Use of satellite-linked telemetry to study Steller sea lion and northern fur seal foraging

R. L. MERRICK, T. R. LOUGHLIN, G. A. ANTONELIS and R. HILL

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One explanation for recent declines in some Alaskan pinniped populations is that ecosystem changes may have reduced the availability of preferred prey. Part of our evaluation of this hypothesis involves the use of satellite-linked telemetry to study Steller sea lion (*Eumetopias jubatus*) and northern fur seal (*Callorhinus ursinus*) foraging. Data on dives (depth and duration) and water temperatures are collected by satellite-linked time-depth recorders (SLTDR) glued to the backs of sea lions and fur seals. These data are then summarized and stored for later transmission. Data are relayed back to land through NOAA Tiros-series satellites and are processed by Service-Argos (a U.S.-French consortium). These transmissions are also used to calculate at-sea and on-land locations of the animals through use of Doppler shifts of the frequency of received transmissions. Ultimately, diving and temperature can be reconciled with at-sea locations to compare foraging areas with locations of known prey stocks.

Richard L. Merrick, Thomas R. Loughlin, and George A. Antonelis, National Marine Mammal Laboratory, Alaska Fisheries Science Center, National Marine Fisheries Service, 7600 Sand Point Way, N.E., BIN C15700, Seattle, Washington 98115–0070, USA; Roger Hill, Wildlife Computers, 20630 N.E. 150th Street, Woodinville, Washington 98072–7641, USA.

Introduction

Recent population censuses of the Steller sea lion (*Eumetopias jubatus*) and northern fur seal (*Callorhinus ursinus*) have documented significant declines through most of their ranges (Fowler 1985; Merrick et al. 1987; Loughlin et al. 1992). These declines have resulted in a listing of both species as depleted under the U.S. Marine Mammal Protection Act, with Steller sea lions also listed as threatened under the U.S. Endangered Species Act.

The cause of these declines remains unknown; however, one hypothesis is that changes in the abundance or quality of preferred prey have contributed to the declines (Merrick et al. 1987; Loughlin & Merrick 1989). Much is known about prey preferences of the two species, but feeding locations and depths, particularly for Steller sea lions, remain largely unknown. A major reason for this lack of information has been the difficulty of obtaining data on foraging locations and diving of free-ranging marine animals. Instruments which record diving depths over time (time-depth recorder or TDR) have existed since the 1970s and have allowed researchers to track some pinnipeds' movements vertically in the water column during foraging trips (Gentry & Kooyman 1986). Coupled with a separate VHF radio transmitter and a ship or aircraft with which to track the animal, it is possible to obtain at least a partial picture of foraging movements (Goebel et al. 1991). Application of this technique has received limited use due at least in part to the high costs of aircraft and ship time and the need to recapture the animal to recover the TDR.

Recent developments in satellite telemetry allow tracking of marine animals using satellite-linked radio tags or platform transmitter terminals (Hill et al. 1987; Hills 1987; Mate et al. 1987; Stewart et al. 1989; Heidi-Jorgensen et al. 1991). Through the Service-Argos system on board NOAA Tiros-series satellites, it is possible to track and retrieve data from free-ranging animals using uplink communications between platform transmitter terminals (PTT) attached to animals and receivers onboard satellites. Locations at sea are determined from the Doppler shift of the frequencies of a series of signals received by the satellite (Fancy et al. 1988; Stewart et al. 1989).

By combining a PTT and a TDR it is possible to simultaneously determine locations and collect diving information while the animal is at sea. The TDR collects dive data which can be reported by the PTT while the animal is at sea or saved for later reporting while the animal is on land. This is particularly important for animals like Steller sea lions which inhabit relatively inaccessible areas, return to their tagging site on an infrequent basis, and are difficult to capture to retrieve the TDR.

In this report we describe a satellite-linked time-depth recorder (SLTDR) developed for pinnipeds and illustrate its use with data obtained from free-ranging Steller sea lions. The report gives a sample of the results of an ongoing study of Steller sea lion and northern fur sea foraging ecology.

