Seals map bathymetry of the Antarctic continental shelf

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[1] We demonstrate the first use of marine mammal dive-depth data to improve maps of bathymetry in poorly sampled regions of the continental shelf. A group of 57 instrumented elephant seals made on the order of 2×10^5 dives over and near the continental shelf on the western side of the Antarctic Peninsula during five seasons, 2005–2009. Maximum dive depth exceeded 2000 m. For dives made near existing ship tracks with measured water depths H<700 m, ~30% of dive depths were to the seabed, consistent with expected benthic foraging behavior. By identifying the deepest of multiple dives within small areas as a dive to the seabed, we have developed a map of seal-derived bathymetry. Our map fills in several regions for which trackline data are sparse, significantly improving delineation of troughs crossing the continental shelf of the southern Bellingshausen Sea.
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1. Introduction

[2] Bathymetry for much of the ocean surrounding the Antarctic continent is poorly known due to the difficulty of ship operations in these remote and frequently ice-covered seas. Given the fundamental impact of bathymetry on oceanographic processes, we seek ways to improve the database of Antarctic depth measurements. This data deficit has resulted in novel approaches to mapping bathymetry, such as using the measured freeboard of grounded icebergs to estimate ice draft and water depth at those points [*Luckman et al.*, 2010].

[3] Instrumenting marine mammals with conductivity-temperature-depth satellite relay data loggers (CTD-SRDLs) is an important technique for investigating their behavior and preferred environmental conditions, and provides a basis to predict impacts of climate change on their habitats [*Costa et al.*, 2010a]. These data can also be used to map ocean hydrography over broad areas including regions typically covered by sea ice see, e.g., *Nicholls et al.* [2008]. With a sufficient number of instrumented individuals, CTD-SRDL data can significantly extend the region of monitored hydrographic variability presently undertaken by the Argo network of autonomous profiling floats [*Boehme et al.*, 2008; *Charrassin et al.*, 2008; *Costa et al.*, 2010a].

[4] In the present study, we exploit the CTD-SRDL data set to map bathymetry rather than hydrography. We use measurements of maximum dive depth by elephant seals foraging over the continental shelf on the western side of the Antarctic Peninsula to demonstrate that these data can be used to augment traditional bathymetry datasets (Figure 1). The seal measurements help map significant troughs cutting across the continental slope from the shelf break to the ice shelves of the Bellingshausen Sea. Mapping these troughs provides information on the flow paths of paleo ice streams and improves our ability to model ocean circulation, including the onshore flow of warm Circumpolar Deep Water (CDW) across the continental shelf [*Klinck et al.*, 2004; *Dinniman and Klinck*, 2004; *Thoma et al.*, 2008] that provides ocean heat to drive basal melting of ice shelves [e.g., *Thoma et al.*, 2008; *Jenkins and Jacobs*, 2008].

2. Dive Depth Data From Instrumented Seals

[5] We obtained dive data from 57 individual southern elephant seals (*Mirounga leonina*) instrumented after molting in 2005 (6 seals), 2006 (12), 2007 (12), 2008 (12), and 2009 (15). The seals were all tagged at a colony near the US AMLR Program's summer field camp at Cape Shirreff, Livingston Island (62° 29'S, 60° 47'W), in the South Shetland Islands, Antarctica. These seals made on the order of $2x10^5$ dives over the region of the western Antarctic Peninsula (wAP) continental shelf; see Figure 1b for dive locations. Each seal was equipped with a CTD-SRDL (or "tag") manufactured by the Sea Mammal Research Unit of St. Andrews University, UK [*Boehme et al.*, 2009]. Locations were derived from the ARGOS PTT transmitters incorporated into the tags. The accuracy and frequency of unfiltered ARGOS locations is quite variable [*Vincent et al.*, 2002; *Costa et al.*, 2010b], so we filtered and interpolated the ARGOS location using a forward looking particle filter to provide a location at the start and end of each dive [*Tremblay et al.*, 2009]. The particle filter provides an estimate for each location, and all of our locations had a 99% confidence interval of being within ~4.2 km of the true position. Further, when multiple positions are used, as done here, the overall quality of the position estimate for that bottom depth improves significantly The typical lateral displacement during each dive was <0.5 km (mode = 0.3 km; mean = 0.42 km), about 10% of the ARGOS position error. Dive parameters are assigned to the location and time at the end of the dive.

