Supporting Information for "An advective mechanism for Deep Chlorophyll Maxima formation in southern Drake Passage"

Zachary K Erickson[1], Andrew F Thompson[1], Nicolas Cassar[2], Janet Sprintall[3], Matthew R Mazloff[3]

Corresponding author: Zachary K Erickson, Environmental Science and Engineering, California Institute of Technology, Linde+Robinson Laboratory, Pasadena, CA 91125, USA. (zerickso@caltech.edu)

[1]Environmental Science and Engineering, California Institute of Technology, Pasadena, California, USA.

[2]Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University, Durham, North Carolina, USA.

[3]Scripps Institution of Oceanography, La Jolla, California, USA.

Contents of this file

1. Supplementary Text
2. Table S1
3. Figures S1 to S11
4. Supplementary Movie (separate file)

Introduction This supplement provides additional information about calibration procedures for nighttime and daytime Seaglider measurements, as well as additional figures in support of the statements made in the main text.

1. Supplementary Text

1.1. Processing of Seaglider data

Seaglider measurements were taken of temperature (T), salinity (S), pressure (p), oxygen (O_2), fluorescence (F), backscatter (b_{bp}) at 650 nm, and CDOM (colored dissolved organic matter). Physical measurements (T, S, p) were taken with a Sea-Bird CTD sail at approximately 1 m vertical resolution. Oxygen measurements were taken with an Aanderaa optode at approximately 2-3 m vertical resolution. Biological measurements (F, b_{bp}, CDOM) were taken with a WETLabs ECOPuck Triplet at 2-3 m vertical resolution. Physical and oxygen measurements were taken to full depth (1000 m), whereas biological measurements were made only to 200 m to conserve battery.

Seaglider data were initially processed using the Seaglider Toolbox provided by Bastien Queste at `https://bitbucket.org/bastienqueste/uea-seaglider-toolbox`, which corrects salinity for cell thermal mass and thermal inertia effects. Temperature and salinity measurements were despiked using a threshold method, with threshold values of 0.025°C and 0.025 PSU (practical salinity units). Salinity values shallower than 2 meters depth and when the glider was stationary were also removed, as were temperature and salinity values outside of the range (-2, 3) °C and (33.5, 35) PSU. Potential temperature and density fields referenced to the surface were calculated using the CSIRO MatLab Seawater Library, at `http://www.marine.csiro.au/datacentre/processing.htm`, version 3.3.1. Fluorescence measurements were converted into chlorophyll concentrations using a scale factor measured by WETLabs in a standard calibration measurement against the diatom *Thalassiosira weissflogii*, and offset independently on each dive such that average values on each dive between 180 and 200 meters are zero

(average offset of -0.03 ± 0.01 mg/m^3 chlorophyll). Backscatter measurements were laboratory-calibrated with a zero-level offset; however, we added an additional offset of -8×10^{-5} m^{-1} such that backscatter values off-shore were negligible at 200 m. All data were smoothed into 5 meter bins using mean values for physical parameters (potential temperature, salinity, potential density, and oxygen) and using median values for biological parameters (fluorescence and backscatter), and were interpolated onto a 5 meter depth by 30 minute grid using an objective mapping technique available at `http://mooring.ucsd.edu/software/matlab/doc/toolbox/datafun/objmap.html`.

1.2. Calibration of chlorophyll measurements

We measure induced fluorescence, a common proxy for chlorophyll. We perform our own calibration of chlorophyll to fluorescence, comparing the estimated chlorophyll values from the factory calibration to Oceancolor data from MODIS Aqua. Due to non-photochemical quenching (NPQ; see §1.3), we only consider chlorophyll measurements during nighttime. We perform a point-to-point matchup between nighttime surface (mean value between 0-20 m depth) Seaglider chlorophyll data and Level 2 MODIS Aqua reflectance data located within 5 kilometers (center of measurement) and 24 hours of the Seaglider surface location. Note that MODIS Aqua has a local overpass time of approximately 13:30. The *Johnson et. al* [2013] algorithm, tuned to the Southern Ocean, was used for this satellite calibration. Valid calibrations are shown in Figure S1. Large amounts of cloud cover are evident, as is a large spread in scale factor. However, the mean value is close to 1 and there does not appear to be a temporal trend, and we therefore choose to use the original factory calibration.

1.3. NPQ Correction

Under high light conditions, physiological responses in phytoplankton, collectively known as non-photochemical quenching (NPQ), are induced to prevent cellular damage [*Cullen and Lewis*, 1995]. These processes reduce fluorescence yield, leading to lower ratios between fluorescence and chlorophyll and, unless corrected for, can lead to large biases in fluorescence-derived chlorophyll estimates. A common correction is to use backscatter as a proxy for chlorophyll within the mixed layer for measurements affected by NPQ [*Boss et. al*, 2008; *Boss and Haëntjens*, 2016].

The following describes our method, resulting in a "NPQ-corrected" chlorophyll dataset (Figure S7). We separate glider profiles into down- and upcasts. We determine daytime hours using the MatLab function `suncycle.m`, available from `http://mooring.ucsd.edu/software/matlab/doc/toolbox/geo/suncycle.html`, with GPS positions and times provided by the glider pre- and postdive, and apply the following correction to all downcast (upcast) data when the predive (postdive) time was in between sunrise and sunset hours. Seaglider measurements were used after they were binned into 5 meter depth increments. For each cast, the mixed layer depth (MLD) was determined as the depth at which the potential density increased by 0.03 kg/m^3 from the value at 10 meters depth [*Dong et. al*, 2008]. Because the only chlorophyll measurement available was derived from fluorescence, values within the mixed layer but deeper than 50 meters (estimated to be the depth at which NPQ effects were no longer felt, see Figures S5,S8) were used to determine the chlorophyll:backscatter ratio. A correction was only attempted if at least 3 such points with valid measurements were present (meaning the MLD must

be at least 65 meters). Only 70 out of 831 daytime profiles (8%) met this requirement. In these instances, the fluorescence:backscatter ratio for that profile was estimated at the mean ratio for all valid observations. To prevent a discontinuity at the MLD, chlorophyll values at and below the MLD were derived solely from fluorescence, at or above 50 meters solely from backscatter (using the previously calculated ratio), and in between as a weighted average of the two methods, with the weights linearly interpolated between the two extremes. When the requirement of three (smoothed) data points between the 50 meters and the MLD was not met, data points which would ordinarily have been weighted 50% or more with the backscatter correction method (included all values shallower than 50 meters) were removed.