Materials and methods

Design of the SLTDR involved an evolution of hardware and software which began in the summer of 1988 with ground-truth tests at Alaska's Marmot Island sea lion rookery (58°12'N, 151°50'W). At that time, a PTT was placed at three locations on the island to determine if signals would be received by the satellite from the types of locations at which sea lions haul out. Signals were received by 81.2% of the 149 satellite passes occurring during the test, an average of 6.4 receptions per pass. Locations were calculated from 55.7% of the passes. The Service-Argos system classifies the accuracy of locations as follows: class 3 is accurate to 150 m, class 2 to 350 m, class 1 to 1 km, and class 0 has no accuracy assigned (Service-Argos 1984). Of 84 location fixes calculated in this test, 27 (32.1%) were class 1, 32 (38.1%) were class 2, and 25 (29.8%) were class 3. Class 0 locations were not available from the Service-Argos system at the time of this test. Differences between class 1 and 3 fixes were around 0.5 km, while class 2 and 3 fixes were essentially identical.

Based on the reasonableness of these results, we decided to proceed with deployment of a unit on a free-ranging Steller sea lion. A 1.0 watt, ST-4 PTT produced by Telonics of Mesa, Arizona, was deployed in January 1990 at Marmot Island (reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA). An adult female Steller sea lion was anaesthetized using Telazol (Loughlin & Spraker 1989), and the unit was attached with epoxy glue applied to mesh spread over the animal's back. This unit transmitted for 46 days. Of 60 at-sea locations produced, 4 (6.7%) were class 2, 12 (20.0%) were class 1, and 44 (73.3%) were class 0. Of 94 fixes received while the animal was ashore, 15 were class 0 locations. We compared these locations with class 3 locations from the same visit ashore and estimated the mean difference between class 0 and 3 fixes to be 1.8 km.

This test proved that signals would be successfully received by the satellite while the animal was at sea. Now the challenge was to develop a unit which would produce locations as well as collect, process, and transmit data on dive depths and durations, surface times, and water temperatures. This new unit (labelled as Type-2) was a packaging by Wildlife Computers of their TDR with a Telonics 1.0 watt ST-5 PTT. Differences between the Type-2 unit and earlier Type-1 designs included incorporation of a thermistor, an improved conductivity sensor for sensing surfacings, and major changes in software. Depth measurements were accurate within 2 m to a maximum depth of 500 m. Temperature was accurate to 0.1°C with a thermocouple response time of less than 120 milliseconds. Size of the SLTDR package was 10 cm by 17 cm by 3 cm with a mass of 800 g.

Unit software controlled data collection, summarization, and transmission. The unit collected data only while the animal was at sea; this was sensed using a conductivity switch. Once the animal had gone to sea the unit collected depth and water temperature readings at 10-second intervals throughout the trip. Depths and temperatures from the first dive of each hour were collected and stored in their entirety for later transmission. The maximum depth, the temperature at the maximum depth, and both dive and surface durations were saved for all dives. Thus, at the end of the trip a complete sequential record of surface times, dive times, maximum dive depths, and temperatures at depth was available for transmission.

Two transmission protocols were used: at-sea and on-land. While the animal was at sea, a data message was transmitted that included histograms of earlier dives. Each day was subdivided into four 6-hour periods (i.e., 2100–0300, 0300–0900, 0900–1500, and 1500–2100 local sun time). Histograms were separately summarized for dive depths and durations for each of the preceding four complete 6-hour periods (a total of eight histograms). The on-land protocol was used for transmission of the hourly dive and temperature profiles, and a chronological record of duration, maximum depth, temperature at maximum depth, and duration of subsequent surface intervals.

During 1990–92 we deployed 45 Type-2 SLTDRs in the Gulf of Alaska (n = 21), Aleutian Islands (n = 15), Bering Sea (n = 1), and Kuril Islands (n = 8). The data presented here were collected from units attached to two adult female Steller sea lions during spring 1992. One unit (14080) was deployed at Latax Rocks, Alaska (58°42′N, 152°30′W), in the Gulf of Alaska on 27 February 1992. The other unit (14072) was deployed at Akun Island, Alaska (54°18′N, 165°31′W), in the Bering Sea on 8 March 1992. These results are presented as an illustration of the data available and analyses possible with SLTDRs.

