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Instruments and Methods

Salinity sensors on seals: use of marine predators to carry CTD data loggers

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Abstract

Diving marine predators have been used to collect data on ocean temperature, but salinity measurements have not previously been incorporated into predator-borne data loggers. Here we present data on initial calibration and field trials of a new conductivity, temperature and depth (CTD) data logger used alongside a satellite-positioning transmitter to provide three-dimensional oceanographic information. This provides CTD data analogous to that collected by a ship-deployed undulating oceanographic recorder. Calibration tests of these units showed a near-field effect caused by the proximity of material to the tag, but demonstrate that the resulting data offset can be removed by post hoc calibration. Field tests of the system were conducted on 16 female Antarctic fur seals (*Arctocephalus gazella*) at Bird Island, South Georgia. These results matched those found by standard ship-based survey techniques, but suggest temporal variability in the structure and location of the two water masses found to the north of South Georgia. Overall, this initial proof-of-concept work is encouraging; future refinement of this technique is likely to provide an additional data source for both oceanographers and biologists.

Keywords: Salinity; CTD; Marine predators; Oceanography

1. Introduction

Semi-autonomous vehicles are an accepted means of investigating the physical and biological characteristics of the oceans (e.g., Brierley et al., 2002). Although robotics has become increasingly important in this field, until recently the use of animals as vehicles for the remote collection of information has been largely overlooked. Here we demonstrate the capabilities of a new sensor system which can be used on oceanic predators such as seals, cetaceans and seabirds. These instruments have the potential to collect information about the oceans that is not only relevant to the study of the ecology of these species but which may also become a useful tool for studying the physical, chemical and biological structure of the oceans (Boehlert et al., 2001; Boyd et al., 2001; Campagna et al., 2000; Charrassin et al., 2002; Hooker et al., 2000; Lydersen et al., 2002; Weimerskirch et al., 1995).

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The use of oceanic predators for remote data collection, although suffering from the inability to predetermine the locations of sample collection, is likely to benefit from the ability of such predators to select foraging areas. Sampling will not be uniform, but in many cases, predators are "adaptive samplers", targeting foraging areas which are likely to coincide with the regions of most interest to biological oceanographers (Guinet et al., 2001; Jaquet and Whitehead, 1996; McConnell et al., 1992; Tynan, 1997). In addition, interpretation of the foraging behaviour of birds and mammals at sea is assisted by the integration of data on the surrounding oceanographic environment (Croll et al., 1998). However, several studies have noted the problems of scale in correlating marine mammal distribution and behaviour with oceanographic data collected via satellite or ship survey (Guinet et al., 2001; Jaquet and Whitehead, 1996). The collection of data using the predator itself to carry instruments can mitigate such problems, because oceanographic data are collected alongside and at the same scale as behavioural data.

Previously, studies investigating the potential for marine mammals to collect oceanographic information have explored the temperature information collected during dives (Boehlert et al., 2001; Boyd et al., 2001; Charrassin et al., 2002; McCafferty et al., 1999; Wilson et al., 1994). The incorporation of a conductivity sensor alongside temperature and depth data loggers would allow the measurement of salinity. This in turn would allow researchers to investigate density structure and mixed layer depth in greater detail (Freeland et al., 1997). However, limitations in the size of sensor available have prohibited the collection of salinity data by this method. Small conductivity sensors, which have previously been available, could only provide very coarse resolution data, useful primarily at the scale of differentiating freshwater from seawater (Sturlaugsson and Gudbjornsson, 1997). For pelagic ocean studies much more precise salinity measurements (e.g., Trathan et al., 1997) are needed. Recently, smaller inductive-cell conductivity sensors, which can be used in tags deployed on marine mammals, have become commercially available. Field trials and calibration of these units via deployment on seals are described here. Modifications of these units for incorporation into satellite transmitting tags are described in Lydersen et al. (2002).

