Exchanges between the Ross Sea and the Antarctic Circumpolar Current happen at the Pacific-Antarctic ridge

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Abstract

The surface waters of the southeast Pacific (south of 50°S) have experienced a cooling and freshening trend in years 2006-2013. Recent studies suggested that an increase in northward wind-driven transport of Antarctic sea-ice, with concomitant sea-ice melt, ~~were~~ the principal mechanism responsible for the observed freshening in the high latitudes of the South Pacific. The transport has been studied with a Southern Ocean 1/12th degree resolution simulation (SO12) and a Lagrangian particle tracking model. Numerical particles have been released in the Ross Sea and advected for 4 years by SO12 velocities. Results showed that particles released at the surface and subsurface in the Ross Sea were advected across the Southern Antarctic Circumpolar Current Front (SACCF) around 140°W, intersection between the SACCF and the Pacific-Antarctic Ridge. This suggests that geostrophic flow and bathymetry are the dominant mechanisms driving particles from the Ross Sea into the Antarctic Circumpolar current.

1 Introduction

The top 2000 m of the Southern Ocean have warmed (Roemmich et al., 2015) and freshened in recent decades (Wong et al., 1999; Aoki et al., 2005; Durack et al., 2012). On the other hand, analyzing Argo data for years 2006-2013, Roemmich et al. (2015) have shown that during that time period, the surface waters of the southeast Pacific (south of 50°S), have cooled and freshened (Wong et al., 1999; Durack et al., 2012). Haumann et al. (2016) suggested that an increase in northward wind-driven transport of Antarctic sea-ice, with concomitant sea-ice melt, is the principal mechanism responsible for the observed freshening in the high latitudes of the South Pacific.

The object of this study is to investigate the origin of the water at the location of the strongest freshening. We hypothesize that the cooling and freshening of the southeast Pacific is caused by an increase in transport of cold and fresh surface water from the recently melted sea ice in the Ross Sea, across the Antarctic Circumpolar Current (ACC). We use a Lagrangian particle tracking model to test our hypothesis and examine where and when water is exchanged between the Ross Sea and the ACC. We examine the mechanisms responsible for these exchanges.

Our study focuses on the Ross Sea, which is located in the Pacific sector of the Southern Ocean (Figure 1). The circulation of the Ross Sea is dominated by a cyclonic gyre called the Ross Gyre (Ross G. in Figure 1). North of the Ross Sea flows the ACC. Winds from the west (blowing in the 40°S-60°S latitude range) drive the ACC, an eastward current around the Antarctic continent (Figure 1). The mean transport of this current is 173.3 $\pm$ 10.7 Sv through Drake Passage (Donohue et al., 2016), which makes it the most powerful current in the world. It is therefore a strong dynamical boundary for water "leaking" out of the Ross Sea. In the Lagrangian model, we seed particles across the Ross Sea, south of the Southern Antarctic Circumpolar Current Front (SACCF). We then quantify the number of particles that make it into the ACC.

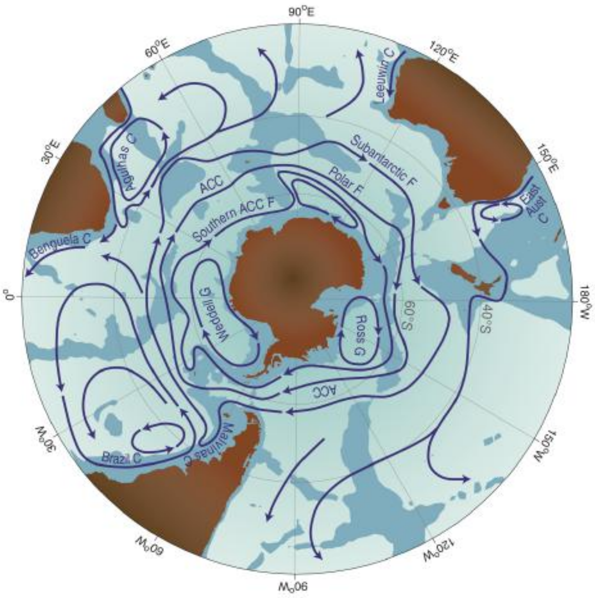

Figure 1 – Schematic of the circulation in the Southern Ocean taken from Rintoul (2011) showing the location of three cyclonic gyres south of the SACCF.