Results

Locations

Ninety-six locations were obtained during March 1992 for animal 14072 (54 on land and 42 at sea) and 212 locations for animal 14080 (112 on land and 100 at sea). On-land locations were spread relatively evenly among the four location accuracy classes (Table 1); however, over one-half of the at-sea locations were class 0. The accuracy of at-sea locations was similar for the two animals; however, on-land locations showed distinctly different distributions (Table 1). Most (64.3%) of animal 14080s on-land locations were class 2 or better, compared to 29.6% for animal 14072.

Table 1. Percentage of at-sea and on-land location fixes by class for female Steller sea lions 14072 and 14080. Class 3 locations are accurate to 150 m, class 2 to 350 m, class 1 to 1 km, and class 0 have no accuracy assigned.

Location	Location class	Animal 14072	Animal 14080	Total
On land	0	38.9%	22.3%	27.7%
	1	31.5%	13.3%	19.3%
	2	22.2%	40.2%	34.3%
	3	7.4%	24.2%	18.7%
At sea	0	59.5%	59.0%	59.1%
	1	19.1%	19.0%	19.0%
	2	21.4%	16.0%	17.6%
	3	0.0%	6.0%	4.2%

One trip made by animal 14080 is shown in Fig. 1. This trip lasted around 20 hours with 10 locations calculated.

Dive depth, duration, and temperature summaries

The histogram records provided data for 755 dives from 43 6-hour time periods for animal 14072, and 3,040 dives from 83 time periods for animal 14080. The summary records provided data on fewer dives: 207 dives from 14072s eight trips and 1,216 dives from 14080s six trips.

Average dive depth for the two animals was 36.5 m and 42.9 m, respectively (Table 2). These differences were significantly different (df = 1,419, t = 2.904, p = 0.004). Mean dive durations were 2.4 minutes for each animal, and mean surface intervals were 4.2 and 4.0 minutes, respectively. Mean water temperature at maximum dive depth was 2.2°C for 14072 and 3.9°C for 14080, a significant difference (df = 1419, t = 51.116, p = 0.000). Water temperatures at depth were distinctly different for the two animals (Fig. 2).

Variations in dive parameters by time-of-day for animal 14080 are only remarkable in the strong mode in dive depth, duration, and temperature during 0600–0859 (Fig. 3). These time-of-day patterns implied that a relationship existed between dive depth, duration, and temperature. Duration (r = 0.733, p = 0.000) and temperature (r = 0.490, p = 0.000) were significantly correlated with depth for animal 14080 (Fig. 4A and 4C). However, only duration (r = 0.208, p = 0.004) was correlated with depth for 14072 (Fig. 4B and 4D).

The chronological trip record can be used to reconstruct the diving pattern from throughout a trip. For example, Fig. 5A was created for the trip by animal 14080 shown in Fig. 1. The animal began diving to around 50 m as soon as it departed Latax Rocks. Around minute 200, dive depths increased to 190 m. The animal continued to dive to these depths for the next two hours. This was followed by a period of shallow dives, and then another deep diving period. Finally, around minute 700, deep diving ceased and the sea lion began traveling back towards Latax Rocks. Tem-

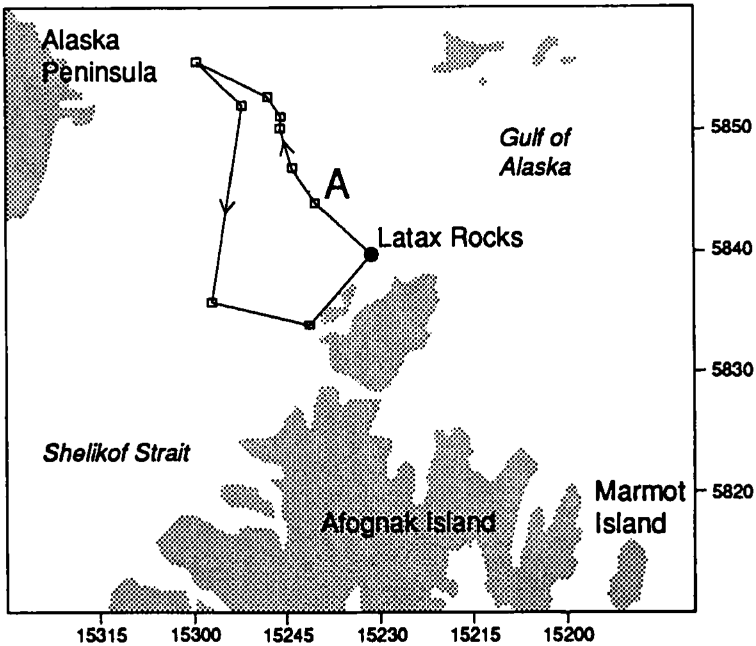

Fig. 1. Sample trip made from Latax Rocks, Alaska by female Steller sea lion 14080 during March 1992. Point A indicates location of dive profile shown in Fig. 6.

