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Upper ocean variability in west Antarctic Peninsula continental shelf waters as measured using instrumented seals

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Abstract

Temperature profile data for the west Antarctic Peninsula (WAP) continental shelf waters, collected from freely ranging instrumented seals (crabeater, *Lobodon carcinophagus* and leopard, *Hydrurga leptonyx*), were used to demonstrate that these platforms can be used to supplement traditional oceanographic sampling methods to investigate the physical properties of the upper water column. The seal-derived profiles were combined with temperature profiles obtained from ship-based CTD measurements and from a numerical circulation model developed for the WAP to describe changes in temperature structure, heat content, and heat flux in the upper ocean waters of the WAP continental shelf. The seal-derived data documented the fall-to-winter transition of the surface waters and the shelf-wide presence of modified Circumpolar Deep Water (CDW) below 150–200 m on the WAP continental shelf. The heat content of the upper 200 m calculated from the seal-derived temperature profiles ranged between 1000 and 1500 MJ m^{-2}; similar estimates were obtained from simulated temperature distributions. The seal-derived temperature measurements provided broader space and time resolution than was possible using any other currently available oceanographic sampling method. As such, the seal-derived measurements provided a valuable dataset for evaluation of temperature fields obtained from a numerical circulation model.

Keywords: Crabeater seal; Ocean observation; Western Antarctic Peninsula; Heat budget; Water temperature profiles

1. Introduction

The lack of consistent and long-term sampling has limited the ability to describe variability in the hydrographic structure of the oceans, especially in remote regions such as the Antarctic. The sparse spatial and temporal coverage and limited upper-ocean variability data have been recognized as impediments to understanding seasonal to decadal signals in climate change (Ocean Observing System Development Panel, 1995; CLIVAR, 1998). Ocean sampling programs that range from long-term time series at specific sites (e.g., Hawaii Ocean Time-series), to large-scale ship-based sampling (e.g., World Ocean Circulation Experiment) to large-scale drifter-based sampling (e.g., First Global GARP Experiment) have been developed to address some of these sampling deficiencies. One notable recent example is the Argo program, which has deployed autonomous buoys that drift passively and transmit an upper ocean temperature–salinity profile every 10–14 days (Wilson, 2000). However, Argo floats cannot work in environments that are impacted by sea ice and have limited capabilities in the Southern Ocean due to the prevailing current patterns, which tend to expel floats from Antarctic coastal waters (see for example drifter tracks in Beardsley et al. (2004)).

The use of marine animals as autonomous ocean profilers is now accepted because of the demonstrated feasibility of deploying temperature and salinity tags on marine mammals (Campagna et al., 2000; Boehlert et al., 2001; Lydersen et al., 2002; Hooker and Boyd, 2003; Biuw et al., 2007), seabirds (Wilson et al., 1992; Weimerskirch

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et al., 1995; Charrassin et al., 2002, 2004; Wilson et al., 2002), turtles (McMahon et al., 2005), and fish (Block et al., 1997; Weng et al., 2005). The datasets acquired from these studies have provided considerable insights into migration patterns, foraging patterns, physiology, and general behavior of numerous species (Costa, 1993; Le Boeuf et al., 2000a; Charrassin et al., 2002; Costa and Gales, 2003; Bradshaw et al., 2004; Costa and Sinervo, 2004; Burns et al., 2004; Block et al., 2005; Weng et al., 2005; Campagna et al., 2006; Shaffer and Costa, 2006; Biuw et al., 2007). While the use of marine animals as autonomous ocean profilers is not new, the environmental datasets generated have rarely been used to address specific oceanographic questions (Costa, 1993; Charrassin et al., 2002; Lydersen et al., 2002). Further tag-collected oceanographic data are collected at a scale of resolution that matches the animal's behavior, which can be extensive for some species, and the measurements can augment traditional methodologies for areas where data are unavailable or difficult to collect. The latter point is especially relevant to Antarctic continental shelf systems that are difficult to access for significant portions of the year and are not frequently or reliability resolved by satellite-based measurement systems. The lack of data for Antarctic continental shelf systems, especially during winter, limits understanding of sea-ice formation, air–sea flux of heat, and water-column variability.

As part of the US Southern Ocean Global Ocean Ecosystems Dynamics (SO GLOBEC) program (Hofmann et al., 2004), satellite tags with temperature sensors were deployed on 18 crabeater seals (*Lobodon carcinophagus*) and one leopard seal (*Hydrurga leptonyx*) (Burns et al., 2004; Kuhn et al., 2006) at sites along the inner and outer portions of the west Antarctic Peninsula (WAP) continental shelf (Fig. 1A, Table 1). The data return from these tags provided temperature observations that spanned the

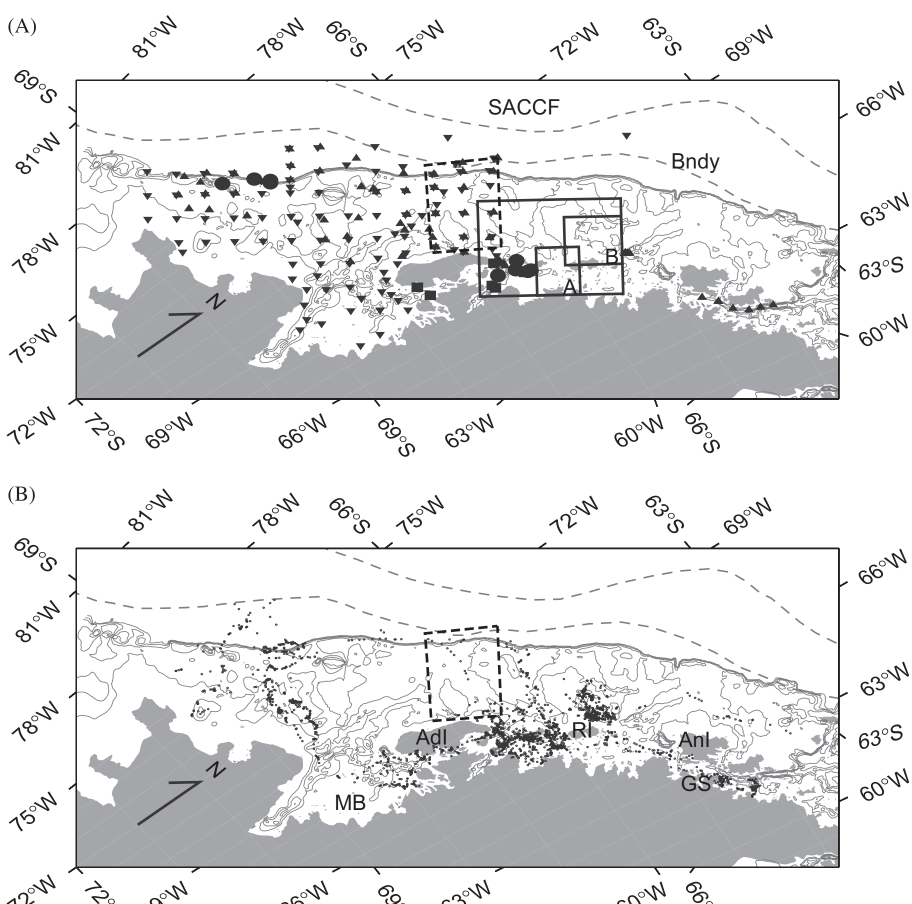

Fig. 1. (A) Locations of the hydrographic stations occupied during the SO GLOBEC survey cruises in April–May 2002 (▲) and August–September 2002 (▼) and places where seals were instrumented in April–May (■) and August–September (●). The dashed-line box indicates the portion of the SO GLOBEC hydrographic grid from which the average vertical temperature profiles were constructed from CTD measurements. The smaller sub-areas (Area A and Area B) used for the regional comparisons of the seal-derived temperatures are indicated. The larger box indicates the area used to calculate heat content and heat flux from the seal-derived and simulated temperature distributions. Bottom bathymetry isobaths (400, 600, 800, 1000 m) and the historical locations of the Southern Antarctic Circumpolar Current Front (SACCF) and the Southern Antarctic Circumpolar Current Boundary (Bndy) obtained from Orsi et al. (1995) are shown. (B) Distribution of the crabeater seal dives that returned temperature profiles during 2002 and the location of the portion of the SO GLOBEC hydrographic grid (dashed-line box) used to construct average vertical temperature profiles. Geographic names are abbreviated as Gerlache Strait, GS; Anvers Island, AnI; Renaud Island, RI; Adelaide Island, AdI; Marguerite Bay, MB.