We describe calibration tests and initial field deployments of these conductivity sensors on Antarctic fur seals (*Arctocephalus gazella*) at South Georgia. Female Antarctic fur seals breed and raise their pups ashore between December and March on several islands in the Southern Ocean. During this time a mother will leave her pup to forage at sea for 5–7 days before returning to continue feeding her pup for a period of 2 days, repeating this cycle several times over the austral summer. Instruments can be attached and recovered from these animals to record their activity at sea during a foraging trip. Since foraging trips are for periods of days, and animals return to predictable locations, it is relatively easy to deploy and recover instruments, making this system ideal for testing new instrumentation on marine predators. Furthermore, oceanographic surveys have been carried out in the region in which female fur seals forage, providing baseline data with which to compare results obtained from these animals.

2. Methods

2.1. Equipment

Inductive conductivity sensors are reported to provide a high level of measurement accuracy and stability. The conductivity sensor we used was available off-the-shelf as a conductivity and temperature data logger (CT-logger, 350 g, model ACT-HR, approximate cost £2500, Alec Instruments, Japan), which determined conductivity using an inductive-cell sensor that measured the rate of decay of an electromagnetic field (Fig. 1). This data logger was rated to 200 m depth and was designed for long-term (up to 2 years) use on moorings at known depths. In order to provide position and depth information in conjunction with this, two additional instruments were required: a depth logger (40 g, Mk7 TDR, approximate cost £1000, Wildlife Computers, USA), and a satellite transmitter (180 g, ST-10, approximate cost £1500, Telonics, USA, which used the

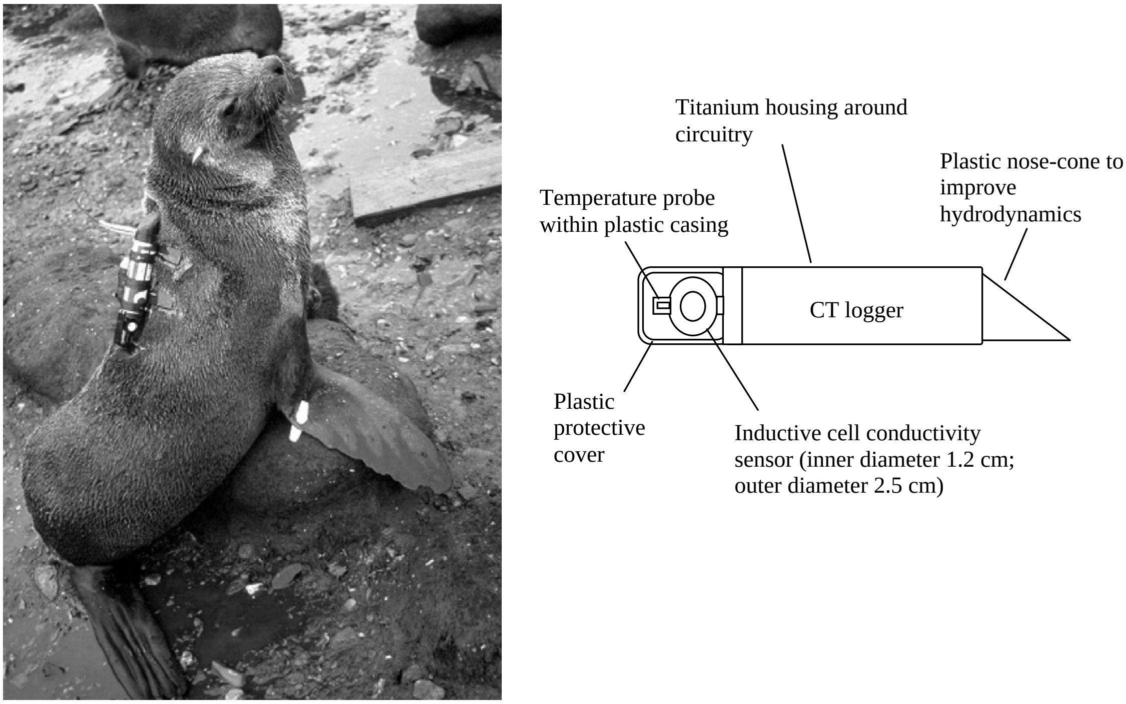

Fig. 1. Orientation of the sensors on an Antarctic fur seal, Bird Island, South Georgia, with illustration of the conductivity–temperature logger.