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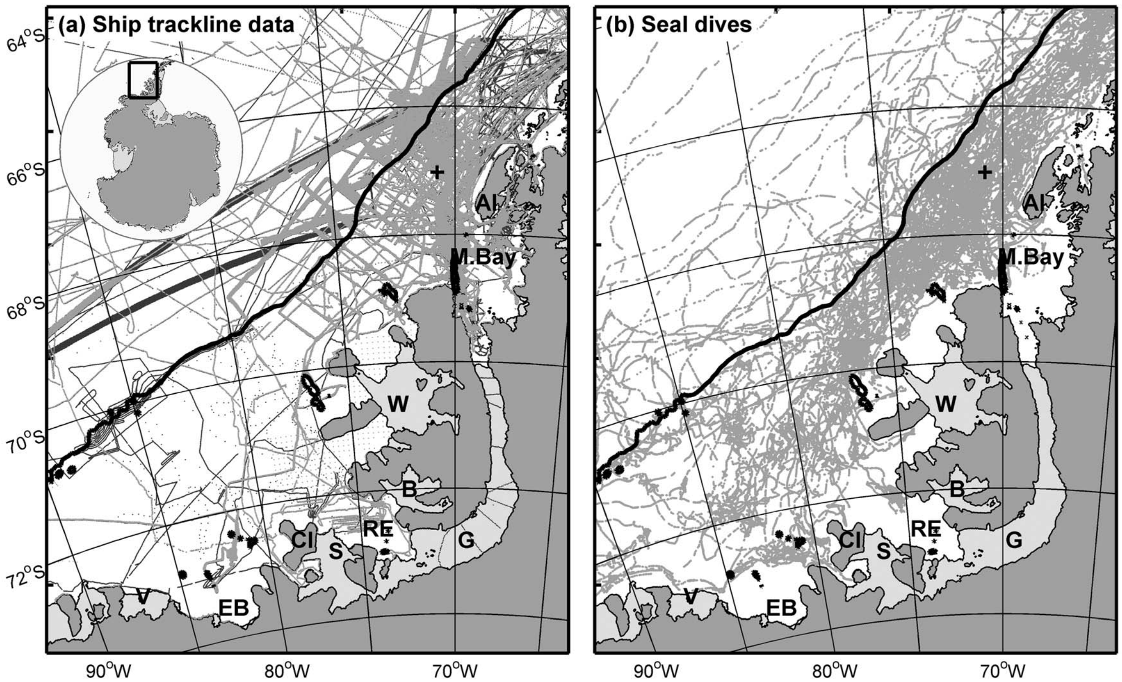

Figure 1. (a) Available ship trackline bathymetry (gray dots) for the western Antarctic Peninsula continental shelf. Darker gray dots indicate recent ship trackline data not used in generating TOPO12.1 (http://topex.ucsd.edu/marine_topo/; see section 4). Location of study region is indicated by the rectangle on the map of Antarctica (upper left). (b) Locations of all seal dives (gray dots) from 2005–2009. In Figures 1a and 1b, locations of five ice shelves are indicated: Wilkins (W); Bach (B); George VI (G); Stange (S); and Venable (V). Case Island (CI), Adelaide Island (AI), Ronne Entrance (RE), Eltanin Bay (EB) and Marguerite Bay (M.Bay), discussed in the text, are indicated. Symbol (+) west of Adelaide Island indicates location of data used in Figure 3. Black line is the 1000 m isobath from TOPO12.1.

[6] Maximum dive depth $D(x,y)$ was recorded for each dive. The depth resolution varied from ~0.5 dbar at the surface to ~5 dbar at the full scale reading of 2000 dbar [*Boehme et al.*, 2009]. The mean and modal values of D for the complete data set were ~350 m; however, a few dives (~0.5% of the total) exceeded 1000 m off the continental shelf. While on the continental shelf, elephant seals feed predominantly on or near the sea floor, thus reaching the sea floor on a high proportion of their dives [*McConnell et al.*, 1992; *McConnell and Fedak*, 1996].