Table 1
Summary of seals tagged during the 2002 SO GLOBEC cruises

Seal	Seal ID	Latitude (°S)	Longitude (°W)	Tag location	Sex	Mass (kg)	Start date	End date	No. of profiles
1	G021	66.612	67.562	CS	M	270.5	18 April	10 July*	404
2	G018	66.861	66.809	CS	M	156.5	16 April	26 April	81
3	G022	67.422	67.579	CS	F	268.0	20 April	None	0
4	G026	67.596	68.244	CS	F	266.0	27 April	18 October*	726
5	G017	66.380	66.725	CS	F	117.5	15 April	2 May*	103
6	G019	76.722	76.722	CS	F	155.5	15 April	22 April	73
7	G023	67.602	68.242	CS	M	174.0	23 April	26 April*	20
8	G024	67.541	67.733	CS	F	256.0	27 April	29 April*	11
9	G040	68.336	75.203	SB	M	301.5	14 August	7 September	49
10	G033	66.377	66.738	CS	F	267.5	6 August	None	0
11	G031	66.335	66.681	CS	F	385.0	6 August	26 August*	112
12	G038	67.149	70.582	CS	M	273.0	9 August	None	0
13	G034	66.538	67.076	CS	F	294.5	8 August	16 September	128
14	G035	66.446	66.941	CS	F	238.0	8 August	12 August	30
15	G036	76.722	66.765	CS	F	207.0	8 August	26 August*	132
16	G039	68.522	75.951	SB	M	246.5	13 August	25 August*	17
17	G037	66.427	67.025	CS	M	197.5	19 August	19 August*	1
18	G042	67.883	76.722	SB	M	224.0	18 August	26 October*	326
19	G041	68.040	74.778	SB	M	269.0	16 August	25 August	40

The latitude, longitude, location of tag deployment, sex, and mass are shown for each seal. Tagging locations are designated as near Crystal Sound (CS) or near the shelf break off Alexander Island (SB). Geographic locations are shown on Fig. 1. Seal identification (ID) numbers G0 number are for cross-referencing the seals to Burns et al. (2004). The tag start and end dates and the number of dives for which temperature data were recorded (small percent of the total dives) are also shown for each seal. Animals for which the tag continued to transmit depth and location data after the temperature sensor failed are indicated by (*). Three seals did not report any temperature profile data. Seal 17 (G037) was a leopard seal (*Hydrurga leptonyx*).

fall-to-winter and winter-to-spring transition of the upper water column, as well as observations of Upper Circumpolar Deep Water (UCDW), which floods the WAP continental shelf below 150–200 m (Klinck, 1998; Smith et al., 1999; Klinck et al., 2004).

The goal of this study is to show that seal-collected temperature data can be used to investigate the physical properties of the upper water column on the WAP continental shelf. This goal is addressed by combining the seal tag-derived temperature measurements with simulated temperature fields from a numerical circulation model developed for the WAP (Dinniman and Klinck, 2004) to describe changes in temperature structure, heat content, and heat flux in the upper ocean waters of the WAP continental shelf.

2. Datasets and methods

2.1. Seal-derived temperature measurements

During the SO GLOBEC field studies in austral fall and winter of 2002, satellite-relay data loggers (SRDL, manufactured by the Sea Mammal Research Unit, University of St. Andrews, Scotland) with a temperature sensor were attached to eight crabeater seals near Adelaide Island in April–May (Fig. 1A, Table 1). An additional 10 crabeater seals and one leopard seal were instrumented during August–September; four near the shelf break off Alexander Island and seven near the north end of Adelaide Island (Fig. 1A, Table 1). The procedures used to attach the SRDL tags are described in Burns et al. (2004) and Gales et al. (2005). The SRDL tags collected information on dive depth, swimming speed, and, for the deepest dive in each hour, water temperature with depth. The pressure accuracy was ± 5 dbar and temperature resolution was $\pm 0.001\,^{\circ}$C. Depth and temperature data were logged internally and summaries were transmitted via the Advanced Research and Global Observation Satellite (ARGOS) system using algorithms and procedures described in Rual (1996) and Fedak et al. (2001, 2002). Three of the tags that were deployed did not return any temperature data (Table 1).

The tag-derived pressure records were used to determine the start of individual dives so that the temperature record could be partitioned into individual vertical profiles of water temperature at locations based on a linear interpolation of distance by time between ARGOS locations (Fig. 1B). Of the tags that worked, an average of 279 temperature profiles, that covered 59 days, were recovered per seal, for an average of almost five casts per day over the average 59-day deployment period (Table 1).

The tagged seals moved throughout the WAP continental shelf area (Fig. 2) and analyses of these distributional data are given in Burns et al. (2004, 2008) and Kuhn et al. (2006). Most of the dives that returned temperature data were from the region between Adelaide Island and Anvers Island and from the continental shelf area off of Marguerite Bay (Fig. 1B) and these data are the focus of this study. The region in which the temperature data were concentrated was partitioned into a $10\,\text{km} \times 10\,\text{km}$ grid

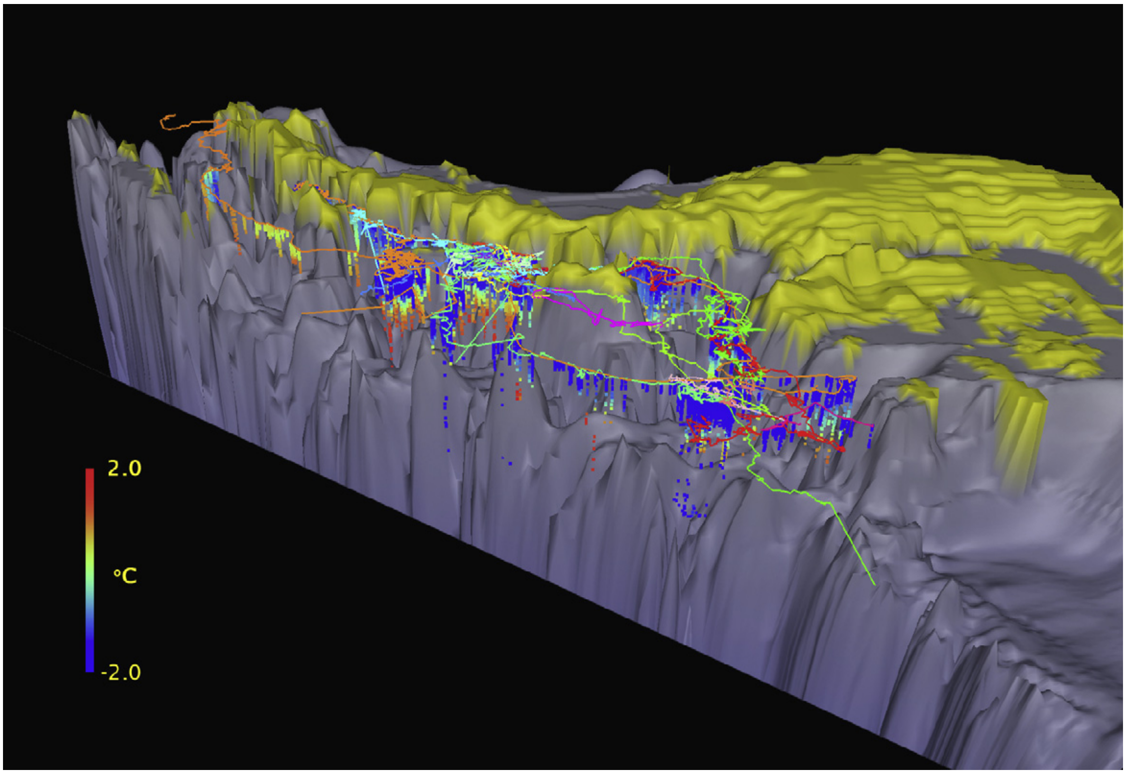

Fig. 2. Composite distribution of individual trajectories from crabeater seals tagged in 2002. The seal temperature profiles are indicated by the vertical lines or series of points descending from the track. The figure is constructed with the viewer looking east towards Marguerite Bay from a point west of the Antarctic Peninsula.

and the number of dives that returned temperature profiles was tallied in each grid cell for each month (Fig. 3). The grid cells were defined using a Universal Transverse Mercator grid in which a distance-based Cartesian coordinate system, with a base point at 77.718°S, 73.0601°W and a rotation angle of 60° to align the coordinate axis with the coastline, was used to define individual cells.

2.2. Comparisons of seal- and CTD-derived temperature measurements

As the seal tags could not be recovered, there was no post-calibration of the temperature sensor. Therefore, coincident *in situ* CTD-derived temperature profiles were used to evaluate the accuracy of the temperature measurements returned from the tags. This comparison was made using temperature profiles obtained from CTD measurements made during the SO GLOBEC survey cruises done in April–May and August–September 2001 and 2002 (Fig. 1A, Table 2). The hydrographic measurements were collected using a Sea-Bird 911+ Niskin/Rosette CTD sensor system, which included dual sensors for temperature and conductivity. Details of the CTD data collection and calibration for the SO GLOBEC cruises are given in Klinck et al. (2004).

