, where the magnitude of $\nabla_H \rho$ is strong, a dipolar structure emerges for the vertical velocity (Fig. 10(d) and (f)).

Fig. 10(c) and (e) indicate that in the KERG20 case $w$ is under-resolved, with patchy structures on the scale of the grid. In the KERG80 case the vertical velocity is well defined and penetrates deep into the water column (panel (f) indicates a maximum local depth of 800 m), which is related to the mixed layer depth (white line in panels (e) and (f)). The mixed layer depth was computed using a mixed layer criterion of $0.05 \times 10^3 \text{kg/m}^4$ and the dashed black lines indicate the location of the vertical slices of $w(x,z)$ (e) and $w(y,z)$ (f). White lines in (e) and (f) indicate the mixed layer depths, while grey lines are isopycnals, with an interval of 0.1 kg/m$^3$. The instantaneous fields are taken at the same model day used in Fig. 9, for both resolutions. Note the different colour scales in (c)–(f).
vertical component (Fig. 10(c)-(f)), this can occur only when the horizontal velocity aligns with extended regions of large $|w|$. The Lagrangian tracking method can be used to investigate this aspect (Sections 4.2 and 5).

Another way to investigate the areas of major up/downwelling is the analysis of the temporal root mean square of the vertical velocity. We have calculated this metric for each resolution case, on a single level close to the surface (50 m depth) and computed the temporal mean over 200 days. We indicate it as $\overline{w_{\text{rms,2D}}} = \sqrt{\overline{w^2}}$. The map, in Fig. 12, shows differences in the location, structure and magnitude at the two resolutions. We identify a region over the shallow plateau (number 1 in figure), where the vertical velocity is weak and the motion is mainly horizontal, at both resolutions. In the KERG20 case the largest magnitudes are found in the northern half of the domain, while at 1/80° resolution we can see two main areas, as indicated by number 2 and 3 in the figure. The second region presents strong vertical motion in the northern region, either located in the lee of topographic features or located in the southernmost area of the meander (74–76°E, 46–47.5°S). Finally, the third region comprises the area from the eastern boundary of the plateau to the eastern side of the domain. In these last two locations the vertical motion is very strong and $\overline{w_{\text{rms,2D}}}$ indicates the presence of filamentary structures.

Following the method presented by Capet et al. (2008a), we examine the vertical profile of the root mean square of $w$ for each resolution. To highlight the contribution over the water column given by the different spatial structures present, the total field has been decomposed into the temporal mean ($\bar{w}$), mesoscale ($w_M$) and sub-mesoscale ($w_S$) components: $w = \bar{w} + w_M + w_S$. For the separation of the spatial scales at the mesoscale and sub-mesoscales, we applied a horizontal low-pass filter based on a spatial 2-dimensional convolution of $(w - \bar{w})$ with a constant rectangular window. The width of the window is 4 points for KERG20 and 16 points for KERG80, so the filter has the same physical dimensions in both cases: the cutoff between the two scales is 1/5°, which corresponds to 22 km in the meridional and 15 km in the zonal directions, comparable to the 1st baroclinic Rossby radius in the KP region (Chelton et al., 1998). The mesoscale component, therefore, includes all the scales and variabilities except the finest sub-mesoscales. We computed horizontal spatial rms metrics over each level, which were then temporally averaged. Its sensitivity to the horizontal resolution is shown by the vertical profiles in Fig. 13.

The notations shown in figure refer to: “$\overline{w_{\text{rms}}}$” = $\sqrt{\overline{w^2}}$, “$\overline{w_{\text{rms},M}}$” = $\sqrt{\overline{w_M^2}}$ and “$\overline{w_{\text{rms},S}}$” = $\sqrt{\overline{w_S^2}}$. We point out that, purely due to the continuity condition, an enhancement of 4 times might be expected with a 4-fold increase of resolution. The rms profiles of $w$ present the highest magnitudes in the KERG80 case, with the
total $w_{rms}$ 11-fold greater than the KERG20 profile. This increase in magnitude is particularly significant in the sub-mesoscale component, which reveals a strong signature close to the surface and to the bottom. The surface signature is dominated by sub-mesoscale activity, while mesoscale-induced vertical velocities are almost independent of depth. On the other hand, the sub-mesoscale component for KERG20 shows only minimal surface enhancement. The peak near the bottom is most likely due to flow interacting with topography. The mesoscale components and the topographically-induced sub-mesoscale velocities are similar in structure, although the magnitudes of each are larger at high resolution. Due to the enhancement of small scale components of velocity throughout the water column, we cannot exclude the presence of inertia-gravity waves in addition to sub-mesoscales. The use of the Lagrangian model is therefore a valuable tool to estimate the net vertical transport.