peratures at the maximum dive depth increased with increasing dive depth (Fig. 5B). Also shown on Fig. 5B are times when a dive profile (open circle) or both a dive profile and a location fix (closed circle) are available.

Dive depth and temperature profiles

We received 107 profiles from animal 14072 and 239 profiles from animal 14080. Figs. 6A and 6B describe one of the dives from animals 14080's first trip (noted as 'A' on Figs. 1 and 5). Here it can be seen that the animal made a relatively slow descent (1.4 m/seconds) to the presumed foraging depth (190 m). The sea lions foraged at this depth for 200 seconds, and then returned to the surface at roughly the same speed as the descent. A location fix was available for this dive and from comparison with bathymetric charts, it appeared that the animal was foraging at the bottom. Water temperatures fluctuated only slightly through the dive, ranging from 5.2°C at the surface to 5.4°C at the bottom.

Discussion

Our goal in development of the SLTDR was to

Table 2. Summary dive statistics as reported from Steller sea lions 14072 and 14080 during March 1992 from chronological records.

		Dive depth		Dive duration		Surface interval		Temperature	
PTT no.	n	x (m)	Max. (m)	x (min)	Max. (min)	x (min)	Max. (min)	x (°C)	Range (°C)
14072	207	36.5	164	2.4	6.0	4.2	42.2	2.2	1.3–2.6
14080	1216	42.9	198	2.4	11.0	4.0	160.0	3.9	2.6–6.3

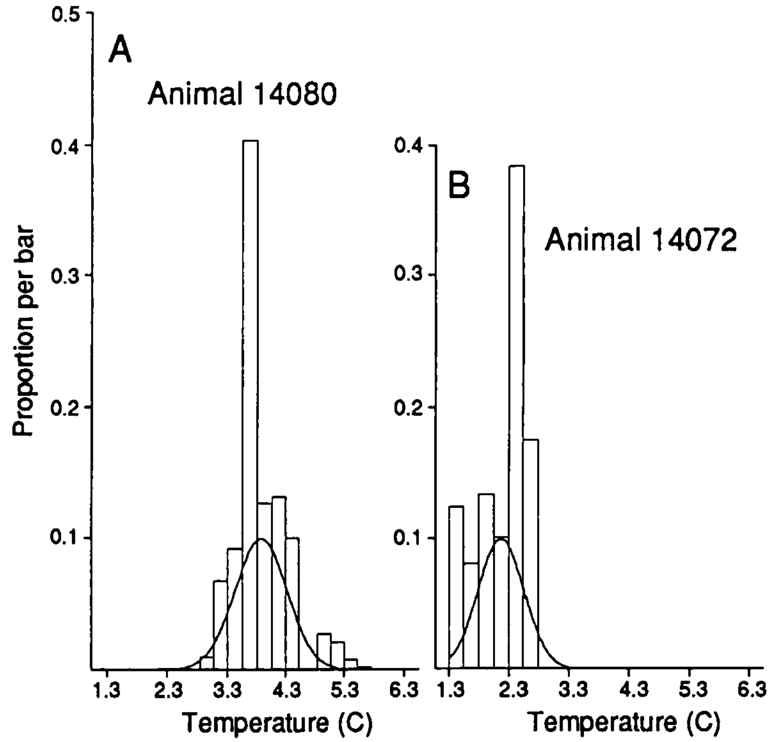

Fig. 2. Comparison of temperature distributions at dive depth for female Steller sea lions 14072 (A, n = 207) and 14080 (B, n = 1216) during March 1992.