Although the seal-derived temperature data were from the 2002 field season, the CTD-derived temperatures from both field seasons were used to increase the overlap between hydrographic station and seal temperature profile locations. The four cruises followed essentially the same fixed grid of stations and differences in station locations between the fall and winter cruises (Fig. 1A) and between the 2 years were determined by sea-ice conditions (Table 2). Combining the CTD measurements from the four cruises is valid because fall and winter surface mixed-layer temperatures are similar in the study region (Klinck, 1998; Smith et al., 1999; Klinck et al., 2004), deep surface convection does not occur during the winter, and temperature conditions below 150–200 m are dominated by intrusions of Circumpolar Deep Water (CDW) (Hofmann and Klinck, 1998; Klinck, 1998; Klinck et al., 2004).

The CTD casts made in the region offshore of Adelaide Island on the four SO GLOBEC cruises (Fig. 1A) were used to estimate average vertical temperature profiles because this region provides the most overlap with the seal measurements. The CTD casts were separated into three regions: offshore (within 10 km of the shelf break and offshore), mid-shelf (between offshore and inshore regions), and inshore (within 40 km of the coast). This partitioning captures the across-shelf variability in the vertical temperature structure (Klinck et al., 2004). The seal-derived temperature profiles, apportioned in the same manner, were then compared to these average profiles (Fig. 4). The seal-derived temperatures covered more of the shelf area in each of the hydrographic regions (Fig. 1B), and as a result include more variability.

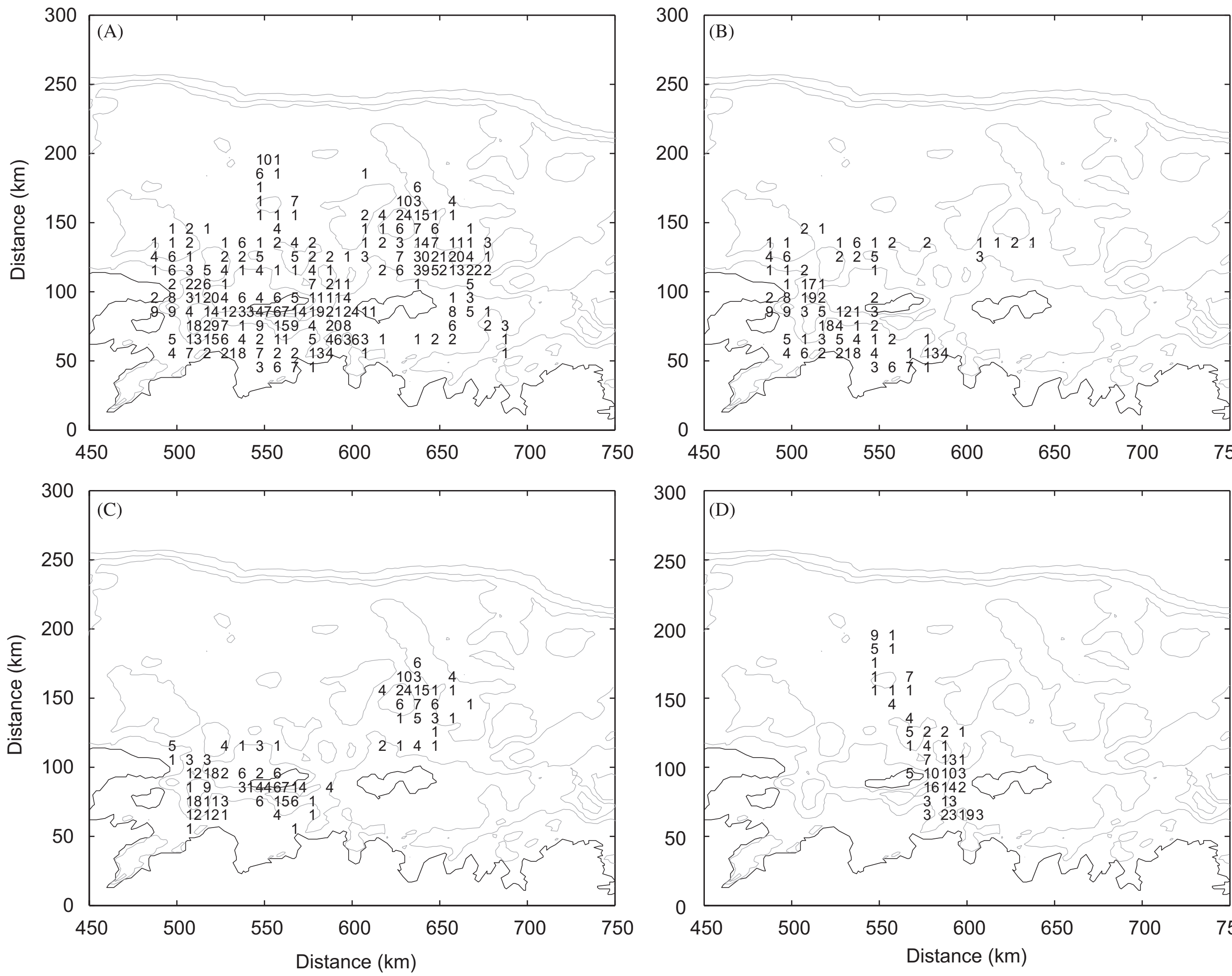

Fig. 3. Total number of seal dives that returned temperature and depth information for April–October 2002 (all data) (A), April 2002 (B), August 2002 (C), and September 2002 (D) within 10 km × 10 km grid cells on the west Antarctic Peninsula continental shelf.

Table 2
Cruise dates and number of shipboard CTD casts made during the SO GLOBEC 2001 and 2002 austral fall and winter cruises

Cruise	Cruise dates	CTD casts	CTD casts/seal overlap
Fall 2001	24 April–5 June	102	18
Winter 2001	24 July–31 August	74	21
Fall 2002	9 April–21 May	107	19
Winter 2002	31 July–18 Sept	130	53

The number of CTD casts is greater than the number of stations occupied during a cruise. The number of CTD casts that were occurred in the areas where the seals returned vertical temperature profiles is also shown.

2.3. Seal-derived depth–time temperature distributions

The movement tracks of two crabeater seals (Figs. 5A and 6A) were used to construct depth–time temperature distributions (Figs. 5B and 6B). The temperature measurements along the tracks were binned at 10-m and 5-day intervals and an average calculated for each bin. Bins with no data were not included in the averages. The near-surface temperature resolution was improved by splitting the surface bin into two 5-m bins. The temperature records from these seals provided coverage of the upper 300 m that was typically based on 10 or more dives and there were often 30–40 dives in the upper 100 m (Figs. 5C and 6C).

The seal-derived temperature measurements in two regions (Fig. 1A) were averaged at 10-m and 5-day intervals, with a value added at 5 m, to produce regional depth–time temperature distributions (Fig. 7). The two regions provide comparison of sporadic measurements due to the transient nature of seal sampling (Fig. 7A and B) versus nearly continuous measurements (Fig. 7C and D). Averaging the seal temperature profiles in limited areas provides representation of depth–time temperature variability for a region without aliasing space into time, which can occur along tracks of individual seals.