A calibration via satellite observations as for fluorescence-derived chlorophyll values was attempted, as in §1.2, but very few valid calibration measurements were found (Figure S2). Instead, the correction was applied for nighttime dives (41 out of 315 profiles, or 13%, fit the 3-point requirement), and fluorescence-derived chlorophyll measurements were compared with the corrected values within the mixed layer, with good agreement found (mean difference of < 0.01 mg/m^3, Figure S3).

Table S1. Glider information for each transect.

Transect	Dive range	Day range†	Max. surface Chl (mg/m^3)	Max. deep Chl (mg/m^3)
1	[9, 53]	[-27, -20]	1.3	1.1
2	[62, 117]	[-18, -10]	1.8	2.2
3	[120, 148]	[-10, -6]	2.1	1.8
4	[154, 182]	[-5, 0]	2.1	1.9
5	[183, 216]	[0, 5]	2.1	2.1
6	[217, 249]	[5, 9]	3.2	2.5
7	[250, 281]	[10, 14]	2.6	2.0
8	[282, 309]	[14, 18]	2.3	2.3
9	[327, 358]	[20, 24]	2.7	2.7
10	[359, 393]	[24, 29]	3.3	2.3
11	[394, 431]	[29, 35]	3.3	3.3
12	[441, 481]	[37, 43]	4.0	4.1
13	[482, 553]	[43, 54]	4.2	4.9
14	[554, 581]	[55, 60]	3.9	4.8

† Day 0 is defined as 01 Jan 2015.

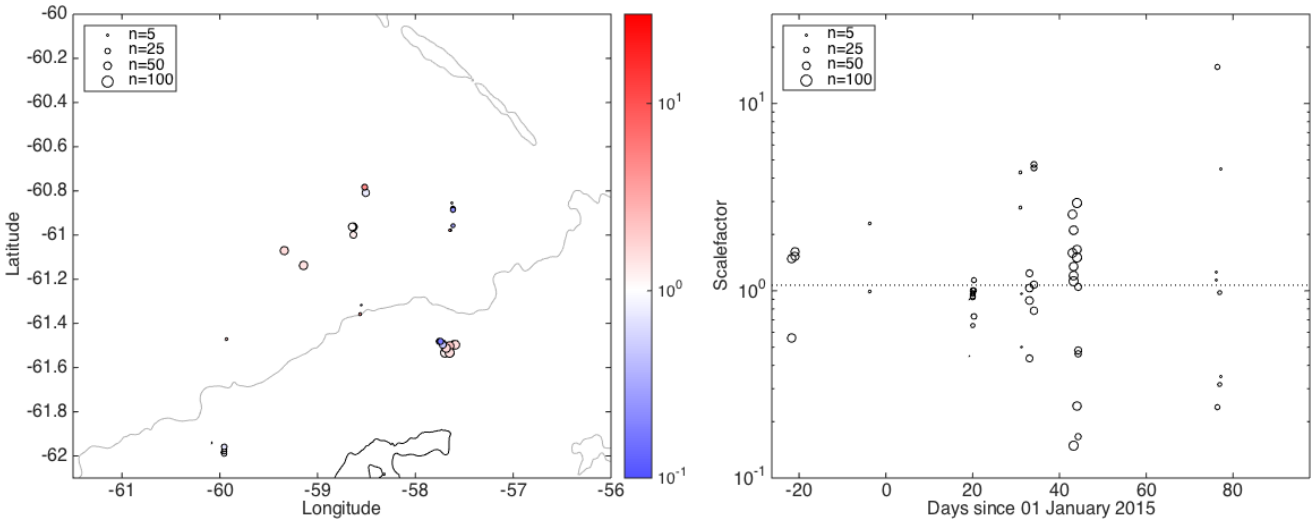

Figure S1. Left panel shows locations of dives with nighttime calibrations, as described in the Supplementary Text. Circle size corresponds to the number of satellite measurements available for calibration, and the color is the remotely-sensed satellite observation divided by the Seaglider measurement. Black and grey lines give the coastline and the 2000 meter isobath, respectively. Right panel shows the same measurements, but plotted against the time of the Seaglider measurement. The average scale factor of 1.07 is given by the dotted line.