combine data available from a TDR with the at-sea locations produced by PTTs. Results of the past 2 year's deployments of fifty SLTDRs on sea lions and fur seals indicate this goal has been achieved. Using the SLTDR, we have learned that adult female Steller sea lions forage close to land in summer (within 20 km), make brief trips (<2 days), and dive to shallow depths (<30 m). In winter, trips are much longer in distance (>300 km) and duration (up to several months), and dives are deeper (often >250 m). Sea lion pups by their sixth month are able to range more than 250 km, although their dives remain shallow (<20 m) and brief (<1 minute). Water temperature data indicate sea lions can forage through a wide thermal regime. First results from adult male fur seals in winter show that they disperse widely from their Pribilof Island summer breeding grounds and frequently dive deep (>250 m).

Using the Type-2 SLTDR we are now obtaining at-sea locations superior in number and quality to those of our earlier experiences with a PTT only. Our January 1990 deployment of a PTT at Marmot Island produced 60 at-sea locations over a 46-day period, and 6.7% were class 2 or better. The deployment on animal 14080 at Latax Rocks (60 km west of Marmot Island) yielded 100 at-sea locations during March 1992 (31 days), and 22.0% were class 2 or better. Part of this difference was due to the improved surfacing (conductivity) sensor on the SLTDR.

Simultaneously, we have obtained data on dive parameters similar to that produced by a conventional TDR. While we do not obtain a full profile for every dive, the combination of chronological records and hourly profiles provides all the data typically used for analysis of dive parameters (Gentry & Holt 1986). These data can also be linked with locations by date and time to determine where the diving occurred. Thus, it is possible to determine whether the animal was foraging in the water column or at the bottom.

The only limitation of the SLTDR compared to a conventional TDR is that it does not provide a complete record of all diving. This is related to the difficulty of transmitting all dive data to satellites during the brief times animals are ashore