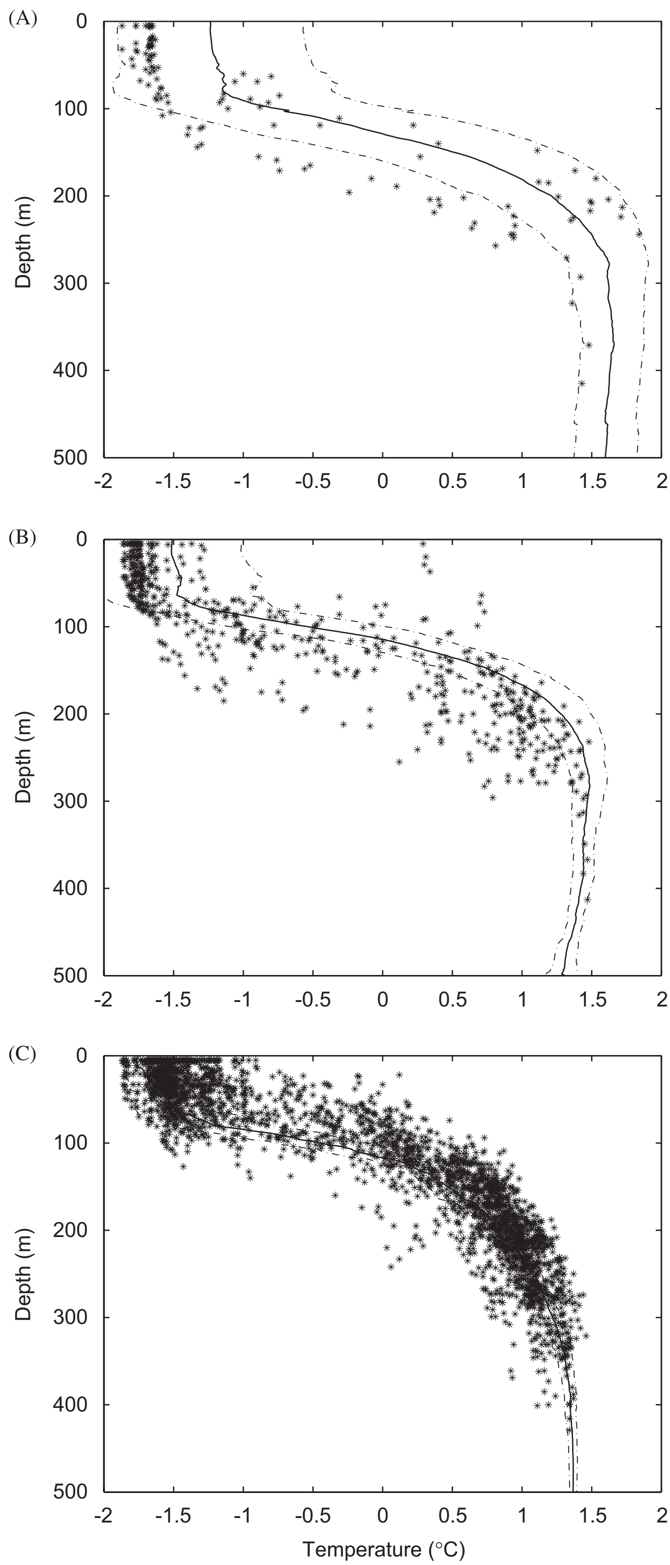

Fig. 4. Comparisons of seal-derived temperatures to average temperature vertical profiles constructed from SO GLOBEC hydrographic observations from measurements made within 10 km of the shelf break and further offshore (A), in the middle WAP shelf (B), and within 40 km of the coast (C). For clarity, only dives deeper than 200 m are shown. The average temperature (heavy line) and one standard deviation (dashed line) were obtained using temperature measurements from all four SO GLOBEC survey cruises. The location of the hydrographic stations used for the average temperature profiles is shown by the dashed-line box in Fig. 1.

2.4. Simulated temperature distributions

Circulation and water properties of the WAP continental shelf were simulated using the Rutgers Ocean Modeling System (ROMS) with a grid spacing of 5 km and accurate representation of the depth and coastline. As part of the circulation simulation, temperature was explicitly calculated within the interior model domain by an advection–diffusion equation for heat. The temperature was specified along the model open boundaries from monthly climatologies and a surface heat budget (e.g., shortwave, longwave, latent heat, and sensible heat fluxes), including the effects of sea-ice, was calculated at every point and used to adjust the surface temperature. Comparisons of the simulated vertical temperature structure with CTD-derived temperature sections taken across the shelf from Adelaide Island in February and July showed that the model, at least qualitatively, represented the seasonal changes in the temperature throughout the water column (see Fig. 9 in Dinniman and Klinck, 2004). Details of the model initiation and forcing are provided in Dinniman and Klinck (2004).

The WAP simulation was started in winter and the temperature distributions used in this analysis were obtained from the second year of the simulation after model adjustment (Dinniman and Klinck, 2004). The simulated temperature distributions were averaged from the 24 vertical layers over 5-day intervals for an area north of Adelaide Island (large box, Fig. 1A) to produce a depth–time temperature distribution (Fig. 8) for comparison to the seal-derived temperatures obtained in the same region. The simulated temperature distribution, although not specific to a given year, can be averaged over areas to create climatological estimates of temperature variability throughout the year.

2.5. Estimation of heat content and heat change

The rate of heat change was estimated by the time change of the vertically integrated heat content of the shelf waters using the seal-derived and simulated temperature measurements from an area north of Adelaide Island (large box, Fig. 1A). The heat content (H) was calculated relative to the surface freezing temperature ($T_f = -1.865\,°C$) at a salinity of 34.0 and a pressure of 0 dbar as

$$H = \rho\, c_p (T - T_f),$$

where ρ is the density of seawater (1027.4 kg m^{-3}), c_p is the specific heat of seawater (3994.6 J °C^{-1} kg^{-1}), and T is the measured temperature value. The integrated heat content was obtained by integrating H from the surface to the middle of the thermocline, which was taken as 200 m (Fig. 9A). The lower limit excluded the large heat content of the sub-pycnocline waters, which was not sampled by the majority of the seal dives. The heat flux was estimated as the time change of the integrated heat content (Fig. 9B). The space and time variability of the seal measurements

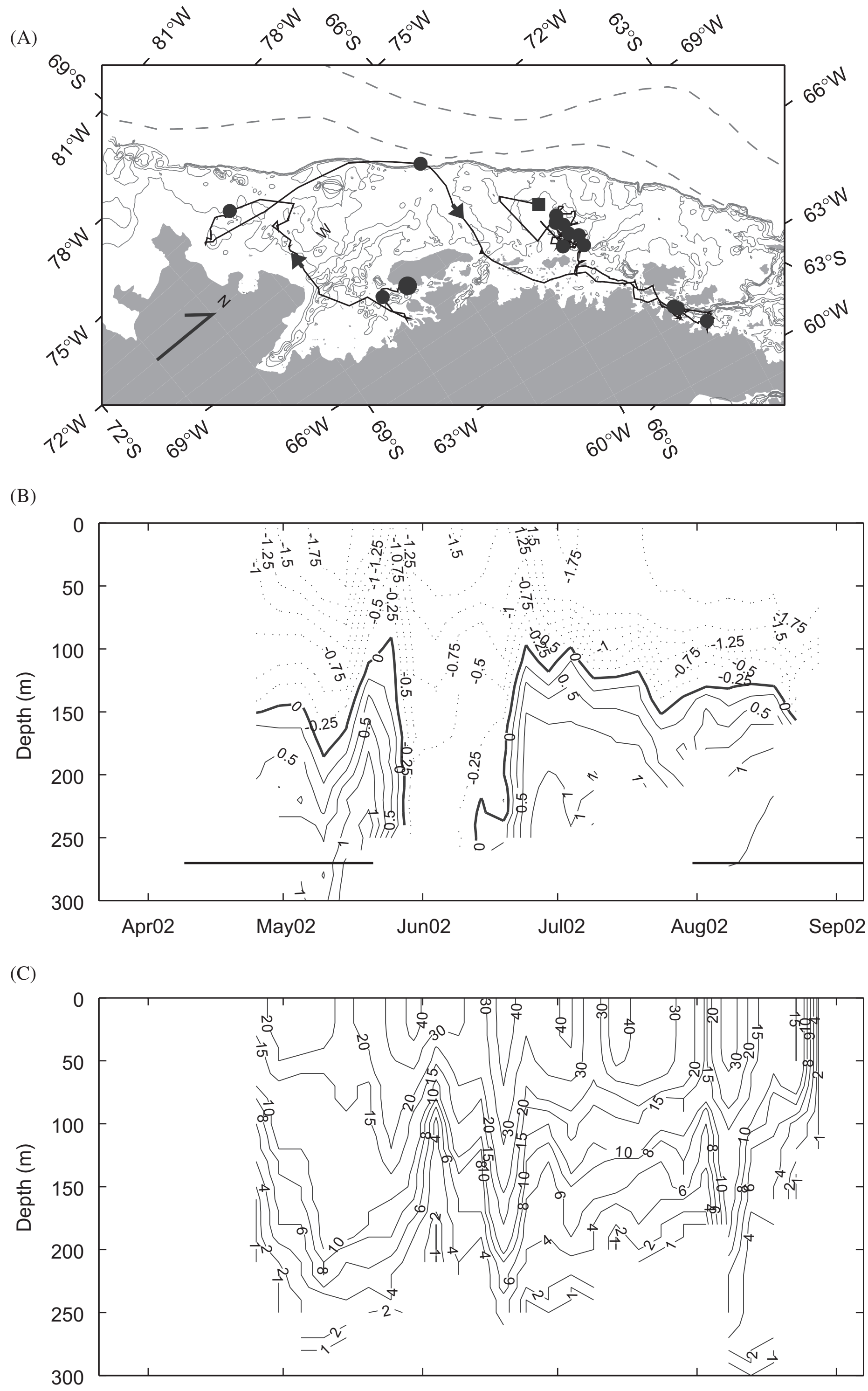

Fig. 5. (A) Track followed by crabeater seal 4 (G026) after being instrumented in late April 2002 (Table 1). The start and end of the track are indicated by (●) and (■), respectively; smaller circles along the track indicate 10-day intervals and arrows indicate direction of travel. (B) Depth–time temperature distribution obtained from measurements made by crabeater seal 4. The 0 °C isotherm is indicated by the heavy line; negative temperatures are indicated by dashed lines. The seal-derived temperatures were averaged into 5-day and 10-m intervals to obtain the temperature distribution. The horizontal lines indicate the times of the SO GLOBEC survey cruises in 2002. (C) Depth–time distribution of the seal dives that were used to construct the temperature distribution.