These results show that the vertical velocity is stronger in the north and east side of the KERG80 domain, while over the plateau both the horizontal and vertical circulations are much weaker than the surroundings. Furthermore, the vertical velocity depends on the horizontal resolution and is enhanced at finer scales, especially near the surface. In the next section we will use the CMS (Paris et al., 2013) to investigate whether this feature results in more advective transport.

4.2. Particle analysis

The CMS Lagrangian particle model (Paris et al., 2013) is used to study the three-dimensional transport of particles in the flow, as a function of horizontal resolution. A series of experiments were implemented, tracking particles both backward and forward in time. The first series of experiments (backward) were designed to test the possible sources of surface water, in the lee of KP (red markers in Fig. 1). Here, 800 particles were placed at 5 m depth in each resolution experiment and their backward trajectories computed for the previous 100 days. An ensemble of
The KERG20 particles are mainly derived from the south side of Kerguelen Island (approximately 95%) and in particular from the shallow plateau. In this case, just 8% of particles come from depths greater than 100 m (Fig. 15(a)). On the other hand, more than 75% of the paths in KERG80 arrive via the circulation coming from the ACC and flowing along the eastern boundary of the plateau (61%) or in the strong meander north-east of the plateau (14%). The waters in this region are upwelled from deeper levels and 25% of the particles come from depths deeper than 500 m and 38% deeper than 100 m. The distribution of the trajectories as a function of depth, and integrated in time, is shown in Fig. 15(a), in which the KERG80 case presents sources of particles substantially deeper than in the lower resolution case.

The second series of tests are run forward in time for up to 100 days and the particles are released at 6 different depth levels: $R_i = \{48, 102, 146, 202, 296, 396\}$ m. We performed two cases: (1) 1000 particles placed at each level in a location north of KP, inside the strong ACC (black markers in Fig. 1); (2) 500 particles released at each depth level, south of Kerguelen Island, as indicated by the green markers in Fig. 1. These last two experiments were performed to study the transport around and over the plateau and understand how the particles are advected in the water column. Fig. 16 shows example paths for the forward experiment (north of KP case), with initial depths at 200 m. At each resolution a fraction of particles flows through the meander in which the particles are mainly transported horizontally and their position in the water column does not substantially change, irrespective of resolution. This behaviour is well represented by the black lines passing through the meander in Fig. 16. Moreover, in the KERG80 case the particles (e.g. yellow and magenta in Fig. 16) coming from locations close to the plateau follow the circulation that develops along the eastern boundary of the plateau. The transport of particles here involves strong high-frequency upwelling/downwelling
(Fig. 16(b)) while carrying the waters into the eastern region of the domain (Fig. 16(a)), which coincides with the area of small-scale activity (Fig. 10). The particles in KERG20 still reach depths of 800 m (cyan line in Fig. 15(b)), but only rarely, and their transitions are much slower (e.g. Fig. 16(b)). We suggest that this behaviour, as will be discussed in the next section, is due to the lack of sub-mesoscale structures.

Furthermore, the KERG80 case generates a rapid spread of particles in the water column, as shown by the example of Fig. 16 and summarised in Fig. 15(b). In Fig. 15(b) we present the number of particles found at different depths, integrated in time for up to 100 days. The diagnostic was evaluated for those trajectories reaching 74°C176E, in the domain defined by areas 2 and 3 of Fig. 12. The dramatic difference in the distributions at the two resolutions is captured in all the experiments. Both the excursions to depths and to shallower levels (down to 200 m) are significantly different in KERG20 and KERG80 and in the lower resolution cases the spreads are more gradual, remaining concentrated closer to the release depths. For those particles reaching a representative arrival depth in the range of (10–150) m (labelled A in Fig. 17) we have evaluated the percentage of their trajectories which had previously passed through other depths (indicated by Sn, n = 1, 2, 3 in Fig. 17). The computation was done for each experiment with particles released from initial depth Ri, i = 1, 2... 6. As expected from the results of Fig. 15(b), fewer particles are found in the surface levels of the KERG20 experiments and, for those trajectories reaching the arrival range depths, KERG80 generally gives more vertical exchange (exceptions are R5 passing through S2). Some particles of KERG80 track an excursion of at least 450 m (approximately 10% in the R6 particle release from 396 m). Particles released from R2,3 quite commonly reach depths exceeding 400 m (S2) or even 600 m (S3) before returning to A in KERG80; this never occurred in KERG20. There are no KERG20 trajectories found in the arrival range coming from depths below 600 m, in contrast to KERG80, in which the % of particles reaching A from below 600 m was as high as 10%.

