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Estimates of the Southern Ocean general circulation improved by animal-borne instruments

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[1] Over the last decade, several hundred seals have been equipped with conductivity-temperature-depth sensors in the Southern Ocean for both biological and physical oceanographic studies. A calibrated collection of seal-derived hydrographic data is now available, consisting of more than 165,000 profiles. The value of these hydrographic data within the existing Southern Ocean observing system is demonstrated herein by conducting two state estimation experiments, differing only in the use or not of seal data to constrain the system. Including seal-derived data substantially modifies the estimated surface mixed-layer properties and circulation patterns within and south of the Antarctic Circumpolar Current. Agreement with independent satellite observations of sea ice concentration is improved, especially along the East Antarctic shelf. Instrumented animals efficiently reduce a critical observational gap, and their contribution to monitoring polar climate variability will continue to grow as data accuracy and spatial coverage increase. **Citation:** Roquet, F., et al. (2013), Estimates of the Southern Ocean general circulation improved by animal-borne instruments, *Geophys. Res. Lett.*, *40*, doi:10.1002/2013GL058304.

1. Introduction

[2] Evidence is accumulating that the Southern Ocean is changing rapidly [*Jacobs*, 2006], and there is an urgent need for comprehensive in situ observations to document the spatial and temporal variability of these changes [*Rintoul et al.*, 2010]. Since the 2000s, the global upper ocean has been continuously sampled by the Argo array [*Gould et al.*, 2004], including the Antarctic Circumpolar Current (ACC) region. South of the ACC, however, the presence of sea ice is a major obstacle for Argo profilers, and until recently, the only observations available were a small number of summertime ship-based profiles.

[3] Since 2004, novel observations of the Southern Ocean have become available through the use of instrumented seals. Conductivity-temperature-depth satellite relay data loggers (CTD-SRDLs) were developed in the early 2000s to sample temperature (T) and salinity (S) profiles during marine mammal dives [*Lydersen et al.*, 2002; *Fedak*, 2004]. While their principle intent was to improve understanding of seal foraging strategies [*Biuw et al.*, 2007; *Fedak*, 2013], they have also provided as a by-product a viable and cost-effective method of sampling hydrographic properties in many regions of the Southern Ocean [*Charrassin et al.*, 2008].

Additional supporting information may be found in the online version of this article.

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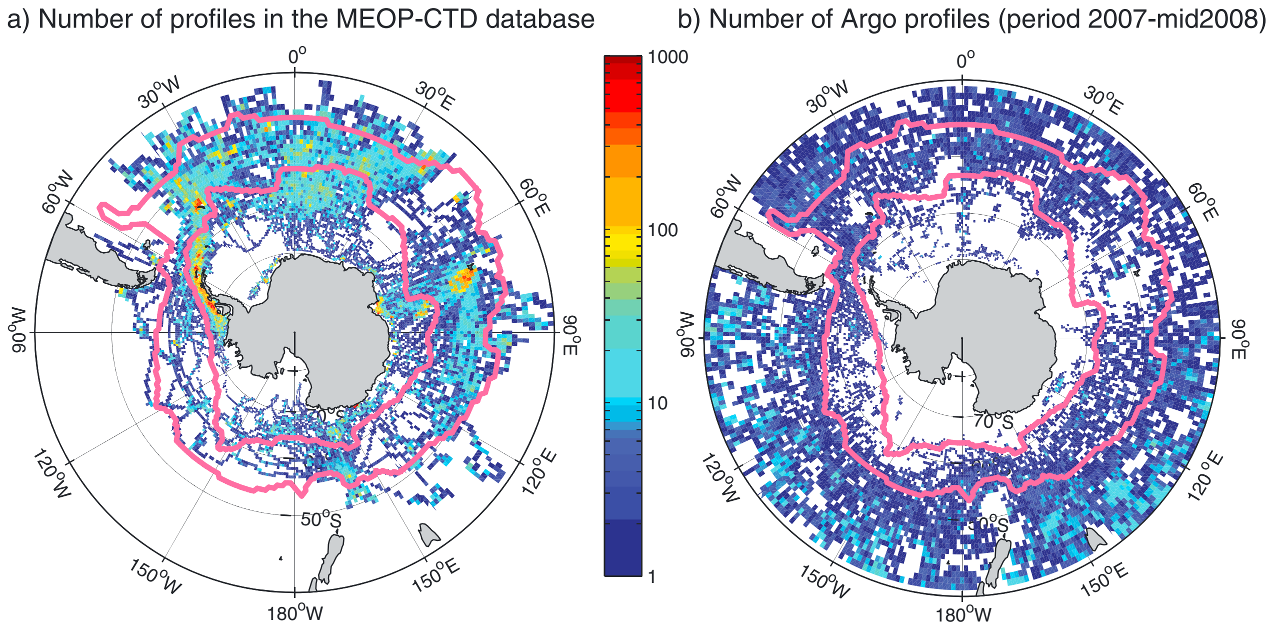