3. Bathymetry Estimation From Seal Dive Depths

[7] We first determined the probability that a specific seal dive was to the seabed, by comparing dive depth with trackline measurements of water depth (H) within a specified small search radius r_s of each seal dive location. Our choice of r_s is a compromise between finding sufficient "co-located" trackline and seal data, uncertainty in seal dive location (~4 km) and the increasing variance of real bathymetry within an area as we increase r_s. For all available trackline measurements within r_s of a seal dive, we calculated the mean and maximum values of these data, H_{av} and H_{max}, respectively.

[8] Using a value of $r_s = 2$ km we found, as expected, that many seal dives were much shallower than H_{av} and H_{max} but few were significantly deeper (Figures 2a and 2b). For $H_{av} < 700$ m, about 30% of all seal dives reached within 20 m of the measured value of H_{av}; we interpret these as dives to the seabed. The limit of $H_{av} < 700$ m encompasses most of the wAP continental shelf with the exception of portions of some deep glacial troughs. The typical difference between H_{max} and H_{av} for $H_{av} < 700$ m is ~20 m (Figure 2c).

[9] Most of the continental shelf region east and north of Marguerite Bay has been extensively mapped along ship tracks (see Figure 1 and *Bolmer* [2008]) and is also densely sampled by seal dives (Figure 1b). For a site west of Adelaide Island (see Figure 1a for location) where $H_{av} = 487$ m, 43 seal dives were recorded within a circle of radius 1 km. The range of D was from 246 m to 494 m (Figure 3) with 13 dives (~30%) being within 5 m of the measured depth, consistent with the previous analysis based on the more broadly distributed data set.

[10] Given a probability of 0.3 that a particular seal dive is to the seabed and assuming that these dives are randomly distributed within the entire sample of dives, we require eight or more dives to have a >95% probability that the deepest dive in a random sample is to the seabed. For each dive, we located all N dives within a search radius r_s of the central dive. If $N \geq 8$ and the central dive was the deepest dive in the set, we identified it as a dive to the seabed. If $N < 8$, we did not record a bathymetry value.

[11] Increasing r_s increases the number of bathymetry estimates obtained by this method but also increases the uncertainty in depth due to true bathymetric variability. Based on seal dive distribution (Figure 1b), reasonable coverage of the continental shelf south of Marguerite Bay with the present dive-depth data set requires $r_s \approx 4$ km.