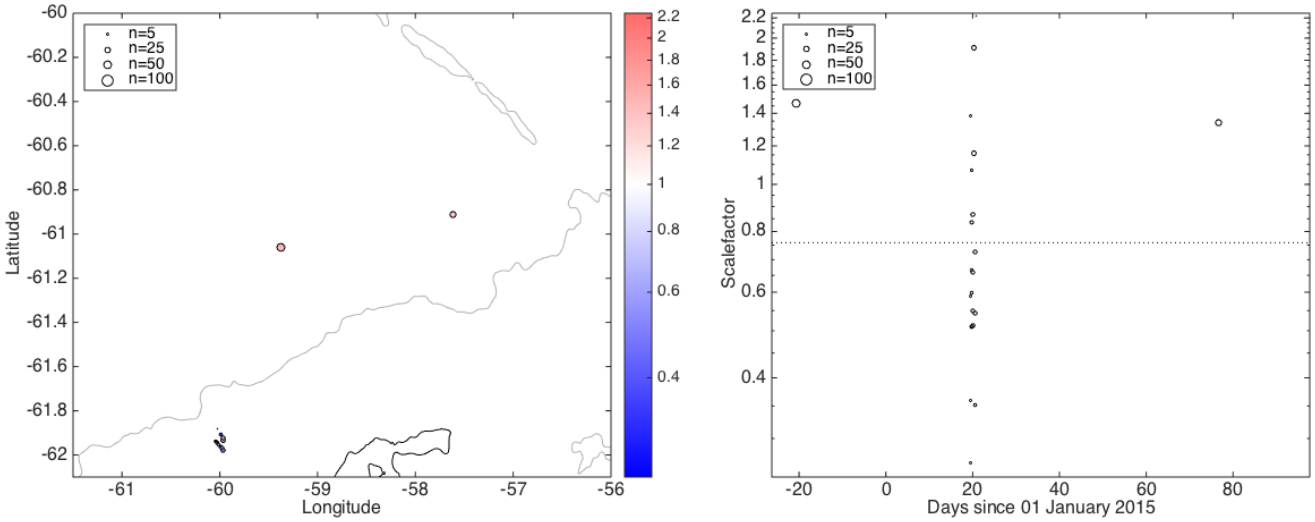

Figure S2. As in Figure S1, but for daytime calibrations to the NPQ-corrected dataset, as described in the Supplementary Text. The average scale factor is 0.76.

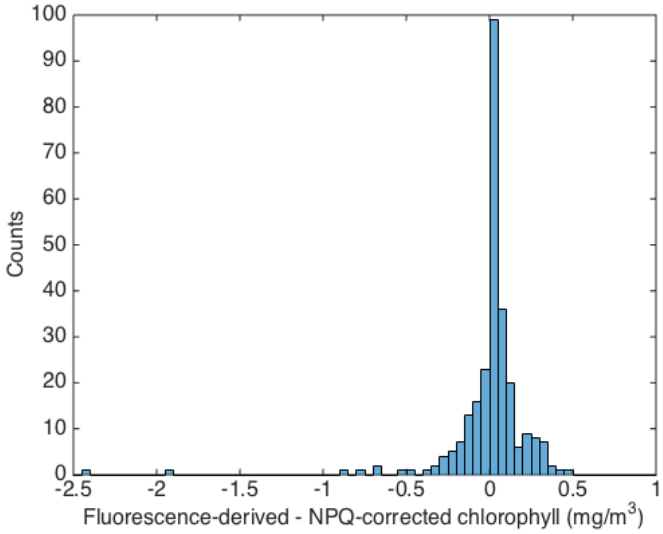

Figure S3. Difference between fluorescence-derived and NPQ-corrected chlorophyll values within the mixed layer.

