Southern Ocean Gas Exchange Experiment: Setting the stage


1. Introduction

The Southern Ocean Gas Exchange Experiment (SO GasEx) is the third in a series of U.S.-led open ocean process studies aimed at improving the quantification of gas transfer velocities and air-sea CO₂ fluxes. Two deliberate ³He/SF₆ tracer releases into relatively stable water masses selected for large ΔpCO₂ took place in the southwest Atlantic sector of the Southern Ocean in austral fall of 2008. The tracer patches were sampled in a Lagrangian manner, using observations from discrete CTD/Rosette casts, continuous surface ocean and atmospheric monitoring, and autonomous drifting instruments to study the evolution of chemical and biological properties over the course of the experiment. CO₂ and DMS fluxes were directly measured in the marine air boundary layer with micrometeorological techniques, and physical, chemical, and biological processes controlling air-sea fluxes were quantified with measurements in the upper ocean and marine air. Average wind speeds of 9 m s⁻¹ to a maximum of 16 m s⁻¹ were encountered during the tracer patch observations, providing additional data to constrain wind speed/gas exchange parameterizations. In this paper, we set the stage for the experiment by detailing the hydrographic observations during the site surveys and tracer patch occupations that form the underpinning of observations presented in the SO GasEx special section. Particular consideration is given to the mixed layer depth as this is a critical variable for estimates of fluxes and biogeochemical transformations based on mixed layer budgets.


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isms controlling ocean mixed layer pCO$_2$ on short time and space scales; (4) elucidate the forcing functions controlling gas transfer; and (5) relate forcing functions to parameters that can be retrieved by remote sensing.

[4] SO GasEx took place on the National Oceanic and Atmospheric Administration (NOAA) Ship Ronald H. Brown from 29 February to 12 April 2008 (yeardays 60 to 103), with 31 scientists representing 22 academic institutions and government laboratories. The experiment was based around two deliberate tracer releases. The first tracer patch was created on March 8 (yearday 68) and studied for approximately 15 days before breaking off the experiment and transiting to Montevideo, Uruguay.

[5] The scientific work during SO GasEx concentrated on quantifying gas transfer velocities using deliberately injected tracers (He/SF$_6$), measuring CO$_2$ and DMS fluxes directly in the marine air boundary layer, and elucidating the physical, chemical, and biological processes controlling air-sea fluxes with measurements in the upper ocean and marine air. The oceanic studies used a Lagrangian approach to study the evolution of chemical and biological properties over the course of the experiment using shipboard and autonomous drifting instruments. The categories of different research projects performed during SO GasEx are listed in Table 1.

[6] The specific research objectives for SO GasEx were to answer the following questions:

[7] 1. What are the gas transfer velocities at high winds?
[8] 2. What is the effect of fetch on the gas transfer?
[9] 3. How do effects indirectly related to wind influence gas transfer?
[10] 4. How does variability in pCO$_2$ and in DMS levels affect the air-sea CO$_2$ and DMS fluxes?

[11] 5. What is the near surface horizontal and vertical variability in turbulence, pCO$_2$, and other relevant biochemical and physical parameters, and how are they related to one another?


[13] 7. Do fluxes estimated by different approaches agree, and if not why?

[14] In this special section, there are contributions focused on different objectives of SO GasEx. Ho et al. [2011], Edson et al. [2011] and Yang et al. [2011] address questions of gas transfer, and factors that affect CO$_2$ and DMS fluxes. Batch et al. [2011] and Moore et al. [2011] focus on understanding the contribution of various factors to carbon cycling in the Lagrangian tracer patches. Del Castillo and Miller [2011] examine the colored dissolved organic matter dynamics during SO GasEx. Dwivedi et al. [2011] use an ocean circulation model along with data assimilation of in situ and remote sensing data to simulate the ocean state during SO GasEx. V. P. Lance et al. (Primary productivity, new productivity and carbon export during two Southern Ocean Gas Exchange (SO GasEx) tracer experiments, unpublished manuscript, 2011), Lee et al. [2011], and R. C. Hamme et al. (Dissolved O$_2$/Ar and other methods reveal rapid changes in productivity during a Lagrangian experiment in the Southern Ocean, submitted to Journal of Geophysical Research, 2011) quantify productivity during SO GasEx.

### 2. Study Site

#### 2.1. Selection Criteria

[15] SO GasEx took place in the southwest Atlantic sector of the Southern Ocean (nominally at 50$^\circ$S, 40$^\circ$W), near South Georgia Island (Figure 1). The location was chosen, based on inspection of available satellite and in situ data (Figures 2 to 12) to fit the following criteria: (1) an air-water partial pressure gradient of CO$_2$, $\Delta$pCO$_2$, of at least 40 $\mu$atm to ensure a large enough signal-to-noise for direct covariance measurements of CO$_2$ fluxes; (2) area with a relatively stable water mass (i.e., relatively weak currents and low mesoscale eddy variability) and a mixed layer depth less