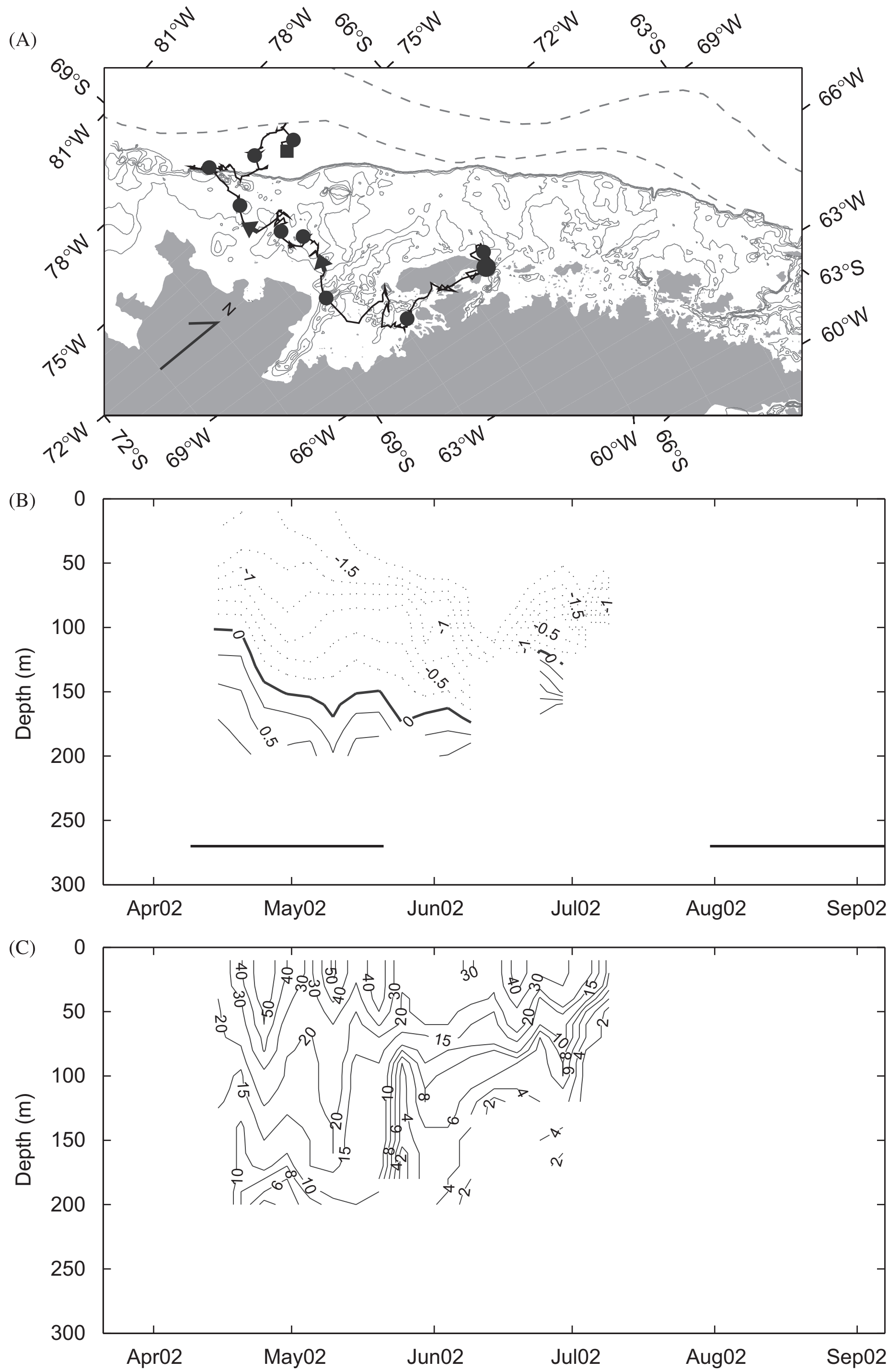

Fig. 6. (A) Track followed by crabeater seal 1 (G021) after being instrumented in mid-April 2002 (Table 1). The start and end of the track are indicated by (●) and (■), respectively, smaller circles along the track indicate 10-day intervals and arrows indicate direction of travel. (B) Depth–time temperature distribution obtained from measurements made by crabeater seal 1. The 0 °C isotherm is indicated by the heavy line; negative temperatures are indicated by dashed lines. The seal-derived temperatures were averaged into 5-day and 10-m intervals to obtain the temperature distribution. The horizontal lines indicate the times of the SO GLOBEC survey cruises in 2002. (C) Depth–time distribution of the seal dives that were used to construct the temperature distribution.

produced variability in the integrated heat content that is amplified by time differencing. To reduce this variability, the integrated heat content was interpolated to daily values and then smoothed with three passes of a 1–2–1 smoother.

The heat content relative to surface freezing was calculated from the simulated temperature fields and integrated to 200 m and time differenced to obtain the heat flux (Fig. 9C and D). The simulated fields do not

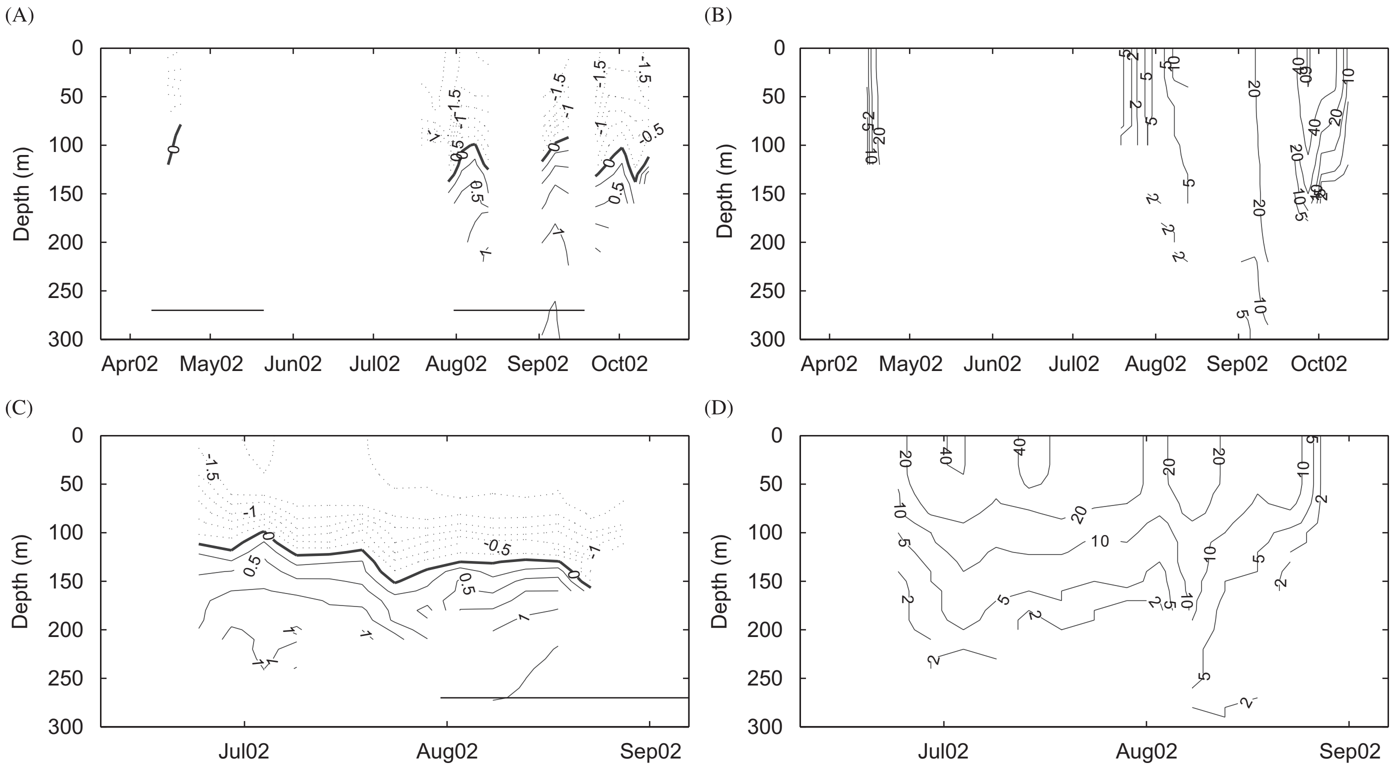

Fig. 7. Depth–time temperature and dive count distributions constructed from seal-derived measurements, averaged at 10-m and 5-day intervals, for sub-area A (A, B) and sub-area B (C, D). The sub-areas are shown in Fig. 1.