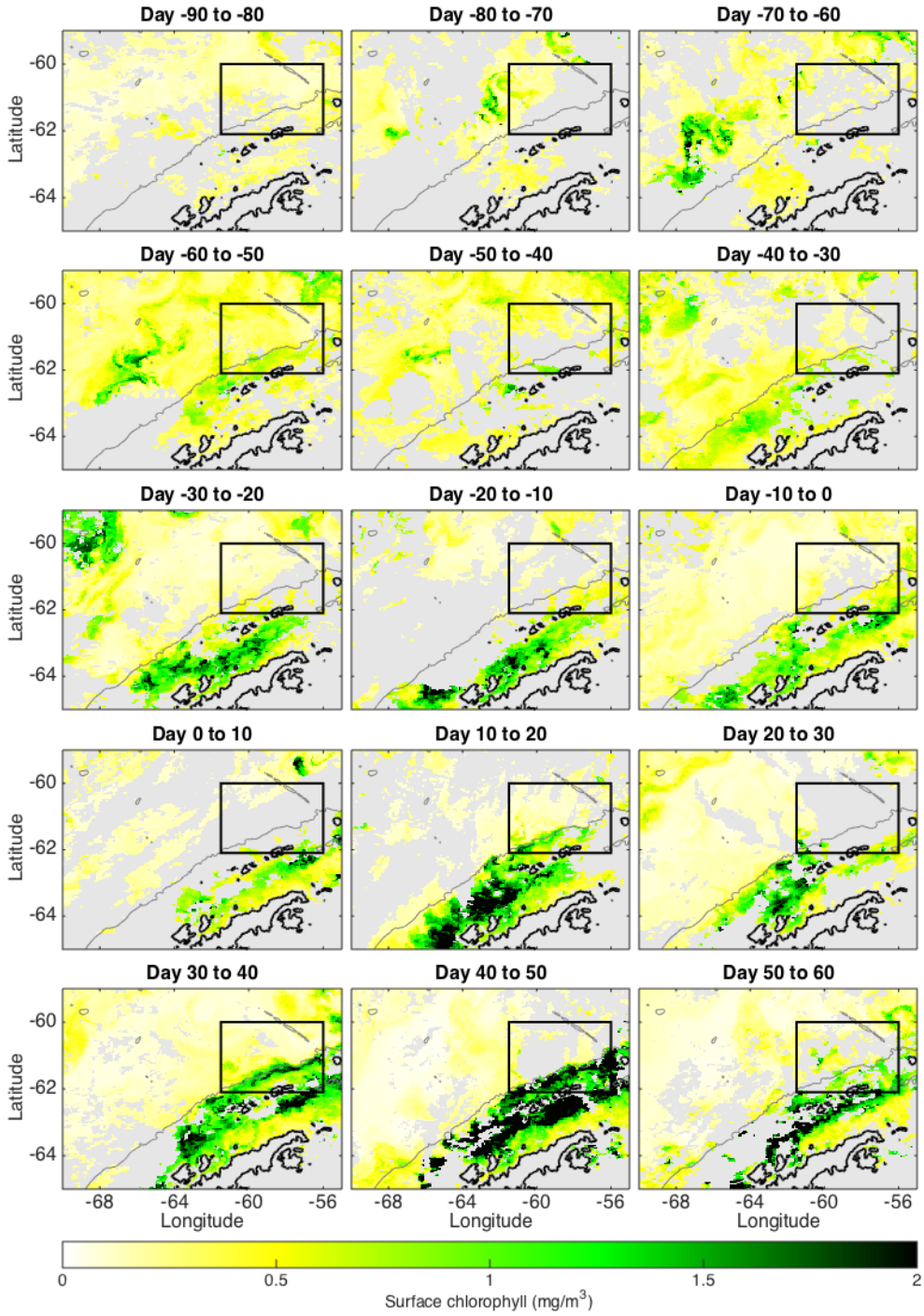

Figure S4. Averaged surface chlorophyll data from MODIS Aqua satellite (4km grid) using the *Johnson et. al* [2013] algorithm over 10 day periods, where day 0 is 01 January, 2015. Note that our Transect 1 starts on Day -27 (see Table 1 in the main text). Grey values indicate no data. Bathymetry contours at 0 and 2000 meters are shown in black and grey. The black boxes give the location of Figure 1a in the main text.

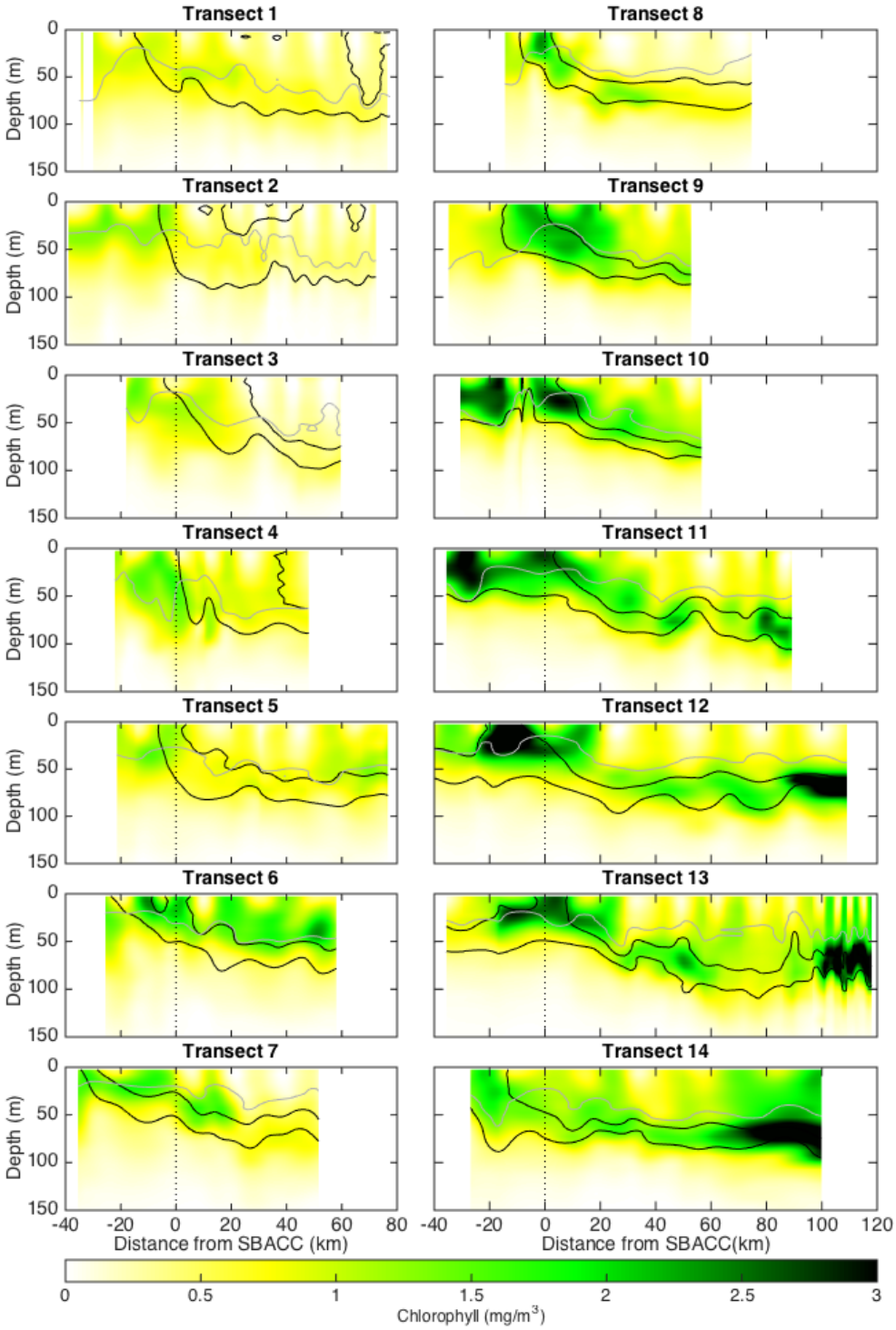

Figure S5. Objectively mapped fluorescence-derived chlorophyll concentrations for each transect (colors) as a function of distance from the 2000 m isobath, shown in black dotted lines. Positive numbers are towards the open ocean. Black curves give the isopycnal contours at 1027.2 and 1027.35 kg/m^3, and the grey curve is the mixed layer depth.