### Table 1. Categories of Research Projects on SO GasEx

<table>
<thead>
<tr>
<th>Research Projects</th>
<th>Method</th>
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<tbody>
<tr>
<td>Direct Flux Measurements (CO$_2$, ozone and DMS)</td>
<td>Air-sea CO$_2$ (NDIR), Ozone and DMS (APIMS) flux systems</td>
</tr>
<tr>
<td>Bulk Meteorology and Turbulent Fluxes (winds, momentum, water vapor, temp, IR, Solar radiation, etc.)</td>
<td>Sonic anemometer, thermometer, pyranometer, pyrgeometer, MicroSAS</td>
</tr>
<tr>
<td>Integrated Gas Transfer Velocities with Deliberate Tracers (SF$_6$ and $^3$He)</td>
<td>Continuous and discrete SF$_6$ systems (GCs) and He isotope mass spec</td>
</tr>
<tr>
<td>Surface and Subsurface variability (CO$_2$, nutrients, calcite, DMS, chlorophyll)</td>
<td>Shipboard underway systems, NDIR CO$_2$ systems, GC, EcoVSF, ICPAES, fluorometer, ACS, ISUS, SuperSoar/TOMASI</td>
</tr>
<tr>
<td>Autonomous Platforms</td>
<td>MAPCO$_2$, SAMI, ASIS, surface drifters, SOLO floats</td>
</tr>
<tr>
<td>Surface and near-surface ocean processes (wave spectra, white capping, currents)</td>
<td>Shipboard radar; microwave altimeter, video camera, ADCP</td>
</tr>
<tr>
<td>Water column hydrography, carbon and related tracers (DIC, pCO$_2$, TAlk, temp, sal, O$_3$, nutrients, DOC, CDOM, PIC, O$_2$/Ar, DMS, particles, TSM, Chl., POC)</td>
<td>SOMMA, NDIR, titration, CTD, Winkler, nutrient autoanalyzer, spectrophotometer, mass spec., GC, HPLC, Chl and CDOM fluorometers</td>
</tr>
<tr>
<td>Productivity rates</td>
<td>$^{14}$C and $^{15}$N incubations, O$_2$/Ar, O$_2$ isotopes, O$_2$ and pCO$_2$ sensors, photosynthesis-irradiance experiments</td>
</tr>
<tr>
<td>Ocean Optics</td>
<td>PAR sensor, FRRF, IOP cage, HTSRB, MIVSM</td>
</tr>
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</table>
than 50–70 m to allow the \(^3\)He/SF\(_6\) patch to be followed for up to 3 weeks; (3) relatively high wind speeds, long fetch, and large waves; and (4) close to the ports of call (Punta Arenas, Chile and Montevideo, Uruguay) to minimize transit time. While the Pacific sector of the Southern Ocean would have been better in terms of winds, fetch and swell, the \(\Delta p\text{CO}_2\) and logistical criteria ultimately led us to the Atlantic sector.

2.2. Site Survey

[16] After arriving at the study site, we conducted an underway survey for 48 h. The main in situ parameters examined during the site surveys were: waterside \(p\text{CO}_2\) to ensure a large enough \(\Delta p\text{CO}_2\), along with productivity measurements from O\(_2\)/Ar, and chlorophyll measurements from a fluorometer; expendable bathythermograph (XBT) temperature profiles (Figures 7 and 9) to determine the depth and variability of the mixed layer; and shipboard acoustic Doppler current profiler (ADCP) measurements of the currents to ensure a region with relatively low currents and velocity shears. In addition to the in situ measurements, we also tried to ensure that we did not inject the tracer on the edge of an eddy by examining tracks of drifters deployed in the SO GasEx study site, remote sensing images of ocean color, sea surface temperature, and sea surface height.

2.3. Surface Underway Surveys

[17] Underway \(p\text{CO}_2\) was measured using a shower type equilibrator coupled to an IR analyzer with procedures and data reduction as described by Pierrot et al. [2009]. Net community production (NCP) was estimated from underway measurements of \(O_2/Ar\) made with an equilibrator inlet mass spectrometer [Cassar et al., 2009], using a mass balance approach and partitioning between air-sea gas exchange and biological \(O_2\) production [Reuer et al., 2007]. Underway chlorophyll fluorescence \(F_{chl}\) measured with a Turner Designs Cyclops7 sensor with wiper, attached to a C6 instrument) and incident photosynthetically active radiation (PAR) (Lance et al., unpublished manuscript, 2011) were
Figure 3. Pre-injection underway surface survey for Patch 1 showing (a) ocean minus atmosphere pCO₂, \( \Delta pCO₂ \), (b) Net Community Production (NCP) from \( O_2/Ar \) measurements, (c) chlorophyll-\( \alpha \) concentration from fluorometry corrected for daytime quenching, (d) salinity, (e) temperature, and (f) mixed layer kinetic energy. Black circle shows injection location. The black line denotes the location of the Lamont Pumping SeaSoar survey (Figures 10–12). Color scales for NCP and chlorophyll have been truncated to better show variability at lower values.

Figure 4. Pre-injection underway surface survey for Patch 2 showing (a) ocean minus atmosphere pCO₂, \( \Delta pCO₂ \), (b) NCP from \( O_2/Ar \) measurements, (c) chlorophyll-\( \alpha \) concentration from fluorometry corrected for daytime quenching, (d) salinity, (e) temperature, and (f) mixed layer kinetic energy. Black circle shows injection location. Color scales for Figures 4a–5f are the same as Figure 3.
collected continuously (1–10 s intervals for F$_{chl}$). Incident PAR data were used to adjust daytime F$_{chl}$ (suppressed by nonphotochemical quenching) to match nighttime average values (dark F$_{chl}$) each day, and periodic measurements of chlorophyll-a concentration (Lance et al., unpublished manuscript, 2011) from the ship’s seawater system were used to calibrate dark F$_{chl}$ in units of mg chl-a m$^{-3}$. Temperature and salinity were measured with a Sea-Bird SBE 21 at the ship’s intake, and by a Sea-Bird SBE 45 as part of other underway systems in the main lab and calibrated against the CTD/Rosette surface temperatures and salinities. Salinities in this paper are expressed on the practical salinity scale (PSS-78).