Figure 1. Number of TS profiles per ECCO grid cell for (a) the MEOP-CTD database, and (b) the Argo profiles used in state estimate experiments. Superimposed in pink are the ACC limits defined as the −1.5 m (southern limit) and −0.5 m (northern limit) contours of sea surface height in the SEAL state estimate.

[4] Within the "Marine Mammals Exploring the Oceans Pole to Pole" (MEOP) program, several international teams agreed to share their CTD-SRDL data sets to produce a single, uniformly calibrated, homogeneous database of hydrographic profiles. Here we present the MEOP-CTD database, a quality-controlled collection of most seal-derived hydrographic data obtained in the period 2004–2010 (publicly available at http://people.su.se/~froqu), and we provide an objective assessment of its contribution to improving the existing observing system.

2. The MEOP-CTD Database

[5] The MEOP-CTD database includes 349 CTD-SRDLs, representing 165,000 TS profiles (see Figure 1 and Table S1 in the supporting information). The majority of loggers were deployed on elephant seals, with a lesser number on Weddell and crabeater seals. On average, profiles are 500 m deep, although some seals occasionally reach 2000 m or more. The MEOP-CTD collection of profiles produces near circumpolar coverage, although some regions such as the Weddell and Ross Seas remain poorly sampled. More than 60% of TS profiles were obtained south of the southern limit of the ACC, where few Argo data exist. The migration distance of seals depends highly on the deployment location and time of the year, ranging from 100 km to more than 5000 km, while the life span of a CTD-SRDL varies from 1 to 10 months (5 months on average). The bulk of measurements were made in the austral autumn and winter, when other in situ data are scarce, yielding hydrographic sections with high spatial and temporal resolution (2.5 profiles per day on average).

[6] CTD-SRDLs record TS profiles during the quasi-vertical ascent of seals [*Boehme et al.*, 2009; *Roquet et al.*, 2011], retaining only the deepest dive in each 6 h time interval, and transmitting profiles in a compressed form (about 20 data points per profile) through the Advanced Research and Global Observation Satellite (ARGOS) system—not to be confused with Argo. Animal positions are determined using ARGOS telemetry information, with a typical accuracy of ±5 km.

[7] Hydrographic profiles were postprocessed using a unified procedure of editing, correction, and calibration [*Roquet et al.*, 2011]. A standard set of tests, adapted from Argo standard quality control procedures, was run to remove bad profiles, spikes, and outliers. When available (i.e., for about 90 CTD-SRDLs), at sea comparisons with ship-based CTD profiles were used to correct pressure-induced biases on TS profiles. For CTD-SRDLs with profiles in frozen areas, a temperature offset was estimated using the local freezing temperature (173 CTD-SRDLs corrected). A salinity offset, which is induced by an external field effect on the conductivity sensor, was estimated using comparison of the deepest salinity measurements with a high-resolution 3 year average derived from the Southern Ocean State Estimate [*Mazloff et al.*, 2010]. An average -0.05 ± 0.16 salinity offset was applied, showing the critical importance of the correction.

[8] Once calibrated, the accuracy of postprocessed CTD-SRDL measurements was estimated to be ±0.05°C in temperature and ±0.05 or better in salinity for CTD-SRDLs built after 2007—against ±0.01°C and ±0.01 for Argo profiles. The achieved accuracy is highly dependent upon availability of ship-based CTD comparisons and the type of water masses sampled during deployment time. In best cases, an accuracy of ±0.01°C and ±0.02 can be obtained. Pre-2007 CTD-SRDLs (about 20% of profiles) used an older technology with a poorer accuracy roughly estimated around ±0.1°C and ±0.1. It must be emphasized that uncalibrated seal-derived data, such as those available on the Global Telecommunication System, feature much lower accuracies mainly because the salinity offset is not corrected.