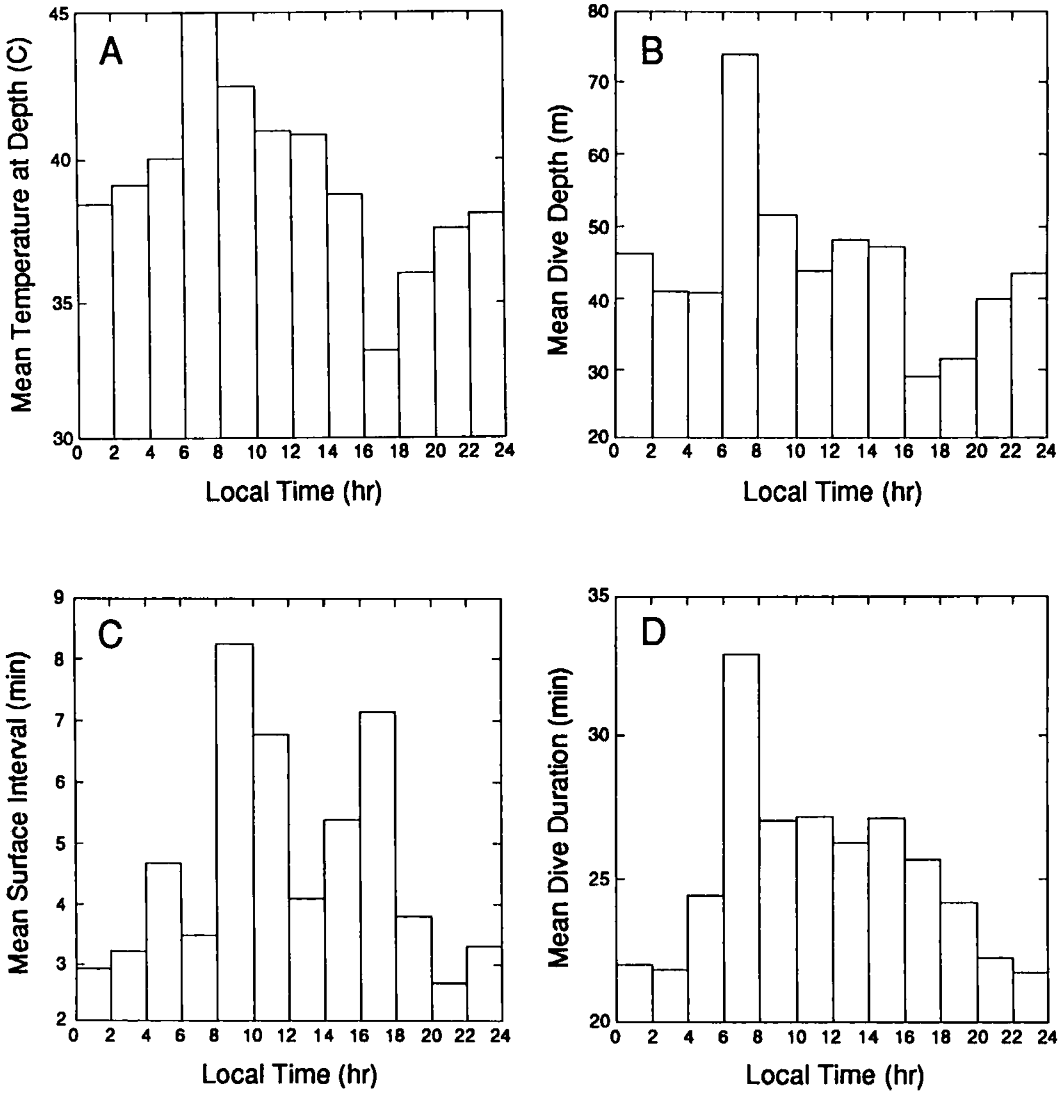

Fig. 3. Mean dive temperature (A), dive depth (B), surface interval (C), and dive duration (D) for 1216 dives made by female Steller sea lion 14080 during March 1992.

and satellites are in view (around 8 minutes per hour at 55° N latitude). Many more dives are reported from the histogram records (e.g., 3040 dives for animal 14080) than are reported in the chronological records (e.g., 1216 dives for animal 14080). This is because it takes much longer to transmit a comparable number of dives in the chronological record format. Our strategy to deal with missing chronological and profile data is to consider the histograms as describing the total number of dives made. The chronological (and profile) records are then considered to represent a subsample of the characteristics of the total population of dives.

Histogram records also ensure that some data is recovered from all animals, even if they do not return to land. This makes the SLTDR a powerful tool for studying wintertime foraging behavior