[18] Mixed layer depths were calculated from XBT deployments during the underway surveys (Figures 6 to 9). The mixed layer was defined as the depth at which temperature was 0.1°C less than the mean temperature between 10 and 20 m. The 10 to 20 m interval was chosen because temperatures shallower than 10 m were not accurate due to the time needed for equilibration. The mean mixed layer for survey 1 was 54.2 m (range 47.4 to 60.7 m), while for survey 2 the mean was 55.0 m (range 41.4 to 68.7 m). Using the 0.3°C criterion as applied to the drifter data (see below) would deepen the mixed layers by 5.2 m on average.

[19] Water velocities were obtained using a hull-mounted ADCP (75 kHz RDI Ocean Surveyor), acquired with University of Hawaii’s Data Acquisition System (UHDAS) and processed and edited using the Common Ocean Data Access System (CODAS) software package. The ADCP was operated with interleaving broadband and narrowband pings. We focus only on the broadband data since it provides higher resolution near the surface and we are interested in the

**Figure 5.** (a and c) NCP versus ΔpCO$_2$ and (b and d) NCP versus chlorophyll for Patches 1 and 2. Note that chlorophyll scale in Figure 5d is expanded relative to that in Figure 5b.

**Figure 6.** Satellite (AMSR–E) SST image for 5 and 6 March 2008 (yardays 65 and 66) with the Patch 1 survey (black line), XBT locations (solid circles, labeled 1–4) and the patch injection site (red circle).
mixed layer velocities. The ADCP data were used to predict the advection of the tracers in the mixed layer as an aid in tracking and surveying the tracer patch. Since the ADCP velocity is at fixed depths, the average velocity between 25 m (the first bin of the broadband data) and 49 m was operationally defined as the mixed layer velocity, with kinetic energy (KE) calculated as 0.5 times the square of the depth-average mixed layer velocity.

Water masses detected by surface spatial surveys surrounding the injection sites had wide ranging properties with \( \Delta pCO_2 \) of \(-100\) to \(-20\) µatm (aqueous < atmosphere), salinities of 33.7 to 33.9, and temperatures of 3.5 to 6.5°C (Figures 3 and 4). The area around Patch 1 showed much higher productivity and chlorophyll than around Patch 2 (compare Figure 3 with Figure 4). A particularly productive water mass was present at the southern end of the Patch 1 site survey, but was not chosen for injection due to a sub-surface eddy with higher velocity shear in that area. Additionally, areas with high kinetic energy (KE) of the mixed layer or areas where KE changed rapidly, indicative of regions with high horizontal velocity shear, were avoided (Figures 3f and 4f).

Although we observed wide-ranging water mass properties in the larger site surveys, the water masses where the tracer was actually injected were much more homogeneous (Table 2). However, there was a water mass with much higher NCP and chlorophyll directly to the southwest of Patch 2 (Figure 4b and more clearly by Figure 8 of Hamme et al. (submitted manuscript, 2011)).

Several distinct relationships can be seen between \( \Delta pCO_2 \) and NCP during the Patch 1 survey, but essentially no relationship was present for the Patch 2 survey (Figure 5). Because NCP estimates are based on mixed layer O\(_2\)/Ar measurements, this measure of productivity integrates over the residence time of O\(_2\) in the mixed layer with respect to air-sea gas exchange, defined as the ratio of mixed layer depth (h) to gas transfer velocity (k), of about 20 days under these conditions, while the residence time of CO\(_2\) is ten times longer. A weak relationship between \( \Delta pCO_2 \) and NCP indicates that the \( \Delta pCO_2 \) signal was mainly caused by a previous episode of productivity that was largely finished by the time of the survey. Except for the highly productive region at the southernmost point in the Patch 1 survey, there was no strong relationship between NCP and chlorophyll concentration (Figure 5). Hamme et al. (submitted manuscript, 2011) show that productivity rates within the tracer patches were changing rapidly. If this was true of the wider region, we might not expect a relationship between biomass represented by chlorophyll and productivity rates integrated over the previous 2 weeks.

2.4. OSU Towed Vehicle Survey

As part of the pre-injection site survey for Patch 1, we resolved the 2-dimensional structure (vertical and zonal) of the study site with the Lamont Pumping SeaSoar [Hales and Takahashi, 2002]. A single ~60 km E-W section ~30 km SE of the injection site was completed before a vehicle failure ended the SeaSoar operations for the remainder of the cruise. Nonetheless, the section provided useful information regarding the horizontal and vertical structure of Patch 1. Conditions were fairly uniform, with

![Figure 7](image.png)

**Figure 7.** XBT profiles 1–4 to correspond with the station locations in Figure 6.

![Figure 8](image2.png)

**Figure 8.** Satellite (AMSR-E) SST image for 19 and 20 March 2008 (yeardays 79 and 80) with the Patch 2 survey (black line), XBT locations (solid circles, labeled 5 and 6) and the patch injection site (red line).
surface T, S, (Figure 10) O_2, and pCO_2 (Figure 11) varying by less than 0.5°C, 0.05, 6 μmol kg^{-1} and 4 μatm, respectively, coincident with low and weakly variable beam attenuation, F_{sub} and optical backscatter (Figure 12).

Despite these small-magnitude signals, the combination of T, S, O_2, pCO_2, and bio-optical distributions identified three distinct hydrographic conditions for the surface waters of this section. The first is a large region of the warmest (T > 6°C), freshest (S < 33.70) water seen at the surface, clearly expressed centered at a longitude of 37.8°W in waters shallower than 40 m. This water carries moderately elevated signals of optical backscatter and beam attenuation, and locally depressed pCO_2. O_2 appears to be at a local minimum, but is still supersaturated with respect to the atmosphere by about 2.2%. The second is a pool of water with essentially the same T as the first, but moderately high salinity (S ∼ 33.73) situated at about 38.2°W. This water has elevated bio-optical signals and O_2 concentrations, the latter corresponding to a supersaturation of ∼2.6%. Finally, there is a water mass with moderate T (5.5–6.0°C) and very high S (>33.75) at the eastern extreme of the line (37.6–37.5°W) that carries strong signals of biomass and O_2 enrichment and pCO_2 depletion.