3. Description of State Estimate Experiments

[9] Our goal here is to quantify the contribution the seal-derived data make to representation of ocean circulation

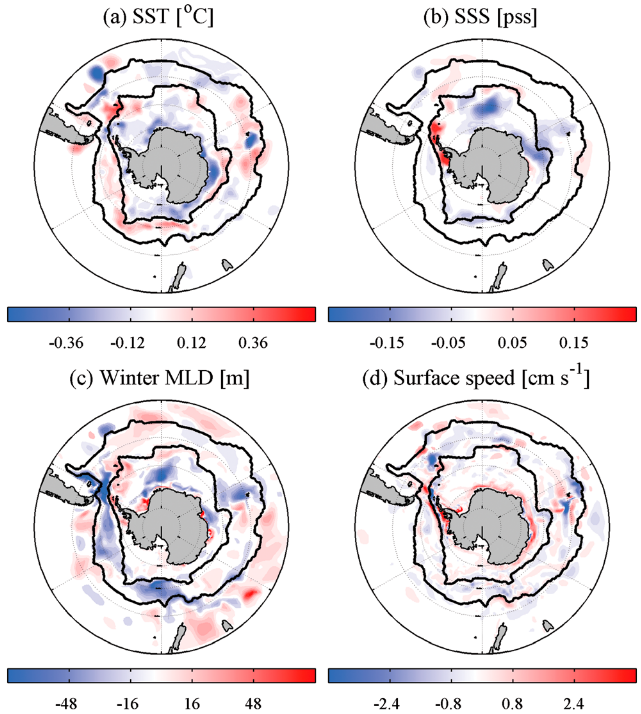

Figure 2. Spatial distributions of differences in mixed-layer properties between REF and SEAL state estimates (SEAL minus REF).

patterns. A direct comparison of seal-derived data with the seasonal climatology WOA09 (World Ocean Atlas 2009) [*Locarnini et al.*, 2010] shows large differences, with standard deviations of 3°C in T and 0.43 (nondimensional on the practical salinity scale) in S (see Table S1). These differences are both related to the undersampling of observations and to the interpolation method used to produce the climatology.

[10] For a more quantitative analysis, we use the ECCO (Estimating the Circulation and Climate of the Ocean) state estimation framework [*Wunsch and Heimbach*, 2013], originally developed to produce dynamically consistent syntheses of most existing data (both in situ and satellite) in the 1992 to present period (products available at http://ecco-group.org). The state estimation technique produces a least squares fit of an ocean general circulation model to a set of observations using the adjoint method. The ECCO model grid is global, with an approximate $1° \times 1°$ horizontal resolution and 50 vertical levels [*Forget*, 2010].

[11] Two 1.5 year long state estimates were carried out for the period 2007 to mid-2008. The reference state estimate (here denoted as REF) was constrained with Argo profiles only (166,000 T + S profiles, see Figure 1b), while the so-called SEAL state estimate was constrained with both Argo and seal data. All CTD-SRDL profiles from the MEOP-CTD database were used to constrain the SEAL state estimate, pooled as if they were all obtained during the simulation period, to obtain an upper limit on the effect of seal data while simultaneously decreasing the computation time. Some inconsistencies between seal and Argo data from different years are possible, but they should be limited given that the main contribution of seal data is expected to occur south of the ACC where few Argo profiles are available.

[12] We focus on a comparison between CTD-SRDL and Argo data, because the number of ship-based CTD casts is too small, and because most satellites cannot operate in ice-covered areas (except for sea ice concentration measurements). The REF and SEAL state estimates will now be compared, using the period April 2007 to March 2008 only and assuming that most of the observed differences are related to the use or withholding of CTD-SRDL data.

4. Results

[13] The SEAL state estimate is closer to seal-derived observations compared to the REF estimate, with a 30% reduction in misfit variance (see Table S1). Interestingly, the REF state estimate itself is already much more consistent with seal data than the WOA09 climatology (94% reduction in error variance), although it was not constrained by seal data, indicating the better skill of state estimation over interpolation techniques as used in WOA09 to synthesize available observations.