In the last group of experiments particles are integrated forward in time from locations south of KP (Fig. 18). The vertical spread of particles show similarities at both resolutions (Fig. 18(c) and (d)) at each depth of release (only particles with 50 m starting depth are shown), while the horizontal paths indicate a sensitivity to the resolution (Fig. 18(a) and (b)). A common pattern in the KERG20 case is a northward circulation above the plateau that drives the particles with release north of 51°C176S along the topographic contours. Moreover, almost none of these particles are found over KP west of 72°C176E in this case. At the highest resolution, the horizontal trajectories show a different behaviour. We found a wide horizontal spread of particles above the plateau, mainly of those particles released north of 51°C176S.

5. Discussion and conclusions

We have conducted a series of experiments in the KP region of the Indian Ocean sector of the Southern Ocean, using the MIT general circulation model and examined the sensitivity of the vertical velocity to the horizontal resolution. We found clear differences in this metric, due to the development of near surface sub-mesoscale frontal structures that only the highest resolution case (KERG80) is able to resolve. Sub-mesoscale flow generates the highest magnitude vertical velocities in the upper part of the water column (down to 500 m). Moreover, the mesoscale component of wM (which is fully resolved at both resolutions) is twice the magnitude in the KERG80 case, compared with KERG20 (Fig. 13). We suggest that the energetic field that emerges in the sub-mesoscale-resolving case (KERG80) feeds back onto the larger scale field (wM), transferring energy from high to low wavenumber structures (Fig. 8). Fig. 13 also shows that in both cases there are strong
signatures of \( \omega_{\text{rms}} \) away from the surface. At depths of approximately 3000 m, the peak in total \( \omega_{\text{rms}} \) and the sub-mesoscale component seem to arise from the interaction between the circulation and the deep topography east of the plateau. The continuity equation suggests we might expect a 4-fold increase of resolution to produce a 4-fold increase of \( \omega \). However, the ratio between the 11-fold increase in total \( \omega_{\text{rms}} \) and 4-fold increase in resolution (ratio of 2.75) is greater than in previous studies. For example, Lévy et al. (2001) showed that \( \omega_{\text{rms}} \) increased by a factor of 1.7 for an increase in resolution of 3 times (ratio of 0.57), using an idealised configuration of an oligotrophic ocean. In the California Current system modelled by Capet et al. (2008a), the authors found that the \( \omega_{\text{rms}} \) increased by 15 times for a 6-fold change in resolution (ratio of 2.5); while in the model configuration of Lévy et al. (2012), representing the western sector of the North Atlantic or North Pacific Oceans, the ratio is just 0.2. We suggest that this higher ratio in our study is most likely due to the higher kinetic energy and the weaker stratification typical of the Southern Ocean. Thus, it is likely that the strong sub-mesoscale effects found in this study may extend to other parts of the Southern Ocean.

The strong vertical velocities that arise in the KERG80 case show filamentary structures (Fig. 10). There is a strong correlation between \( |\nabla \mathbf{u}| \) and high \( w \), as one can infer also from Fig. 11, which suggests the presence of a frontogenetic mechanism. Yet, we point out that this may not be the only (or even the main) mechanism present that generates high values of vertical velocity: high values of \( w \) are found also in regions of low density gradient, away from fronts (e.g. the large \( w \) found around 49.2°S of Fig. 11). Possible mechanisms that might contribute to the observed high vertical velocities are instabilities occurring along fronts (McWilliams and Molemaker, 2011), wind-driven pumping (Lee et al., 1994) or mixed layer instabilities (Boccaletti et al., 2007). The location of vertical circulation indicates similarities and differences between the two runs. A similar behaviour is found over the plateau, where the horizontal circulation is very weak and there is no evidence of frontal activity even in the KERG80 case. Here, \( \omega_{\text{rms},20} \) has low magnitude (Fig. 12). Most of the strong up/downwelling in the KERG20 case happens in a band at latitudes north of 50°S (Fig. 12(a)), while at the highest resolution (panel (b), areas 2 and 3) strong vertical circulations are found to the east of the plateau. These two regions are areas of sub-mesoscale activity and frontogenesis, as seen in Fig. 10, which is a further indication of the role of sub-mesoscales and the importance of capturing their dynamics. Moreover, the influence of the meander and of the topography, which is relevant in locations of small topographic features, are only present in the KERG80 case (region 2). We conclude that the different location and magnitude found at the two resolutions may have a strong influence on the vertical transport of tracers.