Figure 9. XBT profiles 5 and 6 to correspond with the station locations in Figure 8.

Figure 10. Physical hydrography of the pre-injection pumping SeaSoar survey. (top) Temperature (color map, °C) with density (σ_t from 26.5–26.7, white contours, kg m^{-3}) overlain. (middle) Salinity (color map) with vehicle position (black symbols) overlain. (bottom) Brunt-Väisälä frequency squared (N^2, s^{-2}), with the top of the density transition zone (based on the shallowest position of the N^2 = 3 × 10^{-3} s^{-2} contour, white line) overlain.

Figure 11. Dissolved gas distributions during the pre-injection pumping SeaSoar survey. (top) O_2 concentrations (μmol kg^{-1}), measured using a Sea-Bird SBE-43 sensor aboard the SeaSoar vehicle; sensor was factory calibrated, and calibrated sensor output was corrected to match the T-O_2 relationships determined on the cruise using high-accuracy Winkler titrations of surface water samples drawn from the ship’s surface intake line. (bottom) The pCO_2 measured using a membrane contactor interfaced with a LI-COR infrared analyzer.

Figure 12. Bio-optical characteristics of the pre-injection pumping SeaSoar survey. (top) Relative beam attenuation (C_p, m^{-1}), measured using a Wet Labs C-Star transmissometer aboard the pumping SeaSoar. (middle) Chlorophyll fluorometer voltage (uncalibrated), measured using a Wet Labs Wet-Star fluorometer plumbed in the shipboard end of the SeaSoar sample stream; positions of samples indicated by the black symbols. (bottom) Optical backscatter voltage (uncalibrated), measured using a Wet Labs Eco-BB sensor aboard the SeaSoar.
Beneath all of these waters lies a pycnocline, or density transition zone, defined by a band of elevated Brunt-Väisälä frequency squared ($N^2$) bound above by the $\sim 26.6 \times 10^{-6} s^{-2}$ and the 5.5°C density and temperature horizons, respectively. The stratification maximum represents a barrier to mixing, and the shallow limits of the density transition zone can be thought of as analogous to the bottom of the mixed, or mixable, layer. The depths of this feature (white contour in Figure 10 (bottom)) are similar to mixed layer depths determined for Patch 1 (discussed below) in the period prior to the South Georgia excursion. The depth and intensity of this stratification maximum vary across the section from 40 to 60 m and $0.5 \times 10^{-4}$ to $2 \times 10^{-4} s^{-2}$. There are local minima in the depths of this feature beneath the expressions of the first two surface water masses, but beneath the third there is little signal of stratification within the depth range the SeaSoar was able to sample.

Examination of the surface T, S, and $pCO_2$ distributions in the patch surveys immediately following the injection suggest that the patch was centered in a water mass most similar to the second water mass identified above, with a $\sim 40$ m mixed layer situated above a reasonably strongly stratified density transition zone. The lateral proximity of water masses with differing hydrographic properties, including variable mixed layer depths and temporal variations in mixed layer, however, advises caution in the interpretation of the tracer patch as a simple one-dimensional time evolution.

### Table 2. Mean Surface Properties From Pre-injection Underway Surveys Within 0.05° Latitude/Longitude of Injection Site

<table>
<thead>
<tr>
<th></th>
<th>Patch 1</th>
<th>Patch 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta pCO_2$ ($\mu$atm)</td>
<td>$-66.8 \pm 5.1$</td>
<td>$-77.5 \pm 3.5$</td>
</tr>
<tr>
<td>Net Community Production (nmol C m$^{-2}$ d$^{-1}$)</td>
<td>$21.3 \pm 2.6$</td>
<td>$5.0 \pm 3.2$</td>
</tr>
<tr>
<td>Chlorophyll a (mg m$^{-3}$)</td>
<td>$1.06 \pm 0.13$</td>
<td>no measurements</td>
</tr>
<tr>
<td>Salinity</td>
<td>$33.757 \pm 0.004$</td>
<td>$33.754 \pm 0.001$</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>$5.52 \pm 0.07$</td>
<td>$5.05 \pm 0.07$</td>
</tr>
</tbody>
</table>

### 3. Physical Environment

#### 3.1. Winds

Wind speed and direction were measured by 3 sonic anemometer packages deployed from the forward mast at a height of about 18 m above the mean sea surface by groups from University of Connecticut, NOAA’s Earth System Research Laboratory (ERSL), and Lamont-Doherty Earth Observatory (LDEO). Each of the sonic anemometer packages included sensors capable of motion correcting the sonic velocities using the approach described by Edson et al. [1998]. The group also deployed a suite of sensors to measure air temperature, humidity, pressure, and $CO_2$, along with 2 high-resolution cameras, a Wave and Surface Current Monitoring System (WaMoS) 2-D wave radar, and a microwave altimeter to quantify the wavefield and breaking events as described by Edson et al. [2011].

A time series of wind speed and direction was constructed using all 3 sonic anemometer systems. The relative wind direction was used to select the sonic(s) expected to be least impacted by flow distortion; e.g., all 3 sonics were averaged when the relative wind was bow-on but only the port sonic was used when the relative wind was from the port side. An empirical correction for flow distortion based on the orientation

![Figure 13](image-url)
on previous flow distortion studies [Dupuis et al., 2003; Fairall et al., 2003] was applied to the measured winds. This approach increased the usable relative wind direction to approximately ±130° from the bow. Relative wind directions beyond this window were removed and the remaining data interpolated to generate the time series shown in Figure 13. This procedure limited the number of gaps in excess of one hour to 24 during the 37-day cruise with only three gaps longer than two hours.