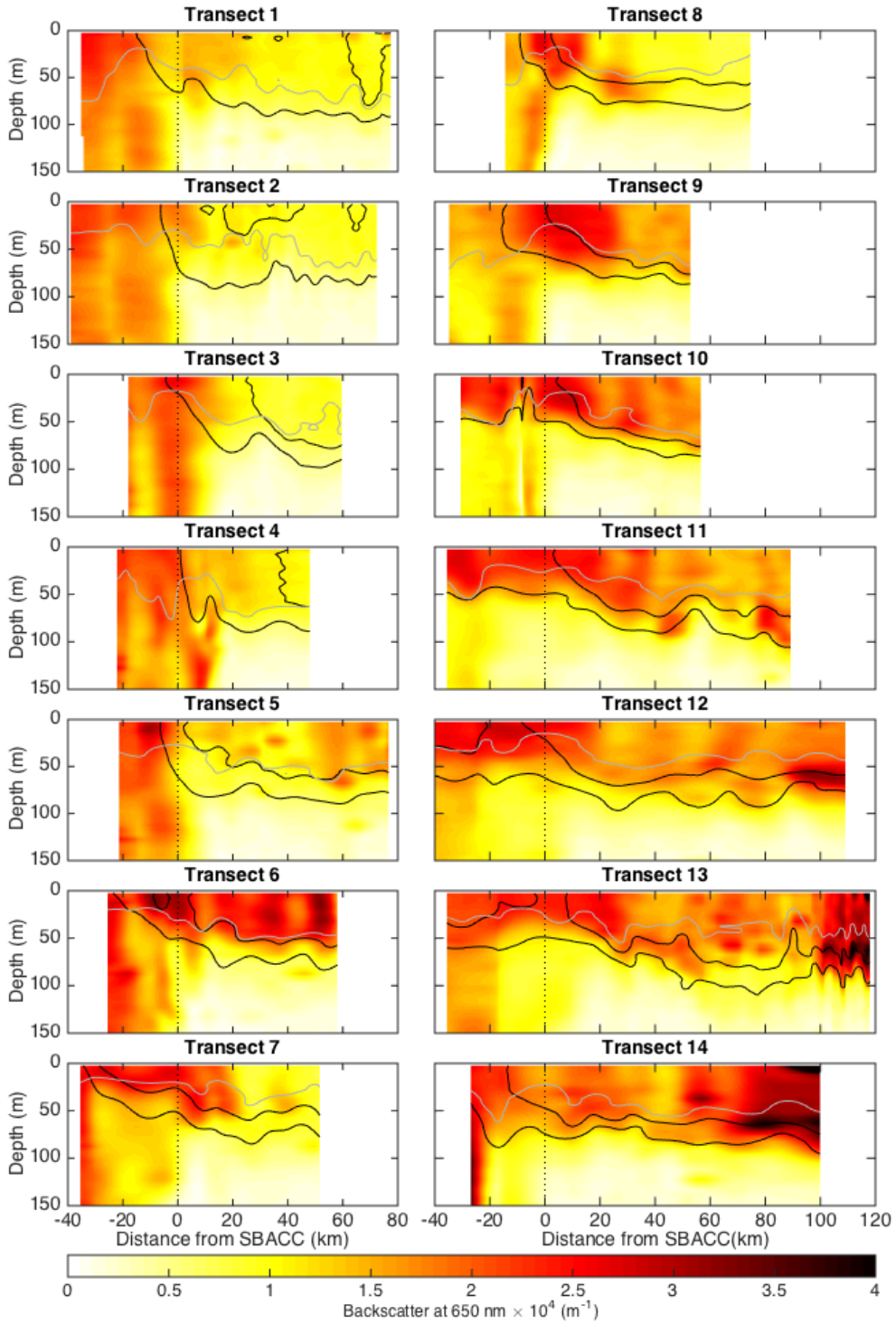

Figure S6. As in Figure S5, but for backscatter measurements at 650 nm.