ARGOS system, with approximately 44 satellite passes per day over the area of our field trials, to provide locations at sea). Conductivity ($\pm$0.01 mS/cm), temperature ($\pm$0.01°C) and depth ($\pm$1 m) were measured simultaneously at 1-s intervals. Geographical position was recorded whenever a satellite was overhead. Approximate errors for this location are of the order of 5 km (see Boyd et al., 1998), although errors are greater in longitude than latitude (Vincent et al., 2002). Satellite positions were accepted or rejected based on an iterative forward/backward averaging filter which identified fixes that would require an unrealistic rate of travel (McConnell et al., 1992). Fixes requiring >2 m/s were rejected, since fur seals rarely travel over extended distances at this speed (Boyd, 1996). Lastly, a 165 MHz radio-transmitter (30 g, approximate cost £100, Sirtrack Ltd., Havelock North, New Zealand) was also fitted to the animal to enable us to locate and recapture the animal when it returned to shore.

2.2. Calibration

One concern in the calculation of salinity is the response time of the temperature sensor, since the temperature may be lagged relative to the conductivity for the water sample measured. To test this we moved the unit from a temperature of approximately 12°C into one of approximately 8°C and measured the response time of the temperature readings. The temperature sensor of the CT-logger was tested against a digital thermometer (Fluke 51II, RS Components, UK, accuracy $\pm$0.05% + 0.3°C).

The salinity calculated from the conductivity and temperature readings of the CT-logger was calibrated prior to deployment, and was retested after the field season. Tests were conducted in plastic tanks of approximately 1 m^3 containing water of varying salinities (approximately 27.75, 30.1 and 33.4). Duplicate samples from each tank were tested against a calibrated salinometer

(Guildline 8400B, Guildline Instruments Ltd., Ont., Canada, accuracy $< \pm 0.002$).

Since the inductive-cell conductivity sensor operates by generating an electromagnetic field and then measuring the decay of this field, measurements will be affected by the proximity of other objects (near-field effect). In order to maximise the likelihood of good uplinks, the satellite transmitter was placed between the shoulder blades of the seal. Although placement of the CT-logger behind the satellite transmitter would have reduced near-field problems, it would have increased the amount of turbulence around the unit. We therefore preferred placement of the CT-logger alongside the satellite transmitter (see Fig. 1 for instrument placement set-up). In this configuration, it was critical to establish the potential effect of the nearby metal on the recorded conductivity. The size and metal content of the satellite tag was greater than that of the TDR or radio-tag. The CT-logger was therefore tested in a salt-water bath with the satellite tag positioned at increments of 1 cm between 0 and 10 cm from it. The effect of the satellite transmitter was tested anterior, lateral or posterior to the CT unit at 2-cm distance.

In addition to the effect of other instruments on the CT-logger, the study animal to which the logger was attached may also have an effect on the electromagnetic field and thus on the conductivity records. The logger was tested in water baths of different salinities when placed on different materials. In addition, we were concerned that the placement of the logger on an animate object rather than on an inanimate object might cause an effect. Since the conductivity measurements are based on decay of the electromagnetic field, it is possible that bioelectrical activity (caused by muscle action) might have a fluctuating effect on the logger measurements. Measurements taken when fastened to a human arm were compared when the hand was actively moving compared to resting. The effect of orientation of the conductivity sensor was also monitored by placing the logger at 0°, 45° and 90° to perpendicular. Lastly, a trial deployment was conducted on a grey seal (*Halichoerus grypus*) in the seawater facility at the Sea Mammal Research Unit (University of St Andrews, Scotland), and measurements recorded from the seal while at least 0.5 m distant from any metallic pipes or other objects were compared to those in the same tank when the instrument was freely suspended before and after attachment.

2.3. Field deployments

Trial deployments of these units were conducted on Antarctic fur seals at Bird Island, South Georgia (54°S, 38°W) during December 2000–February 2001. Selection of female seals was based on large size and the presence of a healthy (i.e., large) pup. Seals were captured and restrained by methods described in Gentry and Holt (1982). The tags were attached by cable ties to nylon webbing which was glued with a quick-setting epoxy to the fur of the seal. The CT-logger, TDR, satellite transmitter, and radio-tag were deployed on female seals for a single foraging trip. The tags were recovered after a single foraging trip by recapturing the animal and cutting the cable ties.