[29] The time series of the wind speed and direction is characteristic of the wind field found in the circumpolar gyre at our latitude of 51°S, with high-frequency variability superimposed on more slowly varying zonal flow. A series of midlatitude synoptic systems generally propagated to the north of our study region during the experiment. The observed high frequency transients are thought to be a result of interaction between these synoptic scale systems and the low frequency planetary scale waves associated with the circumpolar gyre [Cuff and Cai, 1995; Karoly, 1990]. As a result, the wind direction generally oscillated between SSW and NNW over 2–4 day cycles.

[30] A combination of the barotropic component of the temperature field associated with the meandering gyre and warm and cold air advection associated with the northwesterly and southwesterly wind directions, respectively, drove air temperature variability of approximately 5°C (Figure 13). The variable air temperature and relatively stable sea surface temperature caused significant variability in atmospheric stability. Conditions of static stability (i.e., $T_{air} > T_{sea}$) were generally encountered during the first half of the experiment and unstable conditions during the second half.

[31] An example of the synoptic systems to our north and the meandering atmospheric gyre over our study site is shown in Figure 14. Figure 14 shows the position of our study area relative to the daily averaged sea surface pressure and air temperature fields on 22 March 2008 (yearday 82) and 23 March 2008 (yearday 83). The wind direction shifted from south to northwest over this period and the temperature increased by approximately 3°C. The resulting atmospheric stratification switched from unstable to slightly stable conditions during this period. This variability was typical of the conditions encountered during the experiment.

[32] A primary objective of the SO GasEx is to determine the gas transfer velocities at high winds between 10 to 20 m s$^{-1}$. The number distribution of 10 min averaged wind speeds encountered over the patches and for the entire experiment are shown in Figure 15, with the mean and standard deviations
used to determine the Weibull distributions. These distributions have a shape parameter of 3.6 and scaling parameters of 10.1 for just the winds encountered during the tracer patches and 10.7 for the entire cruise. The large value of the shape parameter is indicative of the peaked distribution shown in Figure 15 due to the fairly steady wind speeds encountered during the experiment.

The cumulative percentage of 10 min averaged wind speeds indicate that wind speeds in excess of 10 and 13 m s\(^{-1}\) were encountered over the study region for approximately 38% and 9% of the time, respectively. However, winds speeds in excess of 15 m s\(^{-1}\) were only encountered 1% of the time. Winds speeds in excess of 20 m s\(^{-1}\) were encountered on the transect back to Uruguay and several of the papers in this special section take advantage of these data. The average wind speeds computed for the two tracer patches were very similar, but with significantly more variability in the wind speed measured during the second, longer duration release. The average wind speeds were 9.10 ± 1.71 and 9.11 ± 3.25 m s\(^{-1}\) over the first and second tracer patches, respectively. The maximum wind speed of 16.2 m s\(^{-1}\) over the study region was observed on March 24 (yearday 84) after the second tracer release.

### 3.2. SF\(_6\) Tracer Patch

The SF\(_6\) tracer patch was monitored using an automated SF\(_6\) analysis system that analyzed samples at ca. 1-min intervals [Ho et al., 2002] to quantify the lateral dispersion at the surface. The main aims of the surface SF\(_6\) mapping were to provide a Lagrangian framework for the biogeochemical studies, and to constrain the patch boundaries so that the patch center could be identified.

The continuous SF\(_6\) analysis system consists of a gas extraction unit, which strips SF\(_6\) continuously from the ship’s uncontaminated seawater line, and the analytical unit, made up of a gas chromatograph (GC) equipped with an electron capture detector (ECD), which measures the SF\(_6\). Instrument control and data acquisition are handled by a combination of hardware and software (LabVIEW) running on a personal computer. The system has a detection limit of \(1 \times 10^{-14} \text{ mol L}^{-1}\). At a typical ship speed of 5–10 knots during SO GasEx, a spatial resolution of every 0.15–0.3 km was usually achieved. Concentration data were incorporated in near real-time into a plot of the areal distribution of the patch, by integrating the SF\(_6\) data with the ship’s GPS position. This enabled rapid alteration of ship speed and direction in response to variation in the SF\(_6\) signal and ensures resolution of patch boundaries for distinguishing stations inside and outside the patch. The real-time SF\(_6\) signal was used to determine the center of the patch for discrete \(^3\)He and SF\(_6\) sampling.

After injection, underway SF\(_6\) surveys show that the tracer patches spread to a width of approximately 0.1 degree latitude/longitude (≈11 × 7 km) and were advected to the southeast (Figures 16 and 17).

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**Figure 15.** The number distribution of 10-min average wind speed observations during the experiment. The distribution shown in blue presents the data collected over the tracer patches, while the data distribution shown in red includes the period near South Georgia Island and the transect to Uruguay. Weibull distributions with a shape parameter 3.6 and scaling parameters of 10.1 (bottom curve) and 10.7 (top curve) were determined from fits to the mean and standard deviation of the wind speed measured over the tracer patch and during the entire cruise, respectively.