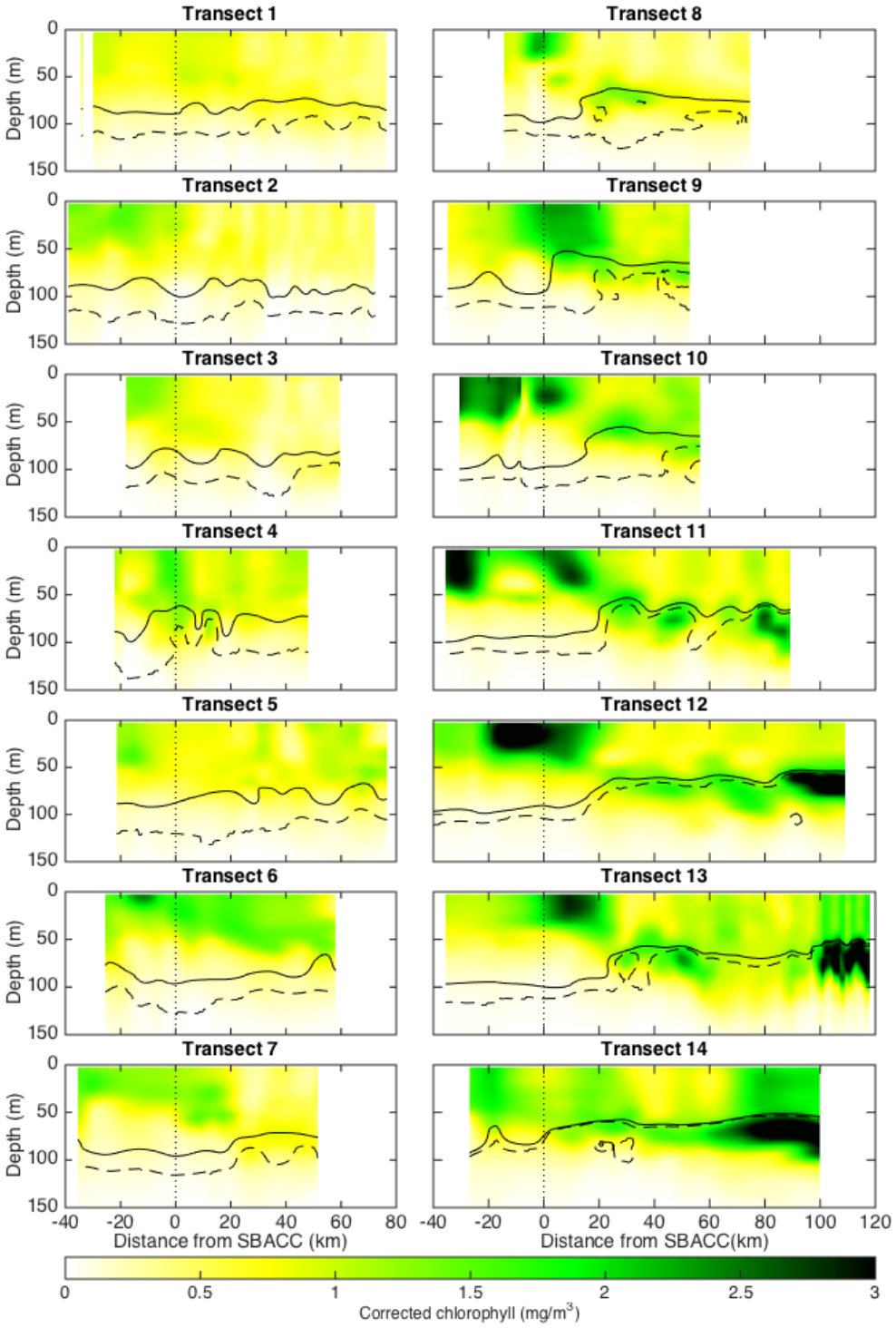

Figure S7. Objectively mapped corrected chlorophyll concentrations for each transect (colors) as a function of distance from the 2000 m isobath, shown in black dotted lines. See Supplementary Text for details on the correction procedure. Positive numbers are towards the open ocean. Solid black curve gives the euphotic depth defined as the 1% of surface radiation threshold. Dashed black curve gives the 0.1 mol quanta/m^2/day isolume, another measure of the euphotic depth [*Banse*, 2004; *Holm-Hansen and Mitchell*, 1991].