The data capacities of the units varied. The CT-logger was limited in memory capacity to record temperature and conductivity at 1-s intervals for a 49.5-h period, and so the start of recording was delayed for 2 days, after which time generally the animal had begun its foraging trip. The Mk7 data logger recording depth was equipped with a wet–dry sensor and began sampling as the animal first entered the water. It had sufficient memory to record depth, temperature and light level at 1-s intervals for 7.8 days.

Since salinity is derived from depth, temperature and conductivity data, the two data sets from the TDR (depth data) and from the CT-logger (conductivity and temperature data) had to be merged post hoc. Time clocks on both loggers were matched prior to deployment and any offset between these was recorded on interrogation at recovery. Data sets from the CT-logger and TDR were merged, with the relative drift between the instruments' clocks taken into account. A standard median-filter smoothing algorithm with a window of 7 s was fitted to the salinity data to smooth the noise in this data set. The resulting conductivity, temperature and depth (CTD) data, together with position information, were then analysed with MATLAB. Salinity was determined using the practical salinity scale, and is presented as a conductivity ratio with no units.

3. Results

3.1. Calibration of CT-logger

The temperature sensor of the CT-logger was accurate to within 0.005°, reaching 95% target temperature within 1 s for temperature changes over 4°C. Salinity estimates from the logger in all three salt-water tanks were accurate to within 0.02 of those measured by salinometer. During calibration tests, the presence of bubbles in the inductive cell was occasionally noted to cause erroneous readings but passing the unit through water cleared entrained bubbles out of the inductive cell, so it is not thought that this would present a large problem during field studies.

As expected, the near-field effect on the conductivity reading was pronounced when the metallic satellite transmitter was immediately adjacent to the CT-logger, and when it was positioned at the back of the unit alongside the inductive cell of the CT-logger (Fig. 2). The scale of effect varied with distance, so that when positioned at the midpoint of the CT-logger, the satellite transmitter had negligible effect when positioned at over 2 cm distance (Fig. 2a). The combination of these two tests suggested that with the satellite tag positioned at least 3 cm from, and ahead of the midpoint of, the CT-logger, it should have negligible effect on the salinity readings.

Placement of the logger on material rather than freely suspending it in seawater also caused a near-field effect. This effect varied depending on the material against which the object was placed (Fig. 3). Variation appeared to be linear such that the step-decrease in conductivity at the salinities to which animals are exposed in the Scotia Sea (approximately 33–34) was less than the resolution of the instrument (0.01), suggesting that applying an offset rather than a correction factor would suffice. Of further concern is the effect of any "wobble" in instrument mount causing the sensor head to vary from vertical. Such movement caused further interference to the near-field and further

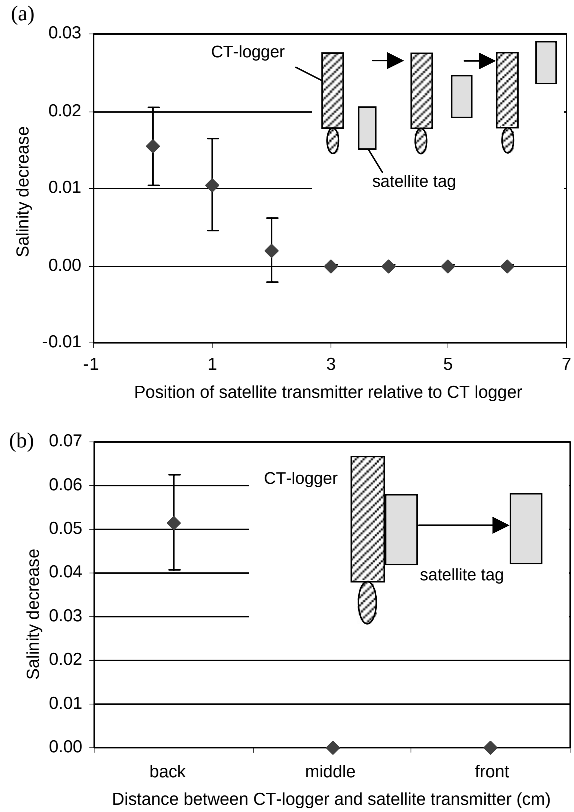

Fig. 2. Near-field effect of the satellite transmitter on the conductivity sensor (a) anterior, adjacent and posterior at 2 cm distance, (b) at 1 cm increments in distance between the units. Average and standard deviation of salinity recorded over 20 s (20 samples) at each position are shown.