We found behaviour consistent with the above flow metrics in the transport of particles. The analysis of the advective transport measured by Lagrangian particle tracking confirms the sensitivity to horizontal resolution. According to the paths shown in Figs. 14, 16 and 18, three different regions can be identified. The first region is characterised by particles coming from south of Kerguelen Island (Fig. 18). In this case the particles able to pass KP and reach the eastern area of the domain originate from a shallow depth (48 m), suggesting that here the vertical transport does not play a fundamental role in driving tracers into the plateau. At 1/20° resolution, a small fraction of particles (less than 1%) is observed on the plateau, while in the 1/80° case we found up to 15%. KERG20 paths are mainly trapped by the current flowing northward, while in the KERG80 case the particles spread more widely over KP, although in 100 days of integration they do not reach the area east of the plateau.

The second region comprises the meander feature and extends from north of KP (at approximately 70°E and 46°S) to the area east of the plateau. The circulation of the meander does not generate vertical displacement of the particles (black lines in Fig. 16) which, in the case of KERG80, may be due to weak sub-mesoscale structures. The lack of sub-mesoscales here may result from the proximity to the upstream boundary, where incoming flow is relatively laminar and sub-mesoscale instabilities are unable to form. Alternatively, the flow dynamics may simply be stabilised by strong shear within the front. Resolving this question would require additional model runs which are beyond the scope of the present paper.

Finally, a third region can be identified. This region is associated with two groups of paths. The first comprises those particles that follow the contours of the bathymetry and come from locations south of 46°S, at the longitude of 70°E. A second group is defined by the trajectories found east of KP. The first group of trajectories are not present in the KERG20 case (top panels of Fig. 16, which shows horizontal patterns of an ensemble of particles released at 200 m and the temporal mean of SSH contours, as represented in Fig. 5). We suggest that the evolution of these particular trajectories is correlated with the position of thermohaline fronts. The different circulation and thermohaline structures that arise in the two different models imply distinct impacts on the transport of particles. In the KERG20 case, the position of the northern front, indicated by SSH contours in Fig. 16, is shifted northward compared to KERG80 and drives the particles far from the boundaries of KP. Conversely, in the 1/80° case the front is placed along the bathymetric contours, driving south-eastward the trajectories coming from south of 46°S. In the KERG80 case, these trajectories experience strong vertical motion due to the presence of strong small-scale filaments. The last group of paths arising in this region are those advected east of the KP, where high frontal activity is present in the KERG80 case (Fig. 10(b)). Here, the impact of the sub-mesoscales is prominent and the particles are transported with rapid transitions upward and downward in the water column (e.g. Fig. 16(b)). The evidence that such behaviour comes from small-scale structures may also be inferred from the comparison with the vertical structure of vertical velocity (see panels (d) and (f) of Fig. 10).

This study highlights the importance of resolving small-scale features in an ocean model, for a correct investigation of vertical transport and circulation. In the KP region this is fundamental if seen in the context of iron sources and transport, which consequently leads to a proper evaluation of the carbon export budget. We also suggest that the need for high horizontal resolution, such as 1/80°, may be dependent on the location. Higher resolution is required in areas such as along the eastern flank of the northern KP, or downstream of the ACC. In contrast, over the plateau the similarity in the two simulations suggests that a lower horizontal resolution may be sufficient to represent the ocean dynamics. From Fig. 10 it is clear that filaments are well resolved at 1/80° resolution. Yet, experiments at higher resolution would be needed to determine whether any additional processes arising at finer scales play a significant role in vertical transport. We are presently undertaking a study aiming to couple such dynamics with biogeochemical processes and understand the evolution of iron concentration in relation to physical structures.

Furthermore, the sensitivity of vertical transport to changes in horizontal resolution has important ramifications for modelling the ocean carbon cycle. Currently, global ocean models use horizontal resolutions that either do not, or barely, resolve mesoscale dynamics. Our results imply that such models may miss important processes that transport nutrients into the surface waters, and thus may poorly represent key processes important to carbon cycling in the upper ocean. It follows that considerable work is needed to understand and (in the absence of sub-mesoscale resolving models) better parameterise vertical fluxes or tracers due to sub-mesoscale processes.
Acknowledgements

Numerical simulations and analyses were conducted using the National Facility of the Australian National Computational Infrastructure. A. Hogg was supported by Australian Research Council Future Fellowship FT120100842. We want to express our thanks to H. Phillips, L. Brannigan and S. Keating for constructive discussions and R. Morrow for providing the altimetry regional-Kerguelen experimental product from AVISO, with support from CNES. SOSE fields used throughout the simulations were provided by M. Mazloff (Scripps Institution of Oceanography, UCSD). We thank both reviewers who helped us to improve this manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ocemod.2014.05.001.

References