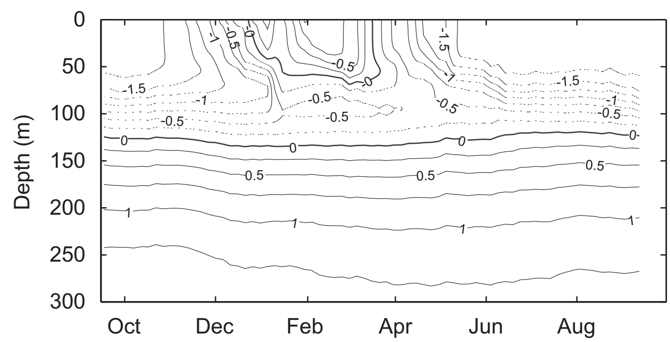

Fig. 8. Depth–time simulated temperature distribution constructed for an area of the WAP north of Adelaide Island (large box, Fig. 1). The 0 °C isotherm is indicated by the heavy line; negative temperatures are indicated by dashed lines.

include the variability seen in the seal-derived fields, so no smoothing was applied to the integrated heat content before calculating the time difference.

3. Results

3.1. Seal dive distribution and sample density

Approximately equal numbers of animals were tagged in April and August 2002 (Table 1). The tagged animals essentially covered the WAP shelf region although there were regions where the seals spent more time (Fig. 2) and the distribution of temperature profiles (Fig. 3A) reflected the tendency of the seals to preferentially use certain areas of the shelf (Burns et al., 2004). The distribution of temperature profiles by month was also consistent with observed changes in the areas of the shelf favored by seals (Burns et al., 2004, 2008). In April, the seals provided temperature profiles mostly around Marguerite Bay and north of Adelaide Island (Fig. 3B). The seals that were tagged in August tended to aggregate in the mid-shelf off Renaud Island (Fig. 3C), which was not sampled routinely by seals tagged in April (Fig. 3B). In August, the seals showed a more confined distribution of animals north of Adelaide Island relative to April (Fig. 3B and C), likely due to the presence of heavy winter sea ice in the area. In September (Fig. 3D), the animals with working tags ranged from the southern end of Renaud Island to the middle of the shelf. During transits between preferred regions, the seals were either not diving deep enough for temperatures to be recorded (<12 m) or were moving rapidly enough that few ARGOS transmissions were received. The tendency for rapid transit between regions results in under-sampling, adding spatial bias to the temperature distributions returned by the seals.

The seals that were instrumented at the shelf break traveled back to the coast (Fig. 1B) and the animals instrumented near the coast, tended to stay there. As a result, most of the seal-derived temperature profiles were from the inner and middle regions of the WAP continental shelf, providing at least one and as many as 50 profiles in

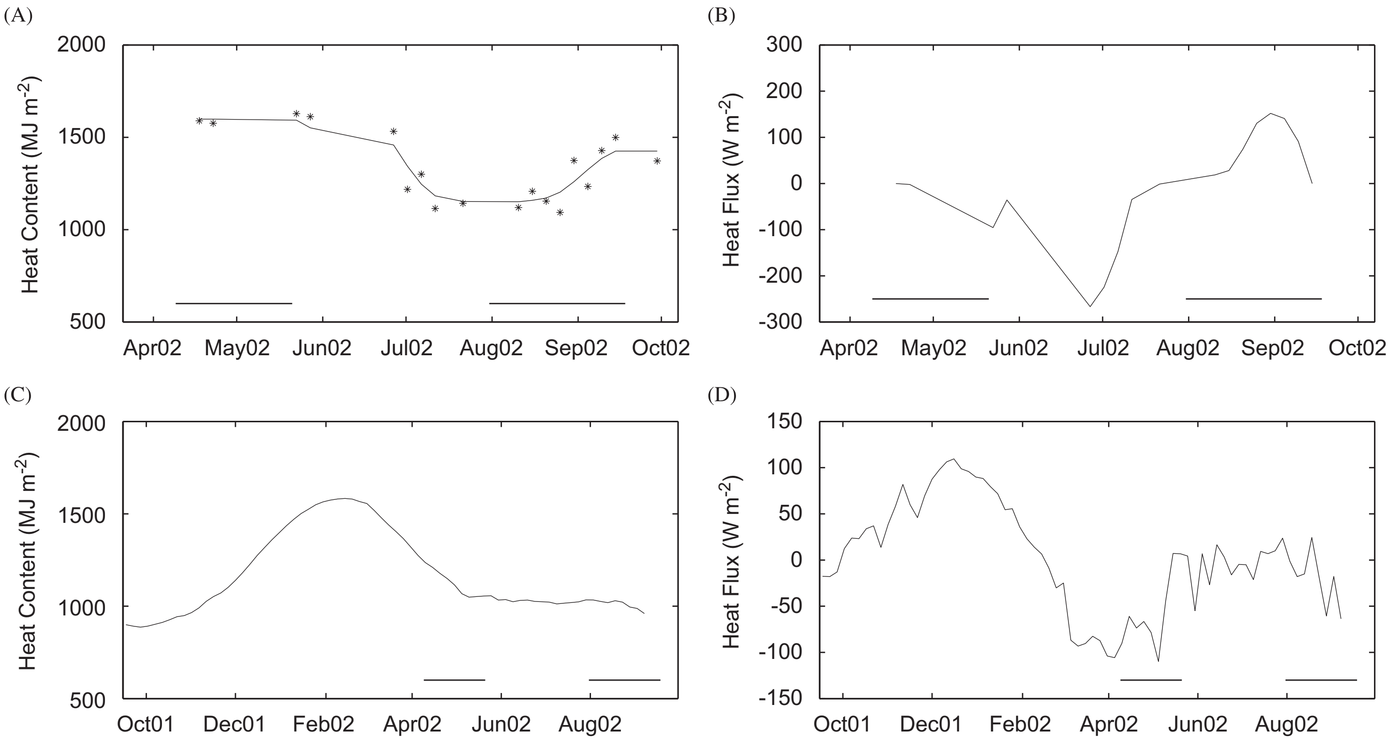

Fig. 9. Vertically integrated heat content (A) and heat flux (B) calculated from temperature profiles made by seals and vertically integrated heat content (C) and heat flux (D) calculated from the simulated temperature distributions for the larger region of the WAP continental shelf shown on Fig. 1. The seal-derived and simulated temperatures were averaged over 5-day intervals. Heat content (MJ m^{-2}) is relative to the freezing temperature at the surface at 34.0 and is integrated over 200 m. Heat flux (W m^{-2}) is the time change of the heat content. Horizontal lines indicate the times of the SO GLOBEC survey cruises. The discrete seal-derived observations are shown by the circles.

some areas (Fig. 3A). These data are from regions that were not sampled during the winter SO GLOBEC cruises because heavy sea-ice cover and relatively unknown bathymetry precluded reaching these regions by ship. Thus, the tagged seals provided some of the first winter vertical temperature profiles from the WAP inner shelf.

3.2. Comparisons of seal- and CTD-derived temperature profiles

In each region, the seal-derived temperatures were consistent with the mean vertical temperature profile and showed scatter that was within the range or larger than that obtained from the CTD-derived temperature measurements (Fig. 4). The temperature values outside of the one-standard deviation were examined to determine their validity and then either retained or eliminated from the dataset. For example, the warm surface temperatures in the mid-shelf area (Fig. 4B) were measured by a seal that was instrumented in late April and then moved into the part of the mid-shelf off Renaud Island (cf. Fig. 1B) where the upper water-column temperatures were still above freezing. This region was not represented in the average vertical temperature profile obtained from the CTD measurements because the SO GLOBEC study region did not extend into this part of the WAP shelf (Fig. 1A). The generally low surface temperature of the mid-shelf average vertical profile is because the majority of the CTD measurements used to create the profile were from times and locations with near-freezing surface waters.

The CTD-derived average vertical temperature profiles in the outer, middle, and inner shelf regions are similar, with near-freezing Winter Water (WW) in upper 100 m, a sharp thermocline, and warm water ($>1.0\,^{\circ}C$) below the thermocline (Fig. 4A–C). Variability in the sub-surface temperature structure consisted of the warmest sub-surface water along the shelf break (1.7 °C at 500 m), derived from CDW (Fig. 4A), and cooling of sub-surface temperatures in the mid-shelf region (Fig. 4B) as CDW is mixed with WW to form a modified CDW (Hofmann et al., 1996; Hofmann and Klinck, 1998). The inner shelf temperature structure showed a deep WW layer overlying modified CDW (Fig. 4C).