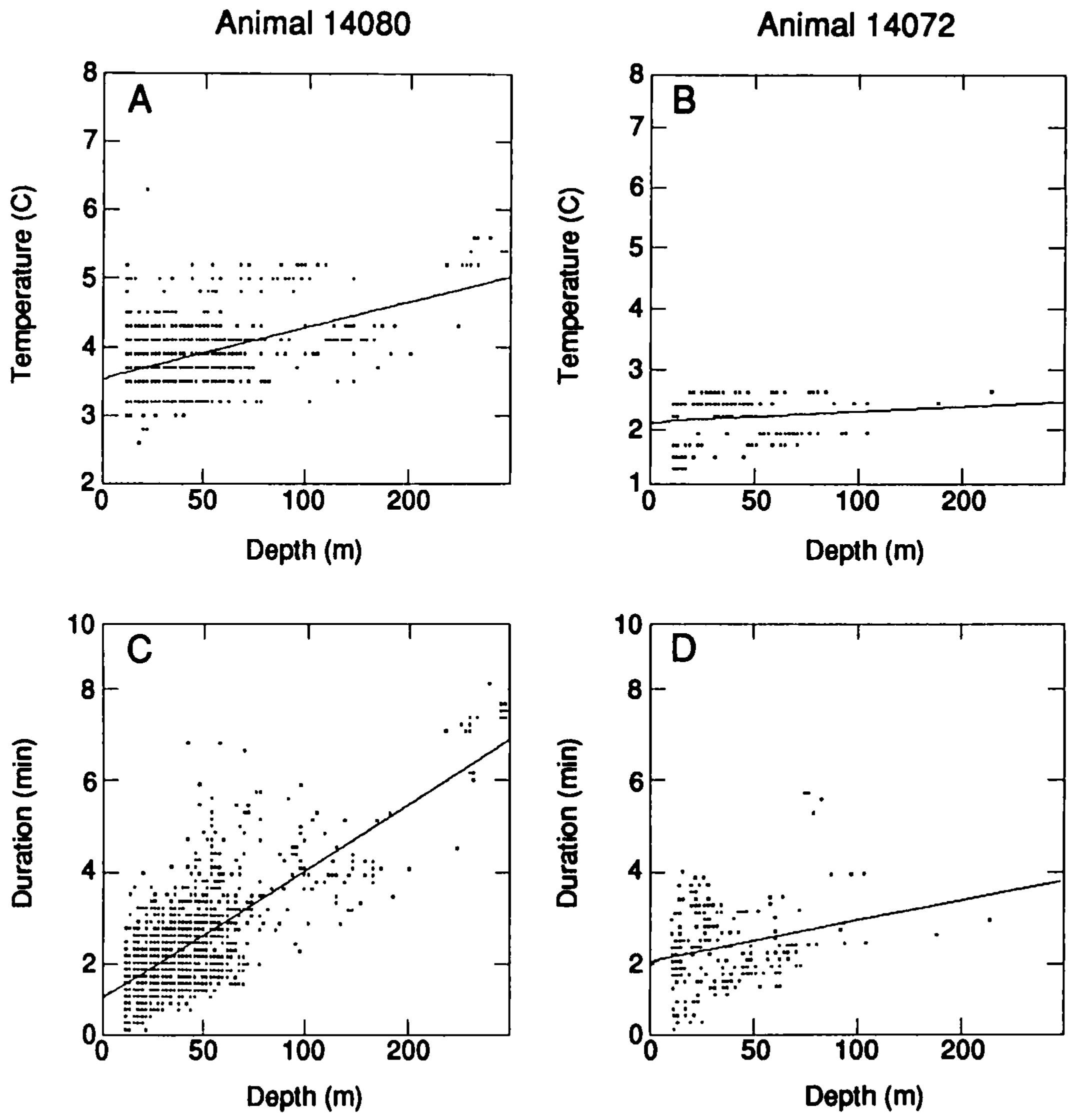

Fig. 4. Distribution of dive duration and temperature for female Steller sea lions 14072 (B & D, n = 207) and 14080 (A & C, n = 1216) during March 1992.

of fur seals and sea lions, both of whom spend prolonged periods of time at sea in the winter.

Incorporation of temperature sensing provides a new dimension to analysis of these animal's foraging ecology: inference of prey availability from the physical features of the waters foraged in. For example, some Steller sea lion prey species exhibit distinct water temperature preferences. Walleye pollock (*Theragra chalcogramma*) prefer water temperatures greater than 2°C (Lynde 1984). While the temperatures at foraging depth for animal 14080 (Fig. 2) were above this range, many of 14072's dives were in water below this limit. Consequently, 14072 may be foraging in water where walleye pollock is not found; she may not be feeding on pollock at those times.

Temperature data available from the SLTDR is superior in at least two ways to that presently available to us from other sources (e.g., satellite imagery and ship-based observations). First, more temperature observations are available because the SLTDR provides a relatively continuous record from throughout the trip. Secondly, the SLTDR provides in situ observations of actual foraging areas. Temperature data are available from a conventional TDR (e.g., Boyd & Arnbom 1991), but they lack associated locations. In so far as animals such as sea lions and fur seals are associated with prey concentrations and oceanographic features (e.g., fronts), these data may also be useful to other researchers (e.g., fisheries oceanographers).