[14] Spatial patterns of differences between mixed-layer properties of the two state estimates are shown in Figure 2 (see also Figures S1 and S2). Typical differences are of order 0.5°C for sea surface temperature (SST), 0.2 for sea surface salinity (SSS), 60 m for winter mixed-layer depth (MLD, definition of *Kara et al.* [2000]), and $3\,\mathrm{cm\,s^{-1}}$ for surface velocity with complicated patterns of negative and positive anomalies seen over most of the Southern Ocean. The largest differences in SST and SSS are found south of the ACC, in the seasonally ice covered zone. This region is markedly cooler almost everywhere in the SEAL state estimate, especially during summertime (up to 1.8°C differences). The ACC area is slightly warmer on average, but with a large spatial and temporal variability in such regions as the Drake Passage (60°W) and the Kerguelen Plateau (70°E). Temperature anomalies fade away rapidly north of the ACC outside the influence zone of seal data.

[15] The pattern of SSS differences (Figure 2a) is not obviously connected to the SST pattern, highlighting the importance of having observations of both T and S. The largest differences in SSS are observed west of the Antarctic Peninsula. There, an SSS increase exceeding 0.2 is observed during most of the year, consistent with a recently documented increase in surface salinity [*Meredith and King*, 2005]. Elsewhere, SSS is reduced on average, especially in the eastern Weddell Sea (0°E) and in the Kerguelen Plateau sector. MLD and SSS differences are generally well correlated, as expected, with salinity being a key controller of upper ocean stratification within and south of the ACC.

[16] Observed differences in surface mixed layer properties south of the ACC are clearly related to changes in the sea ice distribution. A significantly larger sea ice cover (+12%) is seen in the SEAL experiment (Figure 3), most notably west of the Antarctic Peninsula (80°W) and along the East Antarctic margin (between 0°E and 160°E). As expected from an increased production rate of sea ice during wintertime, the mixed layer is deeper and more saline along the continental shelf regions where sea ice is formed and less saline and shallower off the continental slope. As a direct consequence of the observed changes in