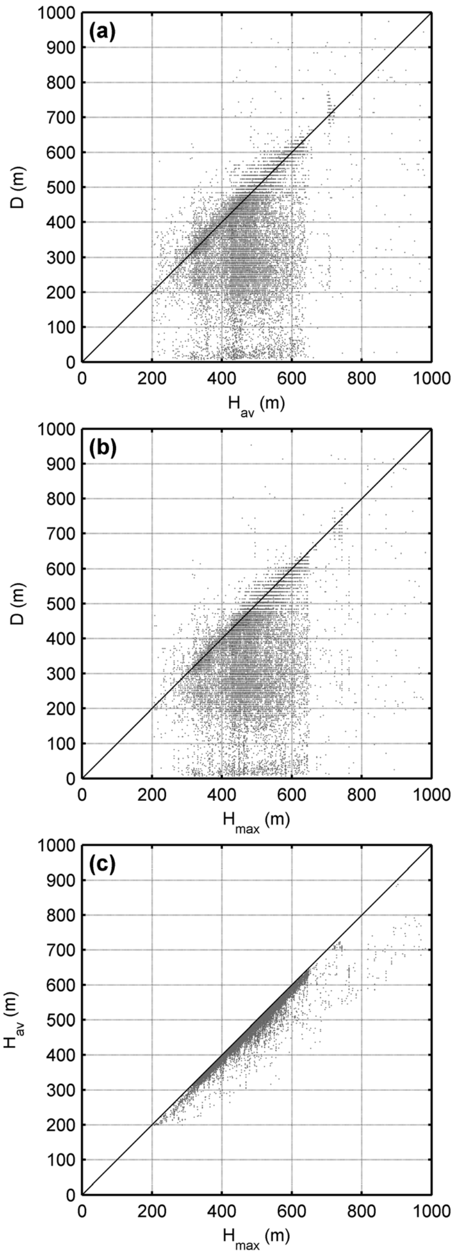

Figure 2. (a) Plot of seal dive depth (D) vs average water depth (H_{av}) for all seal dive locations within 2 km of a trackline depth measurement. (b) Same as Figure 2a, but for maximum water depth (H_{max}) within 2 km of each seal dive location. (c) Plot of H_{av} vs H_{max} for all trackline measurements within 2 km of each seal dive location.

Figure 4b shows the depths of dives interpreted as bathymetry for this value of r_s.

4. Discussion

[12] The map of seal-derived bathymetry (Figure 4b), even though incomplete due to the inhomogeneous distribution of seal dives, reveals bathymetric features that are not well represented in a recent bathymetry grid, TOPO12.1 (http://topex.ucsd.edu/marine_topo/) shown in Figure 4a. TOPO12.1 was developed using satellite marine gravity to interpolate between existing trackline data, following the methodology of *Smith and Sandwell* [1997]. The trackline data set incorporated into TOPO12.1 (points shown in Figure 4a) excludes several recent cruises that significantly improve data density over the southern portion of the wAP continental shelf; see Figure 4c. Differences between seal-derived bathymetry and the TOPO12.1 topography grid, and between updated trackline bathymetry and TOPO12.1, are presented in Figure S1 in the auxiliary material.[1]

[13] The troughs between islands abutting the western side of Wilkins Ice Shelf (WIS) are much deeper than in the TOPO12.1 grid; see features '1' and '2' on Figure 4. In TOPO12.1, sills ~400 m deep (features marked '3') separate the deep troughs of the inner shelf from the shelf break, whereas the seal data indicate a minimum sill depth of ~600 m. The onshore flow of warm CDW along these troughs and into the sub-ice-shelf cavity may have played a role in preconditioning WIS for the large mass loss events beginning in 2008 [*Braun et al.*, 2009]. The same trough system constitutes the primary pathway for deep water into Ronne Entrance and to the southern front of George VI Ice Shelf.

[14] The southernmost trough in our domain (feature '5' on Figure 4), trending northwest from the channel between Case Island and the mainland, is more linear than in TOPO12.1, providing a different view of ice stream behavior during the last glacial maximum; however, more data are required to better map its path across the outer continental shelf.

[15] The seal dive depth data extend the sampling of the deep continental shelf across the northern boundary of Eltanin Bay and north of Venable Ice Shelf west of Eltanin Bay. The seal data more clearly delineate the bank north of Eltanin Bay (feature '6' on Figure 4). Trough and bank features '5' and '6' will influence the cross-slope flow of water into and out of this region where a coastal polynya is frequently found [*Tamura et al.*, 2008]. *Holland et al.* [2010] noted the importance of correctly modeling the Eltanin Bay polynya, as its dense water production can have a significant impact on cross-shelf flows in this region.

[16] Recently acquired trackline data, not included in TOPO12.1, greatly improves the mapping of Ronne

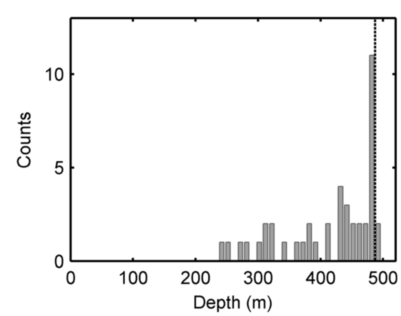

Figure 3. Histogram of dive depth for 43 seal dives within a radius of 1 km of a point east of Adelaide Island (see Figure 1 for location). Mean depth at this site, from ship-based measurements, is 487 m (dashed vertical line). Maximum seal dive depth in this set is 494 m.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL044921.