decrease in the recorded conductivity (and thus the resulting salinity, Table 1). There was no observable change in readings of the conductivity sensor with muscle movement compared to muscle inactivity. However, there was more variability in readings when the sensor was placed on an animate object compared to an inanimate object, even when both were inactive. A similar scale offset was observed during deployment on a grey seal held in the SMRU captive facility, which resulted in a 0.21 decrease in salinity recorded.

3.2. Field tests

The average weight of females to which instrumentation was attached was 37.8 kg (sd

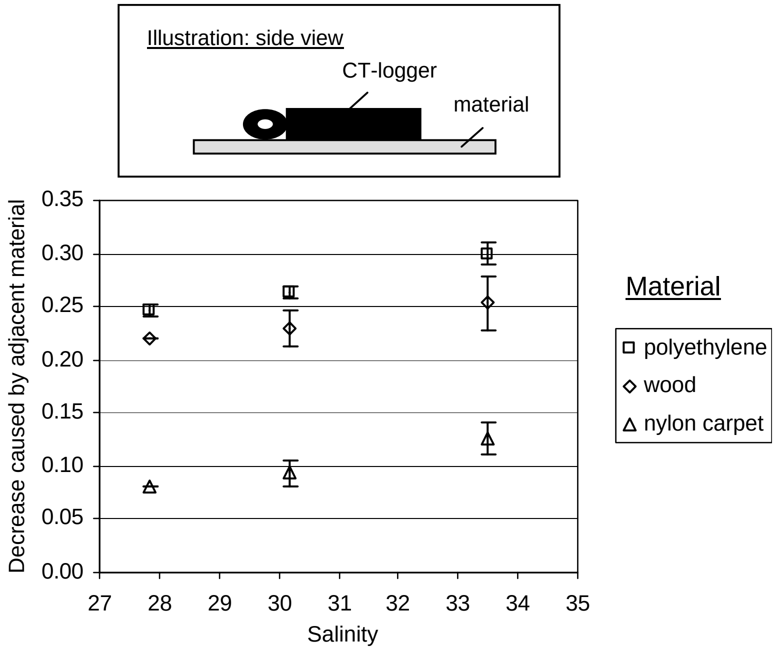

Fig. 3. Near-field step-decrease in salinity recorded with placement on three different material types: polyethylene plastic, wood, and nylon carpet.

Table 1
Effect of placement and orientation against animate object

Placement	Orientation	Salinity: mean (sd) *n*	Offset from free standing
Free standing		33.42 (0.01) 29	
Placed on animate object	Perpendicular	33.19 (0.01) 29	−0.23
	At 45°	32.86 (0.03) 28	−0.56
	Flat	32.43 (0.07) 26	−0.99

Deployments on Antarctic fur seals (see Fig. 1) were in perpendicular orientation.

4.5 kg), such that the instrumentation weighed approximately 1.6% body mass. Of potentially greater concern is the drag for instrumentation deployed on marine species, but the relatively low frontal area of the units used in this study helped to reduce this, and no difference was observed between trip lengths of animals used in this study and other animals monitored, which carried only a radio-tag (British Antarctic Survey, unpublished data).

The two CT-loggers performed well in terms of robustness, and suffered negligible wear and tear when attached to fur seals. The predictability of the seals in terms of time spent ashore meant that delaying sampling for 2 days after attachment to the seal was generally appropriate and the seal was at sea by the time sampling began. On four occasions, however, seals had to be recaptured, and the CT-logger reprogrammed to start 2 days later. In total, data were obtained from 16 successful deployments (Table 2).

One CT-logger was not recovered at the end of the field season, so could not be calibrated post hoc. However, comparison of the two units in a seawater-filled bucket, and also comparison between data collected at sea, showed that one unit read 0.8 higher in salinity than the other. Data were therefore corrected to match the logger that was later recalibrated against a salinometer after the field season, and was found to have remained accurate. The offset caused by the seal to which the loggers were attached has not been corrected, so values presented are relative rather than absolute.