The surface temperatures obtained from the seals over the shelf tended to be colder than the average vertical temperature profiles (Fig. 4A–C). However, the majority of the seal observations were from winter, which provides a bias towards freezing temperatures. The temperatures returned from the few deep dives in the offshore/shelf break region (Fig. 4A) mostly fall within the range of the average profile constructed from the CTD measurements, but some were colder than the average. The spatial distribution of the seal measurements was more extensive than those from the CTD stations (Fig. 1A) and included regions that were not influenced by on-shelf intrusions of CDW, which resulted in cooler temperatures at the same depth. The CTD-derived average vertical temperature profiles were from a region of the WAP shelf, which is a preferred site for bottom intrusions (Klinck et al., 2004; Dinniman and Klinck, 2004), and are biased towards warmer temperatures.

The temperature measurements from seal dives in the middle shelf region (Fig. 4B) fell mostly within the temperature range of the average temperature profile. Surface temperatures were near freezing, underscoring the winter bias of the measurements, and provided good sampling of the WW layer. Many of the seal dives extended below 200 m into the modified CDW layer, and some of these temperatures were outside of the CTD-derived temperature range for the mid-shelf region. Again, the distribution of the mid-shelf seal measurements was more extensive than the SO GLOBEC hydrographic measurements, and thus more representative of the actual spatial variability in the distribution of modified CDW (Prézelin et al., 2004).

The seal-measured temperature structure in the inner shelf (Fig. 4C) matched the average vertical profile but showed more variability than the CTD-derived measurements. Below 200 m, the seal- and CTD-derived temperatures agreed well. This region of the shelf has the least amount of variability in water properties and provides the best gauge of the accuracy of the seal-derived temperatures.

3.3. Temperature structure from a single seal

The longest temperature record returned by an individual seal covered the period from late April through early October and provided 726 profiles (CS 4, Table 1). During this time, the seal traveled from behind Adelaide Island, across Marguerite Bay and the WAP shelf, along the shelf break, back across the WAP shelf, northward into the Gerlache Strait and finally back to the central shelf area (Fig. 5A). During its transit, the seal consistently dove to depths of more than 200 m and frequently went to 250–300 m (Fig. 5B and C). In late April, when the seal was tagged near Adelaide Island, water temperatures were below −1.5 °C in the upper 50–80 m and increased to 1 °C below 200 m. In early May, temperature increased at all depths and remained elevated for about 15 days. At this time, the seal was moving along the shelf break (Fig. 5A) and was near the southern boundary of the Antarctic Circumpolar Current (Fig. 1A). The seal then turned back to the WAP and entered the Gerlache Strait, where cold-water temperatures were encountered. The below-freezing temperatures throughout the water column are consistent with temperature measurements from Gerlache Strait (Smith et al., 1999). In early July, the seal returned to the WAP shelf and remained in a relatively small region for the remainder of the record. The deepening of the −1.5 °C isotherm during this time was due to local heat loss, which resulted in deepening of the winter mixed layer and formation of WW. Towards the end of the record, the seal moved towards the outer shelf and encountered modified CDW (1.0 °C at 200 m).

The track followed by a second seal (CS 1, Table 1) tagged near Adelaide Island in April (Fig. 6A) provided temperature distributions from the shelf region south of Marguerite Bay. This seal moved through Marguerite Bay, across the WAP shelf and then off the shelf. The −1.5 °C isotherm deepened in late April–early May as the seal moved across the WAP shelf. In contrast to the previous seal (Fig. 5), this seal continued moving during the entire time the tag was returning temperature data. Thus, the variability in the temperature distribution reflects regional scale changes, which, in this case, was the transition of the upper water-column waters from Antarctic Surface Water to WW. The increase in temperature after mid-June indicated that the seal crossed the southern boundary of the Antarctic Circumpolar Current.

3.4. Regional temperature variability

The seal-derived temperature profiles from the inner shelf region east of Adelaide Island (Fig. 1, Area A) and the mid-shelf north of Renaud Island (Fig. 1, Area B) were combined to produce regional depth–time temperature distributions. For Area A, temperature profiles were returned (Fig. 7A and B) for three periods of 10 or more days in length, which extend into the fall and winter (Fig. 7B). The surface waters showed a typical winter mixed layer with temperatures of −1.5 °C and colder in the upper 50–80 m. The 0 °C isotherm was between 120 and 150 m and separated the cold WW layer from the warmer modified CDW, indicating the presence of CDW water in the inner shelf.

Area B was more consistently covered by the seals, as indicated by the observation counts (Figs. 3A and 7D). Over the 70 days encompassed by the seal dives, the upper 100 m was sampled by 10 or more dives each day. Typically, five dives per day extended below 200 m to sample the deeper water temperatures. The temperature structure showed deepening and cooling of the surface mixed layer that started in late June–early July. The deeper measurements (below 250 m) showed the presence of modified CDW (1.0 °C at 200 m).

The simulated temperature distribution (Fig. 8) provides a comparison with the seal-derived temperature distributions from Area B. Although the area over which the distributions were obtained differs, the upper ocean processes are similar (Klinck et al., 2004). The winter mixed layer was evident at the beginning and end of the simulation; the latter time corresponds to the time of the seal observations. The structure of upper water column sampled by the seals was similar to that obtained from the simulated temperature distributions. Surface mixing in the fall eroded the seasonal thermocline and the surface ocean cooled to winter conditions. The 0 °C isotherm varied between 120 and 100 m. The temperature of the deep water increased to about 1.0 °C around 200 m. Both the simulated and seal-derived temperatures below 150 m showed little variation over time. The WW layer began to form in March and extended to about 100 m in winter. A similar WW layer thickness was obtained from the seal-derived temperature distribution in this region.

3.5. Heat content and heat flux

The heat content of the upper 200 m calculated from all the seal-derived temperature profiles ranged between 1000 and 1500 MJ m^{-2} (Fig. 9A). The trend in heat content from mid-May to early July was downward, consistent with heat loss due to winter cooling of the upper water column. After late August–early September, the heat content trended upwards. The negative heat flux (Fig. 9B) during the first part of the seal record, with values of -100 to -50 W m^{-2}, is consistent with cooling of the upper water column. After late June, the heat flux trend was upward and remained at about 0 W m^{-2} until the end of the record when it reached a positive value of almost 200 W m^{-2}.

The simulated heat content ranged from a low of 800 MJ m^{-2} in late winter to a high of 1700 MJ m^{-2} in summer (Fig. 9C). During the time corresponding to the seal measurements the simulated winter heat content was about 1000 W m^{-2}, which is lower than that calculated from the seal-derived temperatures. The simulated heat fluxes ranged between $+100$ and -100 W m^{-2}, which were not as large as those obtained from the seal observations.

4. Discussion

4.1. Seals as oceanographers—data space and time resolution

The seal-derived temperature data have limitations that are associated with the method of collection. The seal-deployed tags result in a dataset that does not randomly or evenly sample the environment, a limitation shared with Argo floats and data collected from ships of opportunity. In fact, seals often have specific habitats that they prefer (Fig. 2). A data bias towards these preferred areas is likely to be more of a problem when tags are deployed on a few animals. Deployment of tags on a large number of animals distributed over a large space would potentially provide more even coverage with less spatial under-sampling. However, a bias towards particular areas may be an advantage because the preferences of seals may provide a valuable window into the areas of the ocean that are important or interesting from an oceanographic point of view. Seals are more likely to prefer areas where water masses mix, such as upwelling regions, and around bathymetric features, such as seamounts, that are difficult to sample by ship. In this study, the seals returned a substantial temperature dataset from the inner regions of the WAP continental shelf, which is a poorly sampled part of this shelf.

The dates of tag deployment during the SO GLOBEC field studies were dictated by the availability of research platforms and were not necessarily the most ideal time to deploy tags, either from an animal or oceanographic perspective. In fact, the seal-derived temperature observations correspond to the time when the heat content of the upper 200 m is the least variable (Fig. 9A and C). Temperature observations from late spring (November) through early fall (April) would correspond to when the largest signals in heat gain and loss occur. However, crabeater seals undergo an annual molt around February of each year and thus tags would be lost then. Tags deployed in November might have a higher probability of functioning until they are lost by molting because the coldest period of the year would be avoided, making it less likely that the temperature sensors would freeze.

The tags deployed on the seals were not recovered, a problem common to Argo floats and other expendable data collection systems, which prevents post-calibration of the sensor. Sensor post-calibration was attempted using CTD measurements that were made in the general area where the animals were tagged (Figs. 1 and 4). This approach provides an estimate of sensor reliability, but does not necessarily resolve sensor drift over time or separate sensor inaccuracies from the environmental variability that is captured by individual measurements. The scatter of the seal measurements about the mean temperature profiles (Fig. 4) was within the range of temperature variability of WAP continental shelf waters. Thus, the limited spatial coverage of the CTD measurements does not allow *a priori* exclusion of temperatures that lie outside of the one-standard deviation envelope. However, this approach, when combined with knowledge of when and where the seal measurements were made, provides a means to evaluate the accuracy of these measurements. Increased space and time coverage from ship-based surveys in the areas sampled by seals potentially would increase the robustness of this approach for sensor post-calibration. Also, comparison of multiple dives from the same seal in a confined region could potentially show sensor drift.