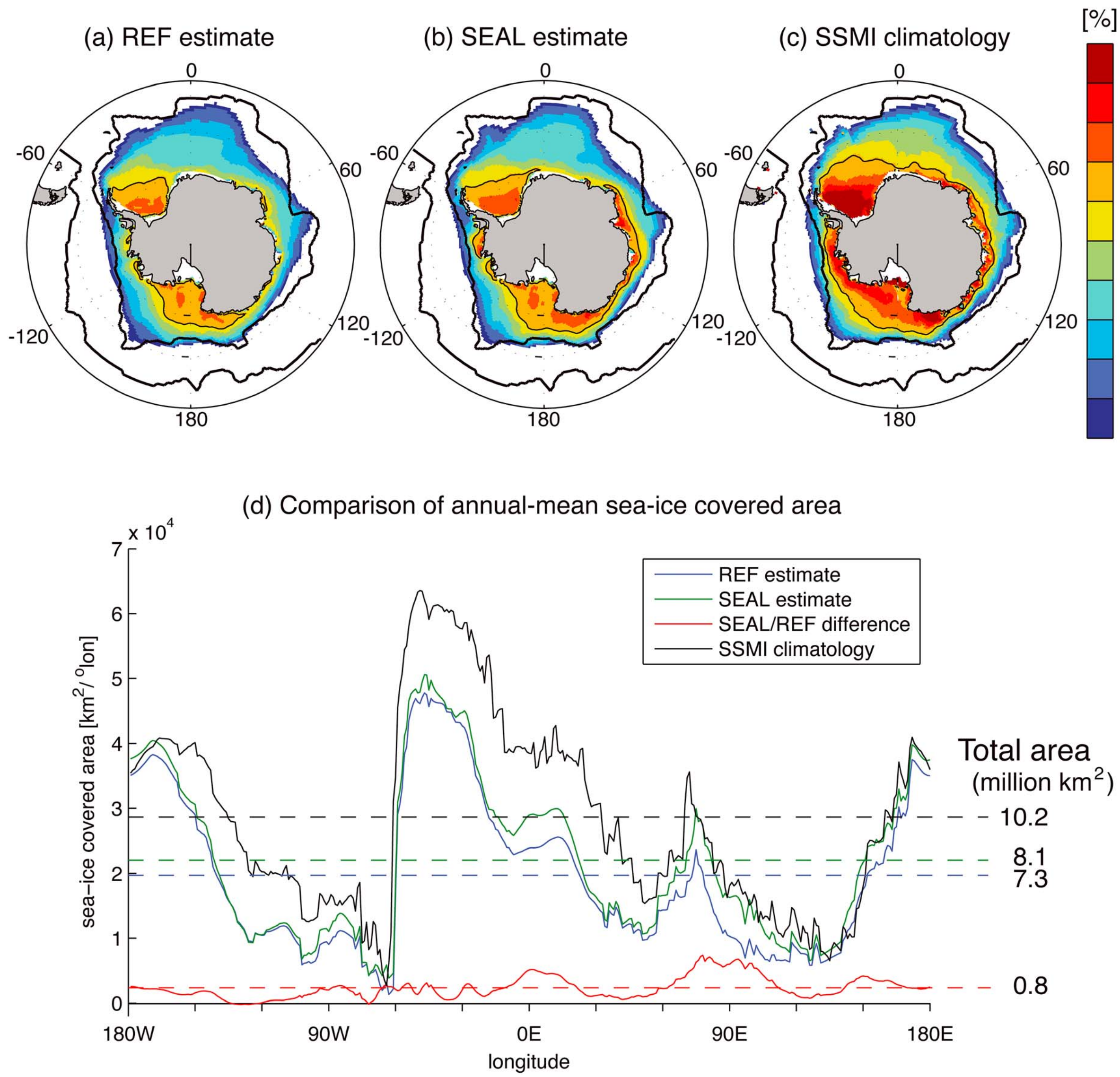

Figure 3. Annual mean sea ice concentration averaged over the whole year period, for (a) the REF and (b) the SEAL state estimates, and (c) for the 2004–2010 climatology of SSM/I satellite observations (the thin black line shows the 60% contour). (d) Comparison of the concentration-weighted sea ice area as a function of longitude.

mixed-layer properties, and thus, in near-surface density gradients, the surface circulation is significantly intensified along the Antarctic continental slope, where lies the westward Antarctic slope current (see Figure 2d).

[17] The distribution of sea ice concentration in the state estimates was compared with independent satellite observations, using a 2004–2010 average of Special Sensor Microwave Imager (SSM/I) data [*Kaleschke et al*., 2001] (Figure 3). Overall, the SEAL estimate of sea ice distribution shows better agreement with satellite observations than the REF state estimate (28% closer on average). The improvement is particularly clear around East Antarctica. Large deficits of sea ice remain around West Antarctica and particularly in the Weddell and Ross Seas most likely due to the still insufficient sampling effort in these regions. More CTD-SRDL data are currently being sampled in these regions, which should allow further improvements in the representation of sea ice in state estimates.

5. Discussion and Conclusions

[18] After a decade of continuous deployments of CTD-SRDLs on seals in the Southern Ocean, a large collection of hydrographic profiles exists with a near circumpolar distribution, turning the long foreseen idea of using marine mammals as integrated oceanographic platforms [*Evans and Leatherwood*, 1972] into reality. The analysis of the impact of seal-derived profiles on a global state estimate shows significant improvements in the immediate region of the data sets, with cooler and fresher surface waters resulting in a sea ice distribution closer to satellite observations. This study is not definitive both because the model resolution at high latitudes is relatively coarse, and the importance of interannual variability and of the heterogeneity in spatial distribution has not been properly assessed. Nevertheless, improvements already seen in the crucial region of sea ice formation are expected to be of growing importance as more seal data become available.

[19] The MEOP-CTD database is constantly expanding, as more CTD-SRDLs are being deployed every year. New sites of deployments are being used, or will be soon, such as the Ross, Weddell, and Amundsen seas, thus improving the spatial coverage around Antarctica. Improvements to the CTD-SRDL technology are underway, in terms of sensor accuracy, life duration, storage capacity, and satellite transmission. The challenge now is to broaden coverage by extending the methods to new sensors, such as fluorometers [*Guinet et al*., 2013], and using more diverse animal types. Miniaturization techniques are improving at a fast pace, and the true potential of animal-borne instruments is yet to be revealed.

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