**Figure 16.** Surface distributions of SF\(_6\) (fmol L\(^{-1}\)) during Patch 1. Colors show optimum interpolation of underway surface SF\(_6\) concentration measurements on logarithmic scale, derived using the GLOBEC Kriging software (EasyKrig3.0) for MATLAB. Green circles show locations of CTD/Rosette casts. Smaller gray dots show cruise track. The patch advected from the northwest to the southeast over the time period of observation from yearday 70 to 74.
3.3. ADCP Velocities

[37] For Patch 1, the mean velocity was toward the southeast with a slight increase over the period of observation (Figure 18). There were significant higher frequency fluctuations due to tidal and inertial motions that could not be separately resolved (Figure 19) with approximately 60% more energy in the meridional component. (The peak in the eastward velocity at $\sim 7 \times 10^{-1}$ cycles per hour (90 min) is an artifact due to the well-known Schuler oscillation of the gyroscope while transiting in a north or south direction.)

[38] For Patch 2, the mean velocity was initially to the southeast similar to Patch 1. However, around yearday 88, the patch stalled for a day or so before starting to move to the southwest (Figure 18). High frequency velocities, including the inertial and tidal motions, were even stronger during Patch 2 compared to Patch 1 (Figure 20), with more energy contained in the zonal component. The high-frequency velocity fluctuations were strongest at the start of Patch 2 observations and decreased over the first 6 days. The storm that forced the end of the Patch 1 survey likely generated the large inertial oscillations in the mixed layer observed at the beginning of Patch 2. Inertial waves propagate out of the mixed layer over several days [D’Asaro, 1985; D’Asaro et al., 1995]. The observed decrease of the magnitude of the inertial oscillations during Patch 2 is likely due to this process.

3.4. Mixed Layer Depth

[39] A key parameter for constraining gas transfer velocities based on mass balances is the ocean surface mixed layer depth (MLD), as it determines the reservoir in contact with the air-sea interface. Conceptually, it can be defined as the depth at which chemical and physical properties are homogeneous, which implies that mixing is active throughout the layer. However, homogeneity of properties is a function of fluxes and transformations in the mixed layer such that its extent can differ for different properties and from the operational definition. For gases, it is assumed that all water in this region is in contact with the atmosphere on time scales that are significantly shorter than the residence time of the gases. The mixed layer is bounded at depth by a region with a sharp gradient in these properties. However, homogenous properties do not guarantee the whole layer is mixing. Additionally, at the base of the mixed layer, there is some exchange between the mixed layer and the pycnocline, through the density transition zone [Johnston and Rudnick, 2009]. Thus, the definition of the MLD depends on the problem that is being addressed. In addition, the depth will vary on time scales from hourly to seasonal due to heating and cooling cycles, wind, and internal wave activity. Below, we operationally define the depth of the mixed layer in several different ways depending on the issue studied.

Figure 17. Surface distributions of SF$_6$ (fmol L$^{-1}$) during Patch 2. Plotted same as Figure 16.
For $^3$He/SF$_6$ dual tracer experiments in the open ocean, the total mass decrease of $^3$He and SF$_6$ in the upper water column must be determined. Some studies, because they were limited by the number of $^3$He/SF$_6$ samples taken, used a density or temperature-based definition of the MLD from CTD profiles [e.g., Wanninkhof et al., 2004]. Other studies with a sufficient number of $^3$He and SF$_6$ samples have used a tracer based definition in which the mixed layer depth is where the SF$_6$ drops to 50% of its concentration in the top 20 m or so [e.g., Ho et al., 2006; Nightingale et al., 2000]. Stevens et al. [2011] proposed a buoyancy frequency-based definition of MLD that fit the tracer MLD from a previous $^3$He/SF$_6$ dual tracer experiment in the Southern Ocean, but was not able to reproduce the tracer

![Figure 18](image)

**Figure 18.** Average mixed layer (a) eastward and (b) northward velocities during Patch 1 and Patch 2 from the 5-min averaged hull-mounted ADCP data (black line). Low-passed (fourth-order Butterworth filter with 36 h cutoff) velocities are shown in red.

![Figure 19](image)

**Figure 19.** Spectra of the average mixed layer velocities for Patch 1.
MLD during SO GasEx, suggesting that this empirical MLD definition is not universal.

When determining the depth over which tracers are ventilating with the atmosphere, a tracer-based MLD is most appropriate. However, even in SO GasEx where a large number of discrete $^3$He and SF$_6$ samples were taken, the vertical sample resolution was 5–10 m, so this identification of the MLD is resolution limited. Here, we provide several estimates of MLD related to the scientific questions addressed based on CTD-density, a one-dimensional numerical model, SF$_6$ concentration, and temperature measurements from the MAPCO$_2$ drifter (Table 3).

3.5. CTD Based

We defined the CTD-based MLD as the shallowest depth with a density at least 0.01 kg m$^{-3}$ greater than the density at 5 dbar. This 5 dbar depth is the shallowest depth that all CTD casts sampled. Only the 1 dbar bin-averaged downcasts of the CTD were examined, as the position of the temperature and conductivity sensors at the bottom of the CTD/Rosette package and turbulence generated by the rosette package may bias the upcasts. As will be discussed below, the presence of internal wave motion and other variability does not warrant determining the mixed layer depth at better than 1 m resolution.

Two CTD casts were made each day: near local noon and local midnight. While downcasts were used to calculate the CTD-based MLD, the tracer-based MLD was based on water collected by bottles fired during the upcast. Comparing the depth of bottle samples with the depth of the same density horizons on the downcast between the mixed layer base and 225 m revealed a mean depth difference of 0.6 ± 4.8 m. Over the time to make a CTD cast (about an hour), the root mean square vertical displacement of isopycnals (and the base of the mixed layer) was on the order of 5 m. The coarse temporal sampling by the CTD and aliasing by internal wave displacement make determining the high-resolution evolution of the MLD from CTD and tracer profiles challenging.

