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Advective pathways near the tip of the Antarctic Peninsula: Trends, variability and ecosystem implications

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ABSTRACT

Pathways and rates of ocean flow near the Antarctic Peninsula are strongly affected by frontal features, forcings from the atmosphere and the cryosphere. In the surface mixed layer, the currents advect material from the northwestern Weddell Sea on the eastern side of the Peninsula around the tip of the Peninsula to its western side and into the Scotia Sea, connecting populations of Antarctic krill (*Euphausia superba*) and supporting the ecosystem of the region. Modelling of subsurface drifters using a particle tracking algorithm forced by the velocity fields of a coupled sea ice-ocean model (ORCA025-LIM2) allows analysis of the seasonal and interannual variability of drifter pathways over 43 years. The results show robust and persistent connections from the Weddell Sea both to the west into the Bellingshausen Sea and across the Scotia Sea towards South Georgia, reproducing well the observations. The fate of the drifters is sensitive to their deployment location, in addition to other factors. From the shelf of the eastern Antarctic Peninsula, the majority enter the Bransfield Strait and subsequently the Bellingshausen Sea. When originating further offshore over the deeper Weddell Sea, drifters are more likely to cross the South Scotia Ridge and reach South Georgia. However, the wind field east and southeast of Elephant Island, close to the tip of the Peninsula, is crucial for the drifter trajectories and is highly influenced by the Southern Annular Mode (SAM). Increased advection and short travel times to South Georgia, and reduced advection to the western Antarctic Peninsula can be linked to strong westerlies, a signature of the positive phase of the SAM. The converse is true for the negative phase. Strong westerlies and shifts of ocean fronts near the tip of the Peninsula that are potentially associated with both the SAM and the El Niño-Southern Oscillation restrict the connection from the Weddell Sea to the west, and drifters then predominantly follow the open paths to South Georgia and the east. Over the 43-year time series, the number of drifters advected into the Bellingshausen Sea decreases significantly by 23% and the travel time to South Georgia shortens significantly by 19% which corresponds to 56 days. We propose that these trends are linked, at least in part, to the increasingly positive trend in the SAM and, as such, this suggests an additional anthropogenic source of change to the regional ecosystem.

1. Introduction

The upper ocean currents near the tip of the Antarctic Peninsula (Fig. 1) are strongly influenced by the complex topography, the fronts of the Weddell Gyre and the Antarctic Circumpolar Current (ACC), and the time-varying atmospheric and cryospheric forcings (Heywood et al., 2004; Loeb et al., 2009; Thompson et al., 2009). The surface currents carry nutrients and planktonic organisms from the northwestern Weddell Sea towards the western Antarctic Peninsula and into the Scotia Sea and thus create important ecological links in the region. Antarctic krill (*Euphausia superba*; hereafter referred to as krill) is one of the key organisms of the Southern Ocean food web (Murphy et al., 2007b). The large-scale distribution of krill is dominated by the surface currents including the fronts of the ACC and the northern parts of the Weddell Gyre (Marr, 1962). Krill abundance is a determining factor for predator success (e.g. Reid and Croxall, 2001), however, there are indications that krill density decreased dramatically in the southwest Atlantic over the last 30 years (Atkinson et al., 2004, 2008). Whilst biological processes can induce changes in krill abundance and distribution, changes in the krill distribution due to changes in the advection by currents can

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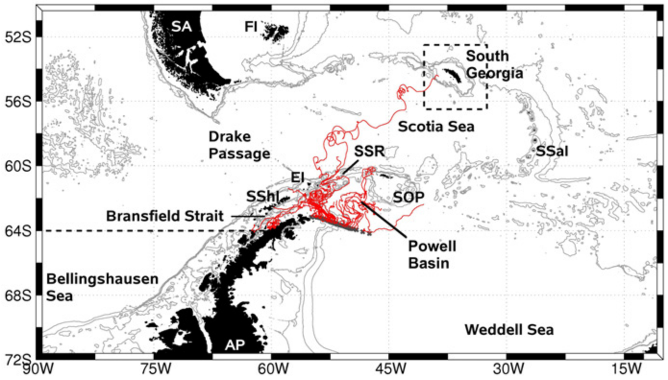

Fig. 1. Map of the study region. The contour lines show the 500 m, 1000 m, 2000 m, and 5000 m isobaths from the Smith and Sandwell (1997) topography. Land is shaded black. Abbreviations of land masses and points of interest marked are: AP—Antarctic Peninsula; EI—Elephant Island; FI—Falkland Islands; SA—South America; SOP—South Orkney Plateau; SSaI—South Sandwich Islands; SShI—South Shetland Islands; SSR—South Scotia Ridge. The dark grey crosses show the start positions of the simulated drifters. The black dashed line and the dashed box around South Georgia mark the boundaries for drifter advection calculations. The red lines show the trajectories of 39 near-surface drifters deployed in February 2007 as part of the ADELIE project (Thompson et al., 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

impact large parts of the Southern Ocean ecosystem (Murphy et al., 2007a, 2007b).