Table 2
Field deployments of CTD-loggers on Antarctic fur seals at Bird Island, December 2000–February 2001

#	Date	Max depth	# Dives > 10 m	# Dives > 50 m	Temperature range (°C)	Distance sampled (km)	Water mass
1	05 Dec	28.0	24	0	0.63–1.31	53.5	S
2	08 Dec	83.4	363	25	0.96–1.66	34.0	N
3	19 Dec	107.6	375	80	0.87–1.74	49.0	N
4	19 Dec	92.5	284	54	0.79–1.82	36.4	N
5	26 Dec	101.5	408	159	0.77–1.97	66.0	S
6	26 Dec	138.8	285	88	0.60–2.13	23.6	N
7	07 Jan	107.4	494	142	0.97–3.01	27.4	N
8	07 Jan	130.3	654	244	0.78–2.60	53.8	S
9	16 Jan	145.6	251	70	0.89–2.89	50.7	S
10	14 Jan	106.8	428	70	0.88–2.57	19.9	N
11	24 Jan	107.5	235	30	0.81–3.71	55.5	N
12	24 Jan	77.3	748	39	1.17–3.27	24.9	N
13	05 Feb	71.9	406	9	3.23–3.74	90.4	N
14[a]	31 Jan	46.8	99	0	1.36–4.96	45.7	N
15	05 Feb	87.5	315	17	2.07–3.99	47.2	N
16[a]	17 Feb	61.0	442	1	2.07–4.03	60.6	N

Water mass corresponds to those shown in Fig. 5: (S) southern, (N) northern. Distance sampled is the straightline distance from start to end of sampling.
[a] All deployments collected the maximum CT data (49.5 h) except the two marked, which returned to shore prior to the end of the sampling period (resulting in 21.7 h data from #14 and 42.3 h from #16).

The instrumented seals made several deep dives during the course of data sampling (Table 2). These dives demonstrate the ability of these instruments to record CTD profiles (Fig. 4). Overall the salinity data recorded were quite noisy, but when examined over an individual dive it can be seen that this noise was manifested in the ascent portion of the dive, whereas during the descent the salinity measurement was fairly consistent (Fig. 4). All further data presented were therefore restricted to the descent portion of dives.

Instrumented seals spent on average 5 days at sea (range 2.5–13 days) and had foraging ranges of up to 218 km from South Georgia (Table 2, Fig. 5a). Faecal samples from these seals, together with data collected concurrently from a digital camera (Hooker et al., 2002) mounted on the shoulders of other fur seals foraging in the same region, showed that krill (*Euphausia superba*) was the main prey being targeted during these dives. Each seal exhibited several bouts of dives during the 2 days of oceanographic sampling (max. depth 146 m, total of 1028 dives deeper than 50 m), and spent on average 8% (range 0.1–21.8%) of their sampled time deeper than 20 m depth (Table 2). Seals often dived through the surface mixed layer and the cold-water thermocline (Fig. 4). Investigation of characteristics of dives to deeper than 50 m maximum depth showed that the bottom of the surface mixed layer generally varied between 40 and 80 m, and the temperature and salinity structure of the water column varied between well mixed and highly stratified.

Overall, the temperature–salinity plots from the seals showed two water masses in the region to the north and southwest of South Georgia (Fig. 5b). The position of the front between these water masses appeared to move north during the period of the study. This was shown by the tracks of individuals characterising the southern water mass (Fig. 5a, blue) in January overlapping spatially with the tracks of individuals from December characterising the northerly water mass (Fig. 5a, red). The fur seals spent 74% of their time in the northern water mass (Table 1). Given that both water masses appeared to be equally available to