For some of the tags, it was possible to identify when the seal-derived data became unreliable. For example, the tag from crabeater seal 3 (G022, Table 1) returned temperatures that were less than -1.8 °C over a period of 3–4 days before complete failure with a final temperature of -5 °C (Fig. 10). Data collected prior to this period appeared to be reliable. The degradation in temperature data could have been due to ice buildup around the tag that occurred when the animal hauled out (Kooyman and Ponganis, 2004).

Transmission of data through the ARGOS system creates a significant bottleneck in collection of data from the seal tags. The tag collects a temperature profile every hour, but ARGOS can only transmit eight bytes per transmission, which limits the information that can be received from the tag. Further, the animal must be at the surface transmitting when the ARGOS satellite is overhead, and depending on its behavior there may be limited

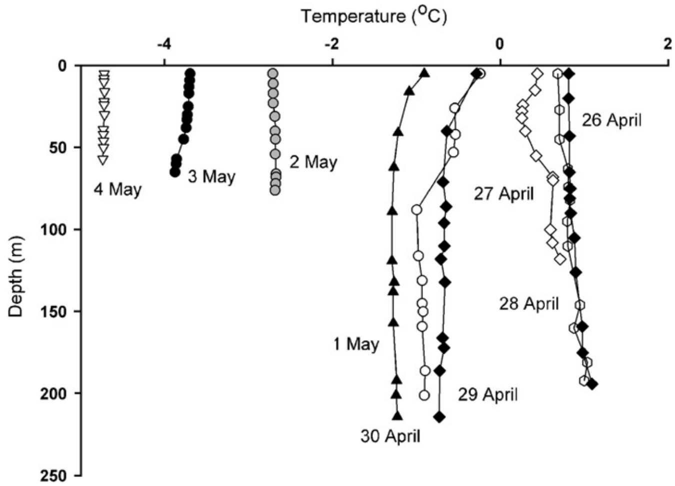

Fig. 10. Time history of the temperature sensor on crabeater seal 3 (G022, Table 1). Tag failure is indicated by temperatures below the freezing point of seawater (−1.82 °C). Data transmission ceased after 4 May 2002.

opportunities for data transmission and reception. In this study, considerable data were acquired because crabeater seals frequently hauled out onto the sea ice, which provided many opportunities for data transmission. Tag recovery would allow acquisition of all the stored data as well as an opportunity for post-calibration of the sensor. Tag recovery would be difficult with crabeater seals, but is relatively straightforward for species like elephant and Weddell seals (*Leptonychotes weddellii*) that either return to their island rookeries or remain in a confined area (Kooyman, 1981; LeBoeuf et al., 1988; Hindell et al., 1991; Costa and Sinervo, 2004).

The ARGOS system is also limited in the quality of the position estimates, which vary relative to the number of transmissions received per satellite pass. For marine mammals in the water, it is often difficult to get multiple transmissions per satellite pass thereby resulting in location estimates of lower quality. A further limitation is that the locations are provided only when the satellite is overhead and the tag is transmitting at the surface. The polar orbit of ARGOS results in it being overhead often, providing 16–20 passes a day. However, this still requires interpolation of the locations of individual profiles between available ARGOS locations. While a number of filtering and interpolation algorithms have been developed to optimize this procedure (Austin et al., 2003; McConnell et al., 1992; Tremblay et al., 2006), the movement patterns of the animal may introduce some position location error. For example, a rapidly moving or migrating animal would have greater location error because less time is spent at the surface, producing fewer locations of poorer quality. A more sedentary animal (hauled out) would have higher location qualities because reduced or no movement would allow multiple positions in the same location increasing both the precision and accuracy of the position estimates. The limitations of the ARGOS system can be overcome by the use of recently developed tags that incorporate positioning technology capable of providing dive-to-dive location accuracy to within 10–20 m.

The tags deployed during SO GLOBEC were state-of-the-art technology available at that time, but recent advances have enabled the inclusion of a salinity sensor (Lydersen et al., 2002; Hooker and Boyd, 2003; Biuw et al., 2007). The addition of salinity to seal-collected datasets has allowed the identification of hydrographic regions that appear to be beneficial for seal foraging. For example, the greatest increases in body condition for elephant seals foraging in the Atlantic sector of the Southern Ocean occurred within the CDW upwelling regions within the Antarctic Circumpolar Current, while high salinity shelf waters or temperature/salinity gradients under winter pack-ice were beneficial in the Indian and Pacific sectors (Biuw et al., 2007).

4.2. Temperature and heat content

The seal-derived temperature time series provided the first observation of the fall-to-winter transition from AASW to WW for WAP continental shelf waters. The WW layer formed in about 30–40 days from late April to early June (Fig. 6B). The observed deepening of the −1.5 °C isotherm was similar to the simulated temperature distributions, which showed the −1.5 °C isotherm deepening over 30–35 days from early April to early June (Fig. 8). This type of comparison suggests that seal-derived measurements can provide data that are useful for evaluation of the skill of a numerical circulation model.

The non-smoothed, seal-derived temperature time series (not shown) showed that the WW layer formed as a result of episodic events that appeared to last for several days, likely the result of atmospheric forcing. Daily sampling of water-column properties with a CTD is potentially sufficient to capture event-induced changes in the surface ocean, such as deepening of the mixed layer. However, the timing of the 2002 SO GLOBEC fall cruise was such that only the start of the WW layer formation was sampled (e.g., Fig. 6B) and sampling frequency during the cruise did not fully resolve individual mixing events. In fact, ship-based sampling was suspended during storm events when winds were strong and the sea state high. This underscores the importance of tags deployed on animals, such as seals, as a method for characterizing the effect of high frequency episodic events on upper ocean properties, especially during times of adverse environmental conditions. To some extent, current meters provide these types of measurements, but this sampling methodology is constrained by limited spatial coverage. Moreover, the seal-derived measurements allowed differentiation of local temperature changes versus larger scale temperature variability (Figs. 6 and 7).

Estimates of the total heat content, which represents the sum of the heat inputs and losses, provide a bulk diagnostic for the temperature structure on the WAP continental shelf. The heat loss estimated from the temperature from an individual seal (Fig. 6B) during the 25–30 days of the fall-to-winter WW formation was 30–35 W m^{-2}. This loss is similar to the sensible heat loss estimated from a vertical- and time-dependent mixed layer-sea ice model developed for the WAP (Smith and Klinck, 2002). The heat content and heat fluxes obtained from the seal-derived temperatures for specific regions of the WAP shelf also agreed with results of the three-dimensional circulation model (Fig. 9). These comparisons show that the seal-derived measurements captured the general trends and patterns in upper ocean heat variability for the WAP continental shelf. The seal-derived data may actually provide a better dataset for evaluation of the skill of numerical circulation models because of the higher space and time resolution of these data, relative to traditional ship survey measurements, and the ability to sample events. Much of the heat flux and many other upper ocean processes are associated with event-scale processes.

5. Summary and future directions

There are advantages to using a variety of animal species to carry tags with environmental sensors. This study showed that crabeater seals offer an excellent platform for data collection along the WAP continental shelf region and within the inshore coastal zone. However, other species, such as southern elephant seals (*Mirounga lepnina*), make long excursions often in excess of 4500 km and thus make an excellent animal platform to obtain data from the open-ocean regions (Boehlert et al., 2001; Biuw et al., 2007). Elephant seals also routinely dive to 600 m, often reaching 1000 m (Hindell et al., 1991; Le Boeuf et al., 2000b), thus providing a more complete view of the water column. Finally, in situations where time series over a smaller geographic domain are required, species such as Weddell seals, which are thought to be more resident than crabeater seals, might offer a better choice for this application (Burns and Kooyman, 2001). Of course greater spatial and temporal coverage may be obtained by the deployment of more tags on animals over a greater geographic region. For example, the recent deployment of 75 CTD tags on southern elephant seals from four rookeries provided coverage over much of the Southern Ocean (Biuw et al., 2007).

Some may question the use of animals for the collection of oceanographic data. This may be a valid point if the data recovered were of interest to a limited or small subset of the scientific community. However, such data are central to studies of the behavior and physiology of the animals at sea (Costa and Sinervo, 2004; Block, 2005; Shaffer and Costa, 2006). Further, the ability to collect oceanographic data at a scale and resolution of the animals' behavior is critical to understanding the physical features of the water column associated with habitat selection in these important apex predators. Such data will provide insights not only into their foraging ecology but will enable the development of predictive models of how these animals might respond to a changing climate.

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