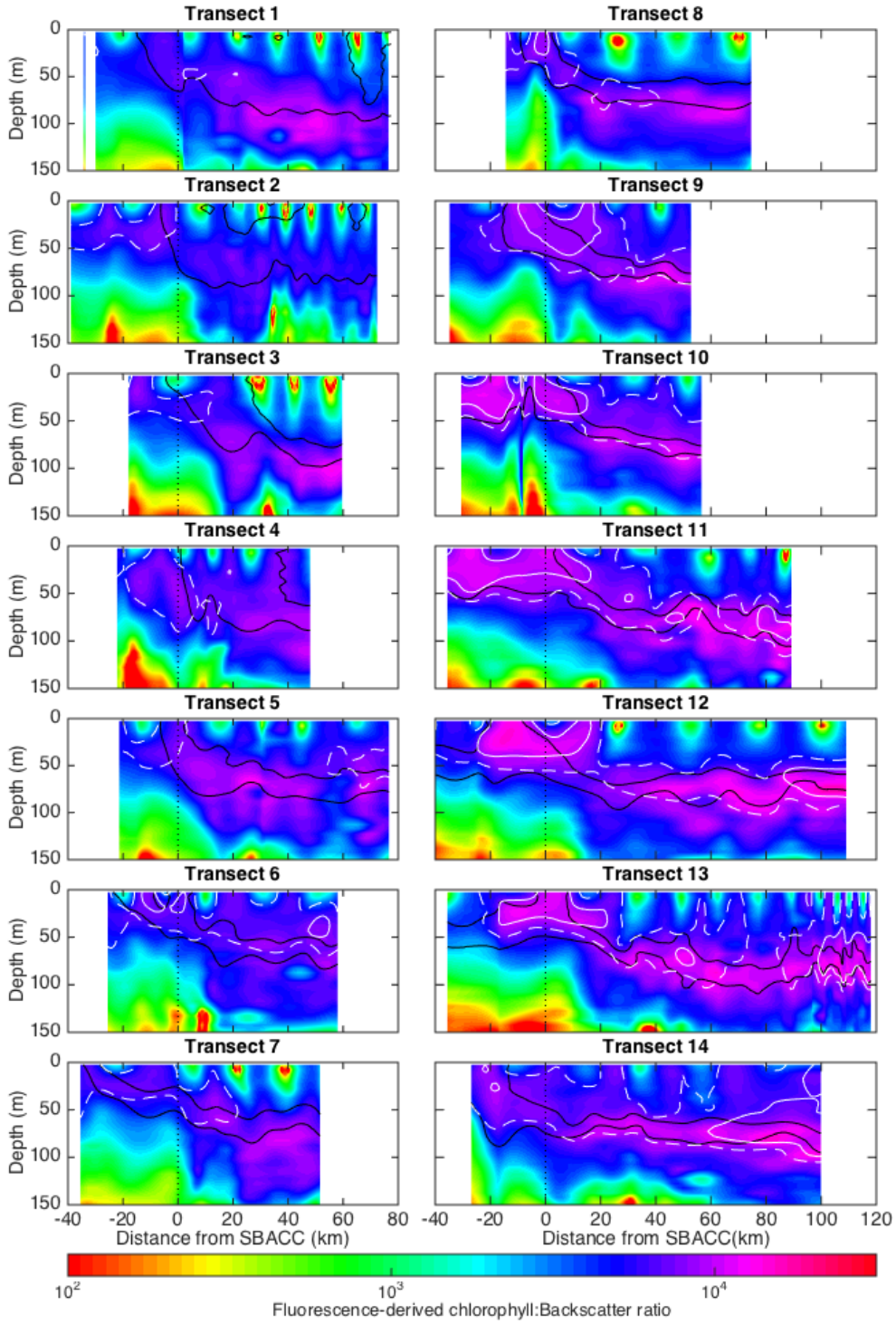

Figure S8. Objectively mapped chlorophyll:backscatter ratio (i.e. Figure S5 : S6) for each transect (colors) as a function of distance from the 2000 m isobath, shown in black dotted lines. Positive numbers are towards the open ocean. Black curves give the isopycnal contours at 1027.2 and 1027.35 kg/m^3. White dashed (solid) contours denote 1 (2) mg/m^3 chlorophyll concentration, from Figure S5.

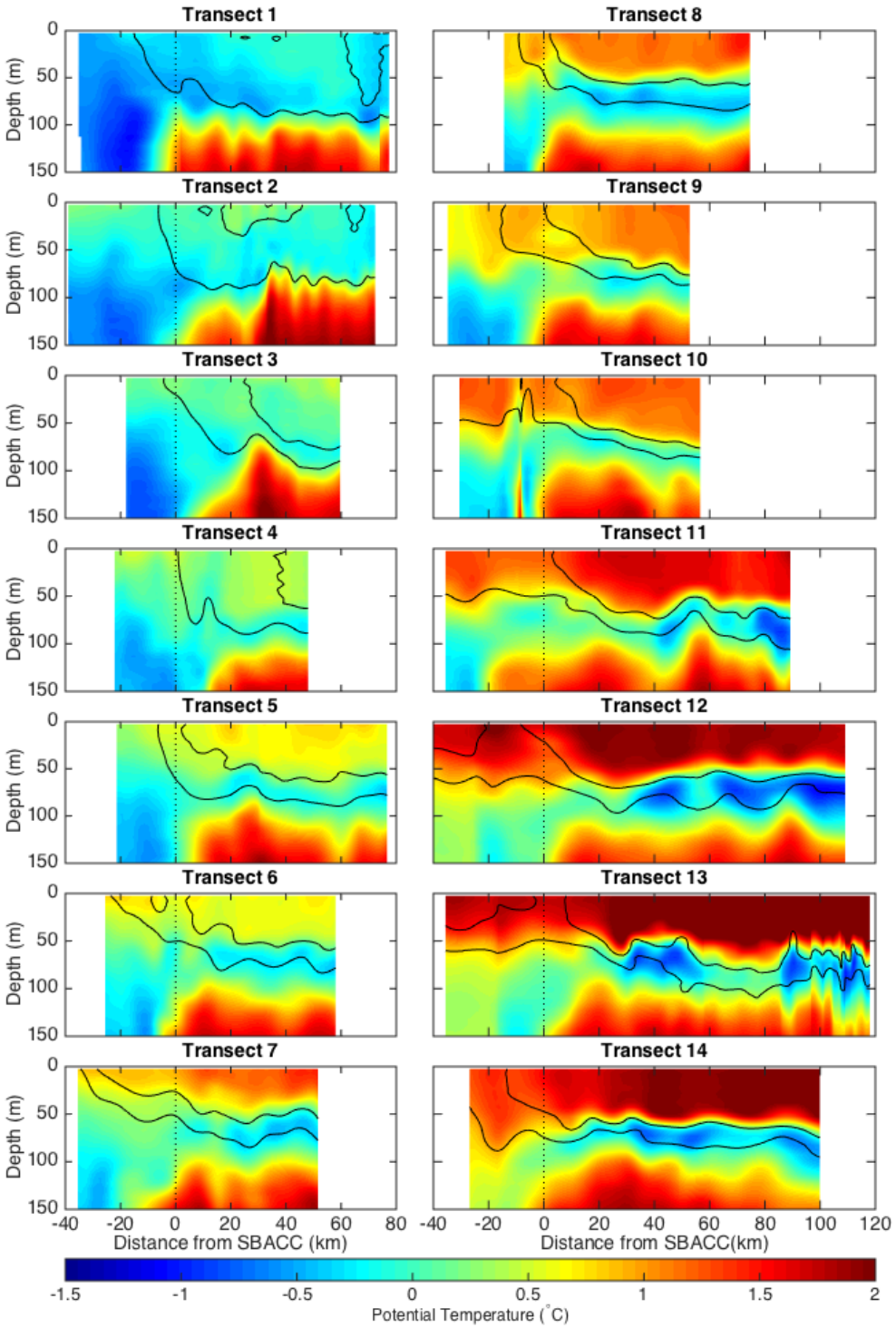

Figure S9. As in Figure S5, but for potential temperature.