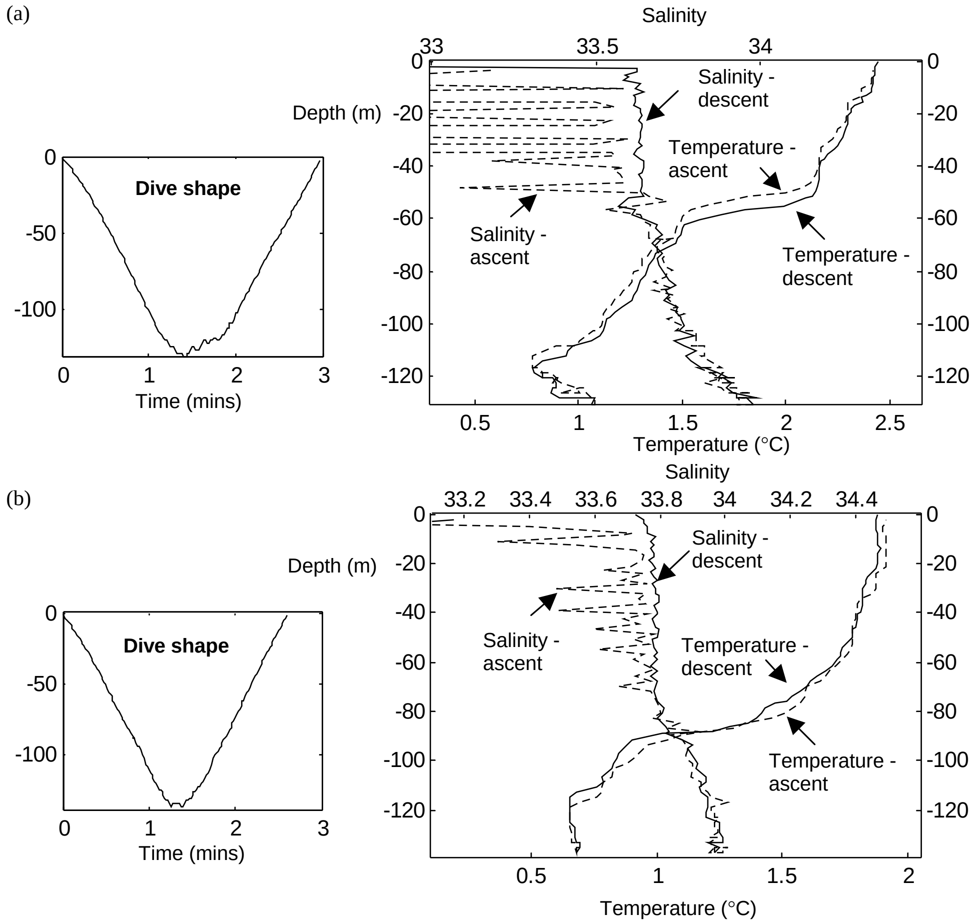

Fig. 4. Illustration of CTD profiles collected during single dives (a) to 130 m during deployment #8, and (b) to 139 m during deployment #6. The differences between descent and ascent phases of data collection are shown.

the seals, this suggests that they may have had a preference for the northern water mass (Chi-sq 4, $p = 0.0455$).

At the scale of the individual, several fur seals spent bouts of dives in water masses showing distinct temperature and salinity characteristics (Fig. 6). Two deployments are illustrated. The coloured sections of dive profile were differentiated by the differences in temperature and salinity characteristics. The first of these (deployment #4, Fig. 6a) appears to have been in water of two distinct salinities with the first dive and later bout of dives during the sampling period in water of higher salinity than the majority of the sampling period. No thermocline was evident in any but the last dive of this period, despite dives to over 80 m depth. The spatial pattern of these water masses can be seen in the satellite track of the fur seal, with waters to the northeast showing higher salinities. The second of these (deployment #8, Fig. 6b) sampled at least four different temperature structures, although salinity was relatively consistent between these. However, the T–S plot shows a discrepancy between deep water in which the seal was swimming at the beginning of the 2-day sampling period and the water during the second and third bouts of dives (shown in different colours). This illustrates the tendency observed in several of these traces for changes in temperature or salinity structure over relatively short scales of