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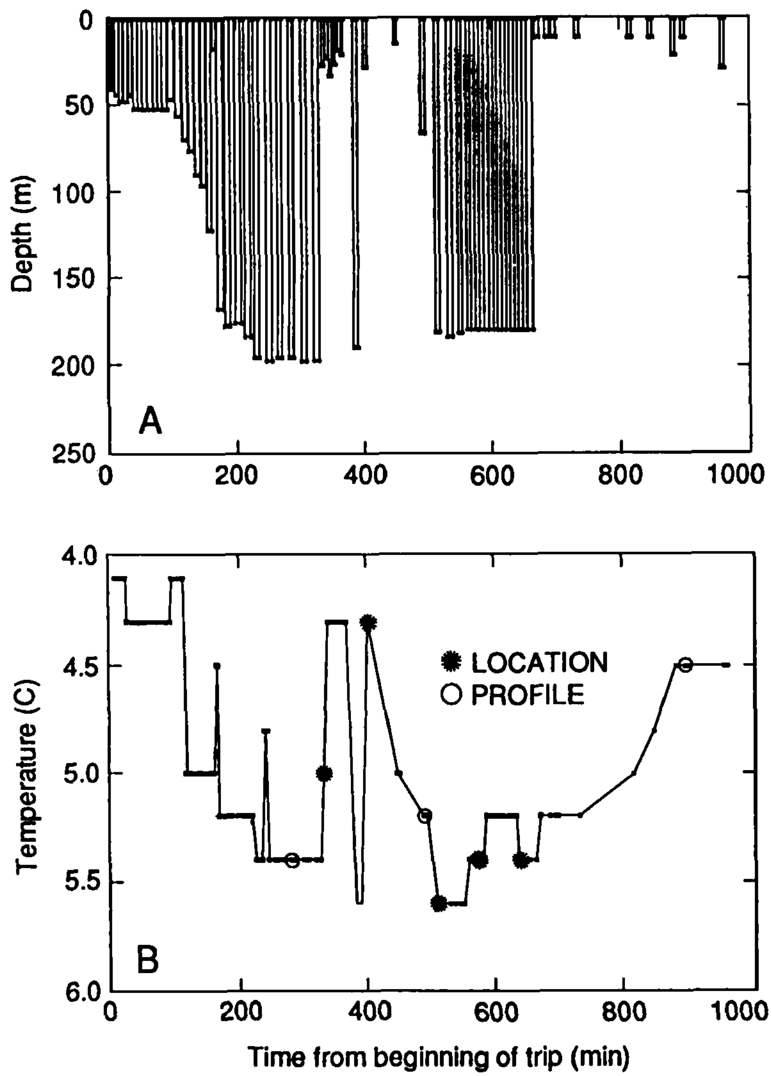

Fig. 5. Dive depth (A) and temperature at depth (B) by time from beginning of trip for a trip (see Fig. 1) made by female Steller sea lion 14080. Point A indicates location of dive profile shown in Fig. 6. Times when a dive profile (open circle) or both a dive profile and a location fix (closed circle) are shown.

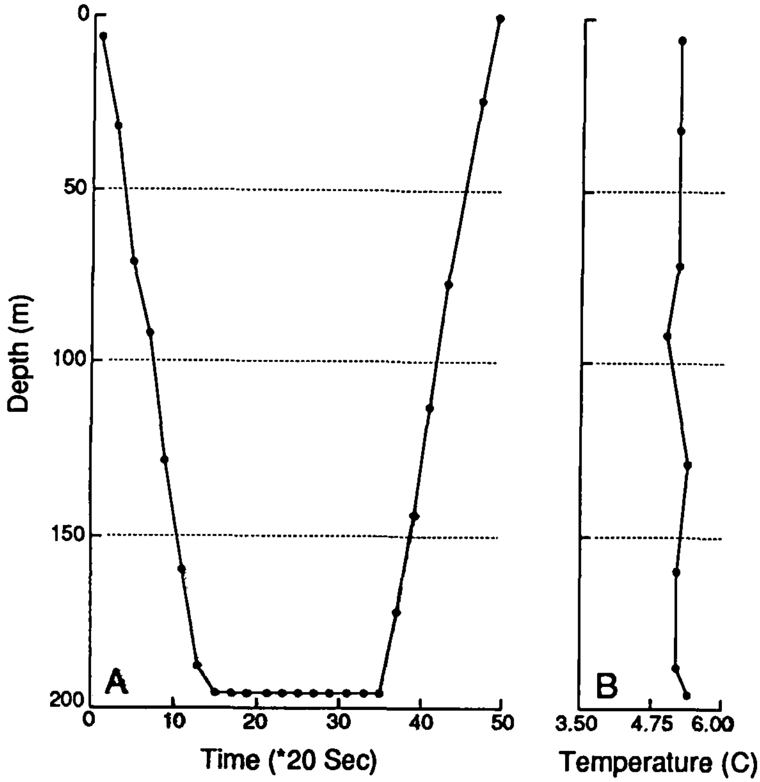

Fig. 6. Dive depth (A) and temperature (B) profile for a single dive of female Steller sea lion 14080. This dive is shown as point A in Figs. 1 and 5.

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