2 Method

To test our hypothesis, we carry out a Lagrangian particle release experiment conducted using Octopus [1], a software package to facilitate off-line particle tracking. Particles are advected by velocity output from a simulation of the Southern Ocean (hereafter SO12) which was run using the MITgcm, an ocean general circulation model (Marshall et al., 1997). We use a 5-year run (April 6, 2006 to April 5, 2011) of SO12. The fields are averaged on-line and archived every 5 days. The model has a horizontal resolution of 1/12th of a degree and 104 uneven vertical levels. The domain of study is 78°S, 40°S, 120°E, 90°W (Ross Sea).

Before starting the particle analysis, we validated the model by comparing its output to observations of sea surface height (SSH) fields created by Archiving, Validation, and Interpretation of Satellite Oceanographic Data center (AVISO, 2018) and to the temperature and salinity products given by WOCE/Argo Global Hydrographic Climatology (WAGHC) (Gouretski, 2018). From this analysis of the model, we concluded that the southern front of the ACC has to be chosen more north than usual to ensure that particles that do cross the front really make it into the ACC.

For the study of particle trajectories, Octopus reads the 5-day averaged horizontal and vertical velocity fields and the mixed-layer depth given by the model SO12. Octopus uses a fourth-order Runge-Kutta scheme in time and a trilinear interpolation scheme in space to obtain particle velocities at the eight gridded SO12 velocity points. A reflective boundary condition at the surface and bottom is implemented. Particles that reach the mixed layer have their vertical position reshuffled randomly every 5 days to provide a numerical representation of the mixed layer turbulence that is not resolved in the velocities.

We conduct two experiments with 12 releases of 10 000 particles, 1 per month for a

1. Octopus was written by Jinbo Wang : https://github.com/jinbow/Octopus

year, initialized in the yellow box of Figure 2 (69°S, 67°S, 180°W, 130°W). We choose the location of the release to be across the Ross Gyre as we want to study how much water from the gyre is exchanged with the ACC. For the first experiment, we initialize the particles at 50 m depth, which is within the depth range of the Ekman layer (100 m depth in Drake Passage, Lenn and Chereskin, 2009). For the second experiment we initialize the particles at 255 m depth to test what happens to particles when they are not originally in the Ekman layer. Both runs last 5 years. Particles are advected every 0.5 days (time step in Octopus). Outputs are saved every 10 days.

Figure 2 shows the stream function obtained as the cumulative integral from Antarctica to 25°S of the vertically integrated zonal velocity. We choose the stream function contour 15 Sv as the southern front of the ACC (blue curve in Figure 2). This front marks the boundary between the Ross Sea and the ACC. This contour is flattened between 148.7°E and 163°E as the region is very turbulent. Our study region representing the Ross Sea, is closed at 120°E and 110°W (vertical blue lines in Figure 2).

We study 5 distinct groups of particles :

— Ross Sea: particles that stay in the Ross Sea (in the blue region of Figure 2)
— North of the southern ACC front: particles that cross the front and leave the blue region (Ross Sea) northward
— West: particles that leave the blue region westward
— East: particles that leave the blue region eastward
— Hit land in the Ross Sea : particles that hit land and that we stop tracking.

To select the particles that really cross the front we use a threshold : if a particle is beyond the southern ACC front for at least 3 time steps (30 days), we consider that it has entered the ACC and belongs to the group of particles that are advected north of the ACC front.