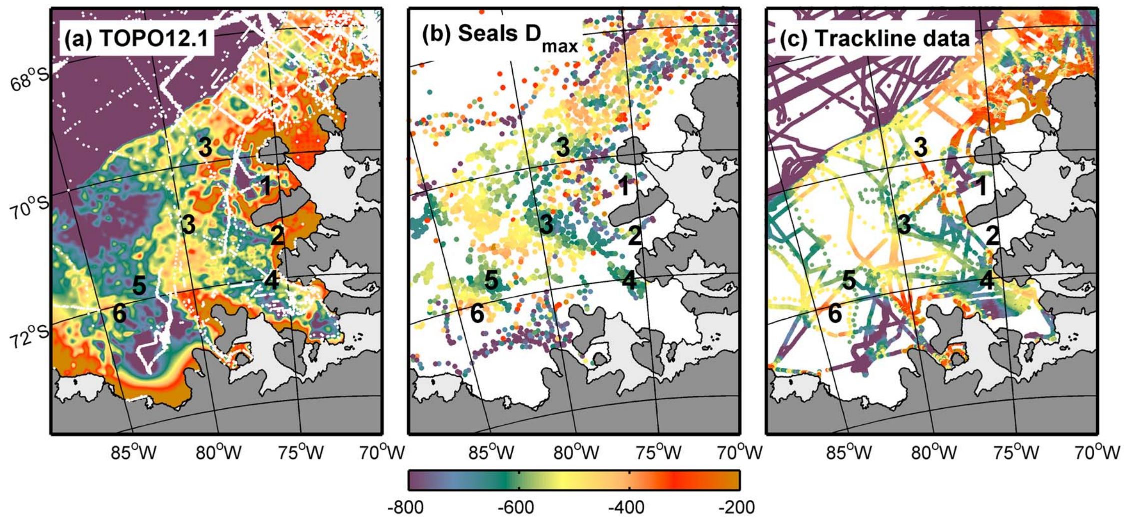

Figure 4. (a) Bathymetry (m) for the southwestern Antarctic Peninsula continental shelf from the Global Predicted Bathymetry V12.1 (TOPO12.1) grid (see section 4). White dots indicate cells in the TOPO12.1 grid containing at least one trackline depth measurement. (b) Depth of seal dives interpreted as benthic dives (see section 3). (c) Depth from updated trackline data set, shown only where at least one measurement is available in a 1 km box. Color scale is the same for all panels and is shown below the map. Identified features 1–6 are described in section 4. Differences between seal and updated trackline data are presented in the auxiliary material.

Entrance and the southern trough (features '4' and '5' in Figure 4c) relative to TOPO12.1. However, even with these new trackline data, the bathymetry derived from seal dive depths significantly improve the coverage of the southern portion of this domain.

[17] Further work is required to improve the map of this region by merging the trackline and seal-derived data sets. Based on the statistics of benthic to total dives, up to ~5% of dives interpreted as reaching the seabed may be shallow: these cells appear as localized shallow points in Figure 4b. Furthermore, occasionally the seal data indicate depths that are significantly greater than found in nearly co-located trackline data (Figure 2), requiring a more rigorous assessment of data quality for both data sets. Nevertheless, the preceding analysis demonstrates that seal dive depth data can be used to improve bathymetric maps for regions with sparse trackline depth data.

[18] There are several benthic foraging marine mammals that are easily instrumented [*Costa and Gales*, 2000, 2003; *Le Boeuf et al.*, 2000; *Arnould and Hindell*, 2001; *Villegas-Amtmann et al.*, 2008]; thus, there is considerable potential for extending this methodology to other regions around Antarctica, in the Arctic, and elsewhere. Furthermore, the instruments used in this study were optimized for collection of hydrographic data. If, instead, the primary goal is collection of bathymetric data, tags can be programmed differently to report the bottom of the dive with depth resolution of less than 1 dbar. Tags that obtain locations from GPS would significantly improve position accuracy, but are not presently available with CTD sensors. However, if bathymetry and water temperature data alone were sufficient, GPS tags that provide spatial accuracy to within 36 m and water temperatures to ±0.1°C could be deployed [*Costa et al.*, 2010b; *Simmons et al.*, 2009].

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