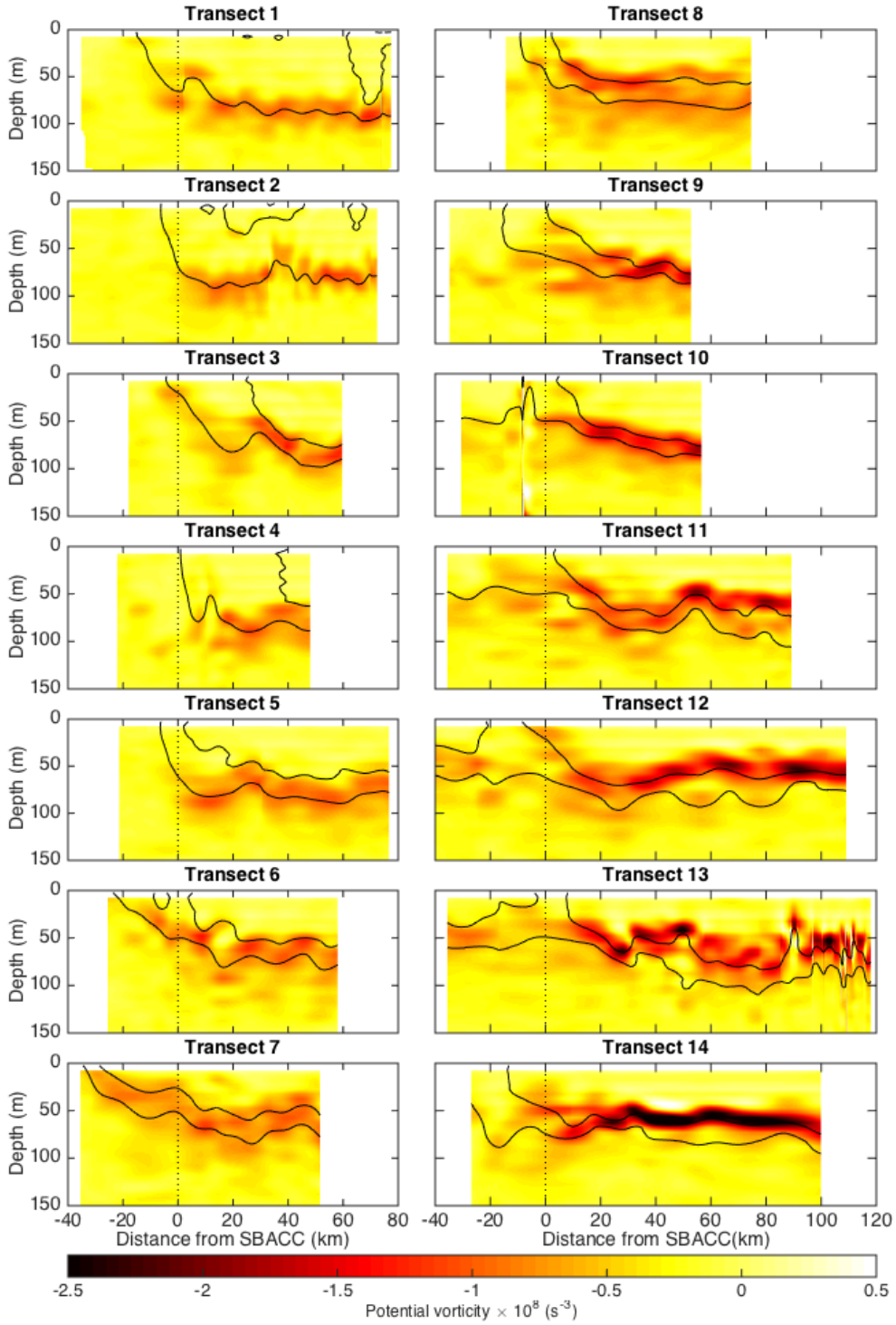

Figure S10. As in Figure S5, but for potential vorticity (PV) as described in the main text.

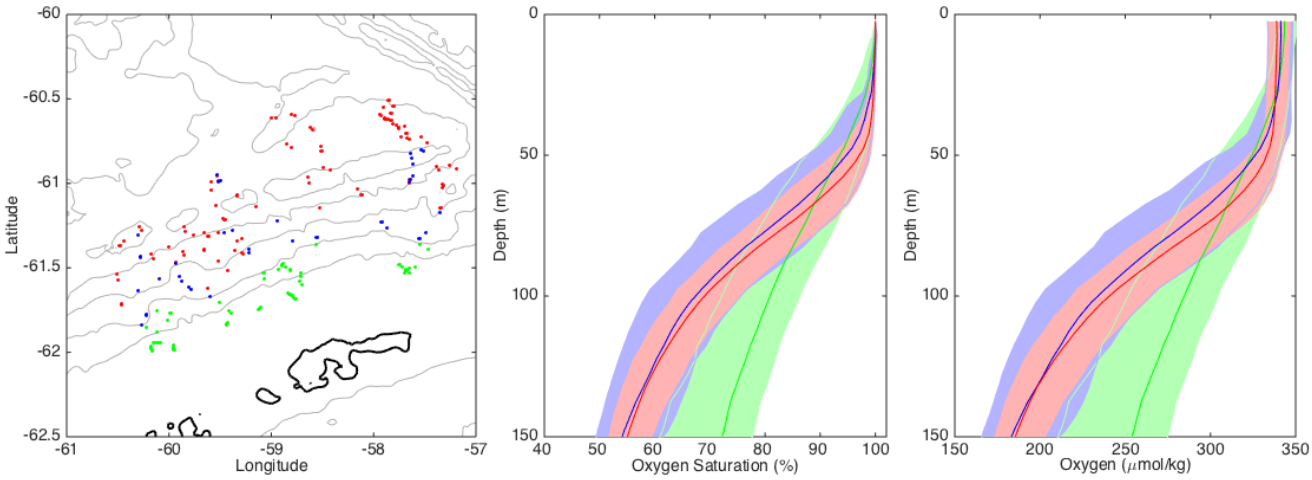

Figure S11. (A) Locations of glider dives poleward (green) of the Southern Boundary of the Antarctic Circumpolar Current (SBACC; approximated by the 2000 meter isobath), and equatorward of the SBACC with (red) and without (blue) a DCM. Only night time dives were used. Bathymetric contours are given every 1000 meters in grey, and King George Island is shown in black. (B) Thick lines show average oxygen saturation levels for the dives indicated in (A), and shading gives one standard deviation about the mean. (C) As in B, but lines and shading show oxygen concentrations.