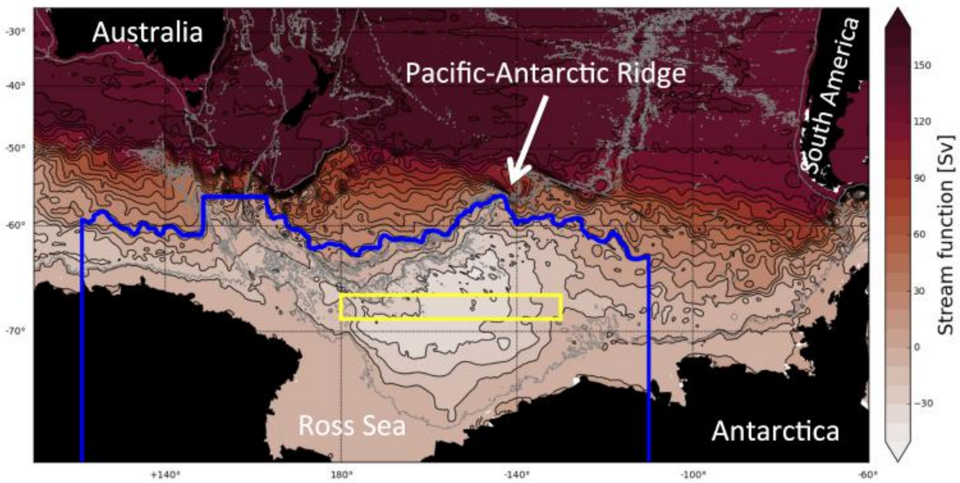

Figure 2 – Stream function obtained as the cumulative integral from Antarctica to 25°S of the vertically integrated zonal velocity. Yellow box indicates initial position of the particles. They leave the blue region to the west (120°E), the east (110°W) or cross the southern front of the ACC defined as the stream function contour 15 Sv and flattened between 148.7°E and 163°E. Grey lines are the z = 3000 m contour.

3 Results

We are interested in the evolution of each group of particles described in section 2 during the experiment. Figure 3 presents the percentage of particles in each group as a function of time. ~~This shows us that initially 100% of the particles are located in the Ross Sea.~~ About 1.5 years after release, they start to exit the blue region of Figure 2, either to the north, to the west, or to the east.

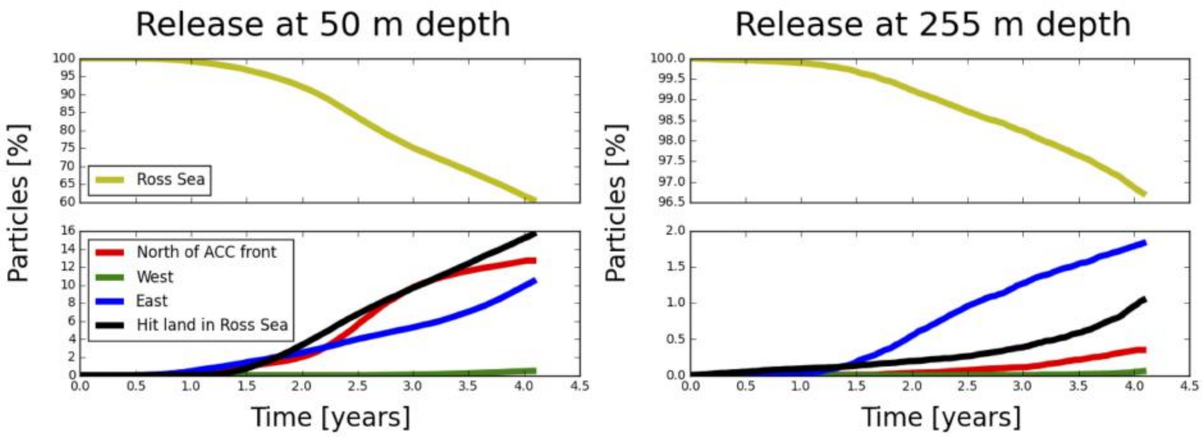

Figure 3 – Percentage of particles according to time that stay in the Ross Sea (yellow line), leave the Ross Sea northward (red line), westward (green line) and eastward (blue line), or hit land in the Ross Sea (black line). Results are for 2 releases of 12 x 10 000 particles in the yellow box (Figure 2) at 50 m depth (left) and 255 m depth (right). Both panels have different y-axis.