3.6. One-Dimensional Model Based

We used the one-dimensional (1-D) Generalized Ocean Turbulence Model (GOTM) to examine the evolution of the mixed layer. GOTM solves the equations for the vertical transport of horizontal momentum, heat, and salt with vertical turbulent fluxes parameterized using a wide range of turbulence closure schemes [Burchard et al., 2005]. For SO GasEx, the fluxes at the ocean surface were estimated from the meteorological measurements made aboard the ship (see above). Because SO GasEx focused on the surface mixed layer and for computational efficiency, the lower boundary of the model was placed at 500 m, at which vertical fluxes of momentum, heat, and salt were set to zero. The model was run with 500 vertical levels with grid resolution of 0.55 m at the ocean surface and 1.3 m at the 500 m base of the model grid. Vertical profiles of hydrography and velocity from CTD casts and the hull-mounted ADCP at approximately the times of tracer injection were used as model initial conditions. Additionally, a separate series of GOTM runs included “nudging” of the model velocities, T, and S to the observations on a 1-day timescale.

The observed velocity profiles, low-pass filtered to remove tides and inertial oscillations, were used to estimate time-dependent horizontal pressure gradients that were imposed as additional model forcing. This forced the 1-D model to produce more realistic vertical shears, which themselves influenced the turbulent mixing. The barotropic and baroclinic pressure gradients, the latter arising from horizontal density gradients assumed here to vary linearly with depth, were estimated from the low-passed ADCP vertical profiles using the assumption of geostrophy at subinertial timescales. For each ADCP ensemble, the pro-

Figure 20. Spectra of the average mixed layer velocities for Patch 2.
files of eastward and northward velocities were fit to a quadratic function of depth.

[47] The results presented here were obtained using the k-ε turbulence closure [Rodó, 1987] to parameterize the turbulent vertical momentum, heat, and salt fluxes in the model. Injection of turbulent kinetic energy at the ocean surface due to wave breaking was specified using the parameterization of Burchard [2001]. Model results were not sensitive to closure scheme; using the non-local K profile parameterization (KPP) for turbulence within the surface mixed layer yielded very similar results.

[48] In general, for both patches, the 1-D GOTM prediction of the MLD agrees with the CTD observations (Figure 21), particularly given that the CTD observations have internal wave displacements on the order of 5 m that are not present in the model. In the model simulations, there are instances where surfaces fluxes (mainly rainfall) produce a shallow mixed layer that is subsequently mixed into the older mixed layer. As expected, the model runs with nudging toward observed mixed layer properties reproduced the observed MLD slightly better.

[49] The evolution of the modeled T, S, and density of the mixed layer without nudging diverges quickly from the observations, especially for Patch 2 (Figure 21). This divergence could be due to incorrect surface forcing but more likely is a result of horizontal advection/diffusion. If the CTD casts really represent the Lagrangian evolution of the mixed layer, then colder, saltier, denser waters must have been mixed into the patch. This water must have come from the south. The CTD casts were made in what was believed to be the center of the tracer patch. However, if the tracer preferentially mixed horizontally in one direction more than the other, a similar result would be seen. In this case, the center of the patch would have moved into colder, saltier water (i.e., to the south).

3.7. Tracer Based

[50] The mixed layer depth used to determine the gas transfer velocity with the deliberate tracer SF6 and 3He
should represent the average depth of water that ventilates with the atmosphere on a daily basis for the entire patch [Ho et al., 2011]. This depth was determined from the depth profiles of SF$_6$ at every sampling station. The tracers were injected near the surface and rapidly mixed throughout the mixed layer. Penetration downward below the mixed layer occurs by slow diffusive processes on timescales significantly longer than air-sea gas transfer. Since sampling with the Niskin bottles was at coarser resolution than the CTD trace, the SF$_6$ gradient at the bottom of the mixed layer was interpolated based on the density gradient. The average mixed layer depths for gas exchange, for every cast where SF$_6$ measurements were taken, were determined from the level where SF$_6$ reached 50% of the averaged concentration in the top 20 m.

[51] In general the tracer based mixed layer depth is greater than CTD-based estimate, because the 50% surface SF$_6$ concentration criteria is deeper than the start of the pycnocline (Figure 22). In other words, the ventilated mixed layer is slightly deeper than the mixed layer defined by stability. This is verified by the combined $^3$He and SF$_6$ profiles, with the mixed layer defined by the region where the ratios of the two tracers are invariant (Figure 23).

3.8. Drifter Based

[52] A drifting autonomous buoy, the MAPCO$_2$ designed by NOAA/PMEL, was used to make high frequency physical and biogeochemical measurements in the tracer patch during the experiment. It was drogued to help it stay with the water mass that contained the tracers throughout the experiment. Below the buoy was a 118 m string of instruments, including 15 HOBO Pro v2 water temperature sensors positioned no more than 10 m apart, that sampled every 30 min with an accuracy of 0.2°C. MLD was calculated as the depth at which the depth-interpolated temperature was 0.3°C colder than the temperature at 5 dbar. To remove 12-h period internal waves present in all of the data with amplitudes of about ±5 m, the data was 18 h low-pass filtered. Following a major rain event that began on 26 March (yeardays 86–89), a low salinity layer at the surface prevented accurate MLD determinations from the drifter temperature data. A detailed analysis of the MAPCO$_2$ data is given by Moore et al. [2011].

[53] The MAPCO$_2$ was deployed on 8 March 2008 (yearday 68), shortly after Patch 1 was created, recovered on 12 March (yearday 72) and redeployed in Patch 1 on 13 March, and finally recovered again on 18 March (yearday 78) after the ship returned from South Georgia Island. The presence of internal waves, documented in the drifter data, complicated estimation of the MLD. In particular, there was a tendency during the first few days of Patch 1 for the CTD casts to occur during the deepest excursion of the internal waves, such that the CTD and tracer based MLD during these casts were likely deeper than the average MLD during this period (Figure 22).