In February 2007, 40 drifters were released at 34 locations along a transect in the northwestern Weddell Sea as part of the Antarctic Drifter Experiment: Links between Isobaths and Ecosystems (ADELIE) project (in the following referred to as ADELIE drifters, see Fig. 1; Thompson et al., 2009). The drifters followed three main paths from the Weddell Sea: into Bransfield Strait to the west, eastward into the ACC and across the Scotia Sea, or they became entrained into a standing eddy south of Elephant Island. The paths are the result of the influence of the three major fronts in the northwestern Weddell Sea: the Antarctic Coastal Current on the continental shelf, the Antarctic Slope Front above the continental slope, and the Weddell Front over the 2500–3000 m isobaths (Thompson and Heywood, 2008; Thompson et al., 2009). Thompson et al. (2009) have shown that the surface currents associated with these fronts near the tip of the Peninsula are strongly steered by topography. The drifters confirmed an advective link between regional ecosystems on both sides of the Antarctic Peninsula and the Scotia Sea as proposed by Heywood et al. (2004).

The Weddell–Scotia Confluence separates the waters of the Weddell and Scotia Seas (Whitworth et al., 1994). At the Confluence and in the Scotia Sea, the ACC fronts and the topography strongly influence the upper ocean currents. In particular the two southernmost ACC fronts, the Southern Boundary of the ACC (SB) and the Southern ACC Front (SACCF), are important for transport of biological material across the Scotia Sea (Murphy et al., 2007b, and references therein). Their position, however, is variable on a range of timescales including seasonal and interannual (Thorpe et al., 2002; Boehme et al., 2008) and Loeb et al. (2009) suggest these variations to be driven by changes in the large-scale atmospheric forcing. The dominant mode of variability in the wind pattern over Antarctica and the Southern Ocean is the Southern Annular Mode (SAM; Thompson and Wallace, 2000), characterised by an oscillation of atmospheric mass between a node centred over Antarctica and an annulus over the Southern Ocean, with associated fluctuations in zonal winds. Since the mid 1960s, the SAM has become more positive due at least partially to anthropogenic forcing from ozone depletion and greenhouse gas emissions (Thompson and Solomon, 2002; Marshall et al., 2006). However, implications for the currents near the tip of the Antarctic Peninsula and potential consequences for transport of particles such as nutrients and plankton are still under discussion. Another major mode of climate variability in the Southern Hemisphere is the El Niño–Southern Oscillation (ENSO) phenomenon, which has a particular footprint in the Southern Ocean in the southeast Pacific sector and stretching through into the southwest Atlantic (Turner, 2004; Meredith et al., 2008). ENSO variability originates in the tropical/equatorial Pacific, and affects the Southern Ocean via atmospheric and oceanic teleconnections (e.g. Turner, 2004); a range of feedbacks in the system can lead to complex high latitude responses on a range of timescales, as shown for e.g. changes in the seasonal cycle of the sea ice cover in the western Antarctic Peninsula (WAP) region (Stammerjohn et al., 2008), the occurrence of sea surface temperature anomalies around South Georgia (Meredith et al., 2008), or the composition of the plankton community at the tip of the Antarctic Peninsula (Loeb et al., 2009).

Finite-duration campaigns such as the ADELIE project have been complemented by modelling studies that can investigate larger spatial and temporal scales. The combination of models and observations has shown a link between krill abundance at South Georgia and the variability in frontal positions and currents in the WAP region (e.g. Hofmann et al., 1998; Fach et al., 2002; Murphy et al., 2004; Thorpe et al., 2004; Loeb et al., 2009). In this study, we focus on the interannual variability and trends of the near-surface outflow from the Weddell Sea over four decades and the implications for the ecosystem of the region. We simulate drifters starting at the same locations as the ADELIE drifters in a 47-year run of the coupled sea ice-ocean model ORCA025-LIM2 (in the following referred to as ORCA025) using an offline particle tracking algorithm. The model, the algorithm, and the statistical tools used in the analysis are described in Section 2. Section 3 gives a description of the drifter modelling results and the pathways towards the WAP region and across the Scotia Sea. Discussion of the interannual variability of the pathways and potential forcing mechanisms follows in Section 4. We conclude with potential implications for the regional ecosystem in Section 5.

2. Data and methods

The drifters are simulated by an offline particle tracking algorithm (Thorpe et al., 2004; Renner, 2010) which uses monthly velocity fields from the coupled sea ice-ocean model ORCA025, run G70 (Barnier et al., 2006; Molines et al., 2006, updated 2007). The two-dimensional algorithm is based on a second order Runge–Kutta scheme as described in detail by Thorpe et al. (2004) which includes horizontal advection and diffusion. The position of a particle at timestep $k+1$ is thereby given by

$$x^{k+1} = x^k + u^{k+1/2}\Delta t + d\cos\Theta, \tag{1}$$

$$y^{k+1} = y^k + v^{k+1/2}\Delta t + d\cos\Theta, \tag{2}$$

with x,y denoting the position of the particle, u,v the horizontal components of the current velocity, Δt the timestep of the tracking algorithm, and $d\cos\Theta$ the random walk component simulating the effects of small and mesoscale motion. Modifications to the random walk component were made to include the variability of the dispersion in relation to the location of the drifters above the continental shelf, the slope and the deep ocean (Renner, 2010; Trasviña et al., 2011). The direction of the random movement Θ is given by

$$\Theta = 2\pi R_\Theta, \tag{3}$$

where R_Θ is a random number distributed uniformly between 0 and 1 (Thorpe et al., 2004). The magnitude of the random