At the end of the 4-year study period, at 50-m depth, 60% of particles remain in the Ross Sea, while at 255-m depth, 96% of particles remain in the Ross Sea. Some particles that stay in the Ross Sea hit land after a year. ~~We can see that~~ some particles leave eastward (10% for the 50 m run and 2% for the 255 m run) and a very small percentage of particles leave westward in the Antarctic Coastal Current (less than 1% for both runs). We can also see that 12% of the particles in the 50 m run cross the ACC front but less than 0.5% cross in the 255 m run.

Figure 4 presents as a probability density function, the depth, longitude, month and time of the experiment ~~that~~ the particles cross the ACC front. For the 50 m run, particles cross the ACC front mostly at the surface (between 0 and 40 m depth). In contrast, the depths of crossing for the 255 m run cover a wider range of depths with a maximum around 600 m. Interestingly, particles seem to be crossing mostly around 140°W. Particles cross the front earlier for the 50 m, with a maximum around 2.5 years. For the 255 m run, particles start crossing after 1 year and their number increases gradually with time, the maximum is therefore at the end of the experiment.

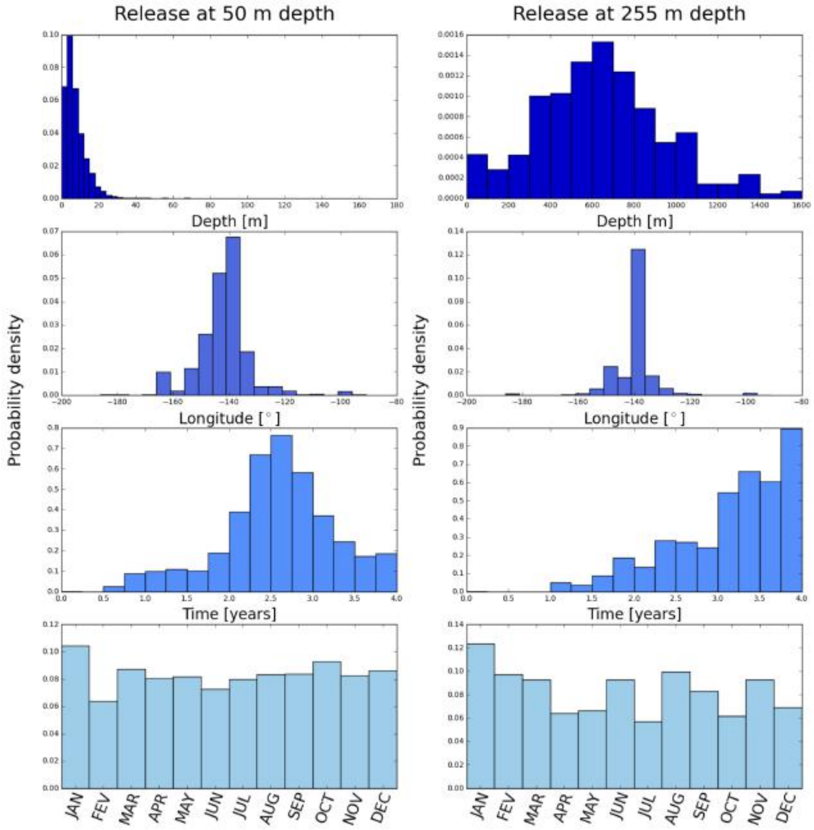

Figure 4 – Probability density function for the depth, longitude, time and month of crossing of the ACC front for the particles that leave the Ross Sea northward. Results for the 2 releases at 50 m depth (left) and 255 m depth (right) as above (Figure 3). All panels have different y-axis.