[54] The drifter based MLD increased from 32 m to a maximum of 54 m on 17 March (yearday 77), the day before the ship returned and the MAPCO$_2$ buoy was recovered. Both the MAPCO$_2$ and CTD data show that the average mixed layer density decreased slightly over this same period. Neither the CTD nor tracer based estimates show the consistent deepening of the MLD seen in the MAPCO$_2$ estimates (Figure 22 and Table 3), which may be partially attributed to the ±5 m excursions of the internal tide. MAPCO$_2$ recorded a significant warming event that shoaled the MLD to 24 m on 18 March (yearday 78), which was corroborated by the CTD cast performed when the ship returned to the MAPCO$_2$ location (Figure 22 and Table 3). Traces of the original patch were found near the drifter when it was recovered, but the MLD inferred from the SF$_6$ measurements was substantially deeper than the CTD or drifter MLDs. This is reasonable, because a thermal shoaling of the mixed layer due to surface heat fluxes would not be manifested in the tracer concentrations.

[55] The MAPCO$_2$ was deployed into the second patch on 22 March (yearday 82). The MLD increased from 48 to 58 m by 26 March (yearday 86) when there was a rainstorm. The rainstorm did not alter the temperature structure enough to affect the drifter based mixed layer depth estimates, but the changes in salinity recorded by the CTD casts indicated that the rain caused the mixed layer to shoal to <15 m. This shoaling is not reflected in the tracer based estimates, again because a density-induced stratification event will leave significant tracer concentrations below the mixed layer (Figure 22 and Table 3).
Around the time of the rainstorm, the tracer patch sheared in two. The largest fraction of the tracer patch essentially stopped moving. However, MAPCO2 and some portion of the tracer patch continued their southeasterly advection until the drifter was recovered 31 March (yearday 91) approximately 50 km from the primary patch. The CTD, GOTM, and tracer based MLD estimates apply to the primary tracer patch, while the drifter documented MLD changes in the portion that moved to the southeast. Despite this separation, the ship and drifter based MLD estimates were similar within the error imposed by excursions of the internal tide (Figure 22).

3.9. Vertical Diffusivity From 1-D Model

As might be inferred from the variability in MLD (Figure 21), vertical mixing within the upper ocean likely underwent large fluctuations during SO GasEx. Maximum vertical turbulent diffusivity for heat within the mixed layer in the 1-D GOTM runs was typically in the range $10^{-2}$–$10^{-1}$ m$^2$ s$^{-1}$, occurring within a broad region in the interior of the mixed layer (Figure 24a). The maximum diffusivity is, however, 1–2 orders of magnitude lower during periods when the MLD decreases as a result of weak winds combined with surface heating (e.g., prior to yearday 72.5 during Patch 1) or precipitation (e.g., yeardays 86–87 during Patch 2). A timescale for vertical homogenization of the mixed layer can be estimated as: $\tau = \frac{H_{ML}}{K_{max}}$, where $H_{ML}$ is the mixed layer thickness and $K_{max}$ is the maximum diffusivity within the mixed layer. A typical mixing time is on the order of 24 h, but can be as short as 4–5 h during periods of rapid deepening of the mixed layer and an order of magnitude longer during brief periods of weak mixing (Figure 24b).

Diffusivity within the mixed layer decreases toward the surface as eddy length scales are reduced near the boundary. Diffusivity strongly decreases near the bottom of the mixed layer; however, the diffusivity at the base of the operationally defined density based mixed layer varies over

![Figure 22](image-url) Mixed layer depth based on $\rho(z)-\rho(5$ dbar) $\leq 0.01$ kg m$^{-3}$ (red circles), $0.5 \times [SF_6] = [SF_6]_{20m}$ (blue squares) and $T(5$ dbar)$-T(z) \geq 0.3^\circ C$ from MAPCO2 drifter (black line = 30-min frequency, cyan line = 18-h filter applied).

![Figure 23](image-url) Depth profiles of temperature, $SF_6$ and $^3$He/$SF_6$ normalized to their respective mixed layer values for Station 27 (51.32°S, 37.563°W; yearday 86.08). As shown here and Table 1, the CTD-density based mixed layer (56 m) depth is shallower than that based on change in $SF_6$ concentration (64 m).
at least 5 orders of magnitude (Figure 24c). This emphasizes the importance of distinguishing between the actively mixing layer and the well mixed layer, the latter resulting from the time history of mixing [Brainerd and Gregg, 1995]. High vertical diffusivity at the mixed layer base is associated with deepening of the mixed layer, most clearly seen after yearday 72.5 in the Patch 1 simulation and to a lesser extent during yeardays 86.6–89.9 during Patch 2. During the latter period, there are intervals when mixing within the mixed layer and at its base weakened, likely due to strong surface heating during daytime hours. Mixed layer shoaling generally occurs concurrently with periods of weaker mixing at the mixed layer base. However, not all times of weak mixing are accompanied by shoaling of the mixed layer, because mixed layer shoaling requires a mechanism of active re-stratification, such as surface heating or precipitation.

4. Conclusions

[59] We described the site selected for the Southern Ocean (SO) Gas Exchange Experiment (GasEx) and the general mixed layer dynamics as background to study questions related to gas exchange and CO₂ fluxes in the Southern Ocean. Using ship, buoy, and remote-sensing based methods to study changes in Lagrangian tracer patches, the contributions in this volume address research questions ranging from improved gas exchange parameterizations to better understanding of Southern Ocean biological processes.
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References


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