4 Discussion

Thanks to two releases of Lagrangian particles we show that a much larger percentage of particles cross the ACC front for the 50 m run (up to 12%) than for the 255 m run (<0.5% for the 255 m run). Particles cross only at the surface of the ocean for the 50 m run which suggests that the surface provides a more efficient pathway for particles to cross the southern ACC front. Particles also cross at a wider range of depths for the 255 m run as water subducts into the ACC. Whereas in the 50 m run, particles stay at the surface and therefore cross at a smaller range of depths.

The time histograms show that the particles of the 50 m run cross earlier in time than the 255 m run due to faster surface velocities. The histograms for the months of crossing do not enlight a specific month of crossing. There is therefore no seasonality for the crossing of the front. This is probably because in winter, there is also an input of ice melt as ice expands northward, south of the ACC (Abernathey et al., 2016).

At the surface, to obtain the total current, one must add the geostrophic flow to the Ekman transport (Fieux, 2017). But in some cases, one effect is stronger than the other. This is a question we asked in this study: are particles crossing the front because of a strong Ekman transport or mostly geostrophic flow? The ACC zonal winds are strong in the Southern Ocean which causes a northward Ekman transport at all longitudes. In this study, particles seem to be crossing the front around one specific latitude (140°W). This implies that Ekman transport is not the dominant mechanism driving particles across the southern front of the ACC.

At this longitude, the southern front intersects the Pacific-Antarctic Ridge as seen in Figure 2 (shown as the z = 3000 m contour). The front seems to be curving around one of the fracture zones of the ridge. This is the specific location of "leaking" for these two runs. This suggests that bathymetry plays a role in the exchange of water between the Ross Sea and the ACC. The importance of bathymetry for the circulation has been discussed by Thompson and Sallée (2012), who showed that zonal asymmetries in the topography enhances the crossing of particles over fronts. Our results similarly suggest that the presence of the ridge and the fracture zone are expected to affect the circulation. The flow seems to be following the high topography of the ridge until it reaches the fracture zone where the flow becomes more turbulent and allows water to leave the Ross Sea.

5 Conclusion

From the two runs carried out in this study we found that a larger number of particles initialized at the surface tend to cross the southern ACC front than those initialized at a deeper depth. Geostrophic flow seems to be the principal mechanism in place, as particles cross around one specific longitude (140°W). This is the location of the intersection of the southern front of the ACC with the Pacific-Antarctic ridge. We therefore conclude that bathymetry must play an important role in particles crossing from the Ross Sea into the ACC.

Although our preliminary results are promising, many discrepancies remain. First, the model SO12 run is for 5 years which does not capture decadal and longer timescale velocity variabilities of the system. Since a longer run is not available, an option would be to loop Octopus every 5 years.

Second, we need to conduct other releases of particles to have more robust statistics on the crossing of the ACC front by particles. These releases need to be done at other depths and locations of the Ross Sea.

For future investigation it would be interesting to look at temperature, salinity and depth changes along the trajectories of the particles to verify what happens as particles are advected around, which will also enable us to refine the threshold: instead of saying that particles are considered to have crossed the front after 3 time steps, we could use salinity as a diagnostic.

Lastly, to confirm what we have seen in Octopus' results, it would be relevant to look at salinity data along the southern front of the ACC to verify that salinity decreases around 140°W ~~which~~ would confirm that fresher Ross Sea water is mixing with ACC water at this location.

As noted in the introduction, the motivation of this work is to understand why the southeast Pacific has freshened and cooled over the past decade. This study is a first step towards answering this question: we have shown that exchanges of water occur between the Ross Sea and the ACC, but do they then exchange with the Pacific as well? In the next stage of this work, we would carry a similar analysis to identify the origins of the surface waters from the southeast Pacific.

Acknowlegments

This study was made possible thanks to Jinbo Wang who wrote Octopus. I thank Isabella Rosso, Bia Villas Boâs and Guilherme Pimenta Castelao for helping when it came to running Octopus and coding in Python. I also thank my advisors Matthew Mazloff, Ivana Cerovečki and Sarah Gille for the scientific advising and thoughtful guidance throughout the project. This work was supported by NSF grant OCE1658001.

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