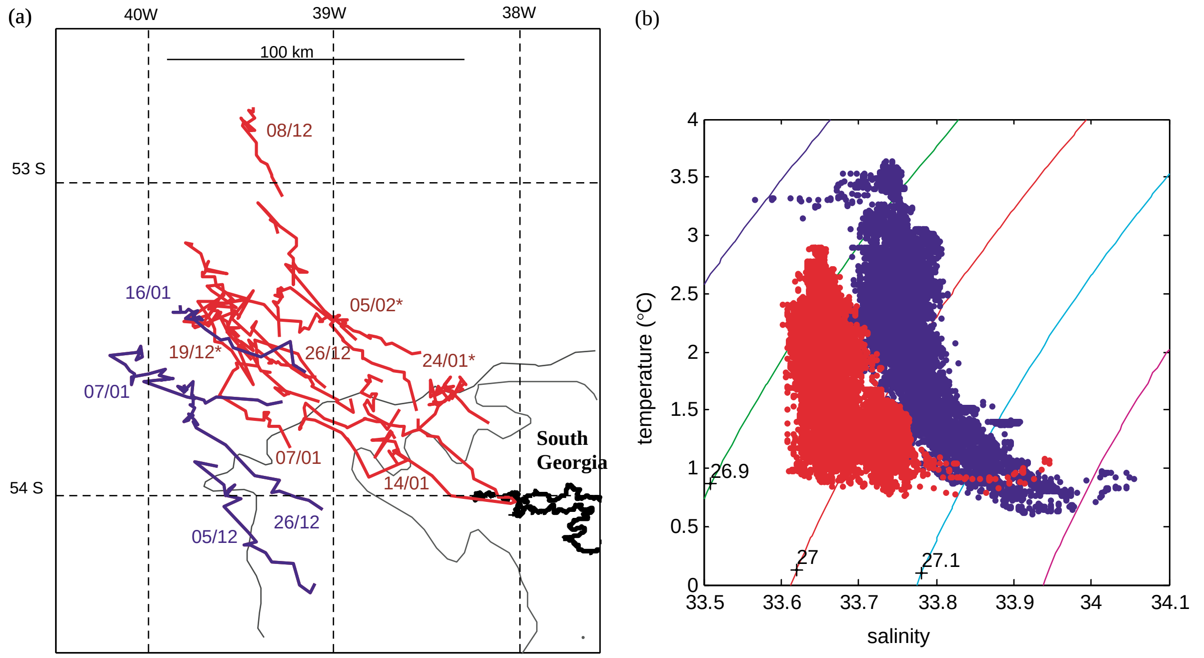

Fig. 5. Instruments collecting conductivity, temperature and depth data (CTDs) were deployed for a single trip on 16 Antarctic fur seals between 5 December 2000 and 19 February 2001. (a) Satellite recorded tracks of fur seals carrying CTD data loggers during data collection (49.5 h of each foraging trip), designated by blue or red trackline. (b) CTD data consistently showed two distinct water masses. Potential temperature versus salinity plot is shown for descent data collected from all animals. Isopycnals are marked in 0.1 kg m^{-3} intervals. All deployments showed general characteristics of one of two water masses, designated by red and blue tracklines in the map. The two distinct water masses appeared to be related to the spatial and temporal positions at which data were collected. Dates of the trips are shown (* indicates two trips at the same date and approximate location).

time (and space) between bouts of dives, and, based on the dive profile, at times without any discrete period of time at the surface between bouts of dives (Fig. 6b). Four of the fur seals appeared to remain in a single water mass of a consistent temperature and salinity structure for the 2 days during which the instrumentation was sampling (data not shown).

4. Discussion

This logging unit is the first to have provided comprehensive, quantitative information on salinity and density collected by attachment to marine mammals (this study and Lydersen et al., 2002). Units performed well in field trials and measurements from instruments on fur seals captured the main features of the surface oceanography of the region when compared with ship-based sampling (Brandon et al., 2000). However, this work demonstrates that the near-field problems incurred during attachment require further consideration or calibration if data are to be used in an absolute rather than relative form.

The majority of problems with the units, caused by near-field effects, could be avoided by appropriate placement of the instrument and by post hoc correction. The near-field effect caused by other metallic objects was a problem only at proximities less than 3 cm with the satellite tag beside the inductive cell of the CT-logger (Figs. 1 and 2). The near-field effect caused by the animal to which the unit was attached appeared to show little variation between animals such that different animals overlapped in T–S plot characteristics (Fig. 5b). The offset caused by the near-field effect also showed little variation across the salinities to which fur

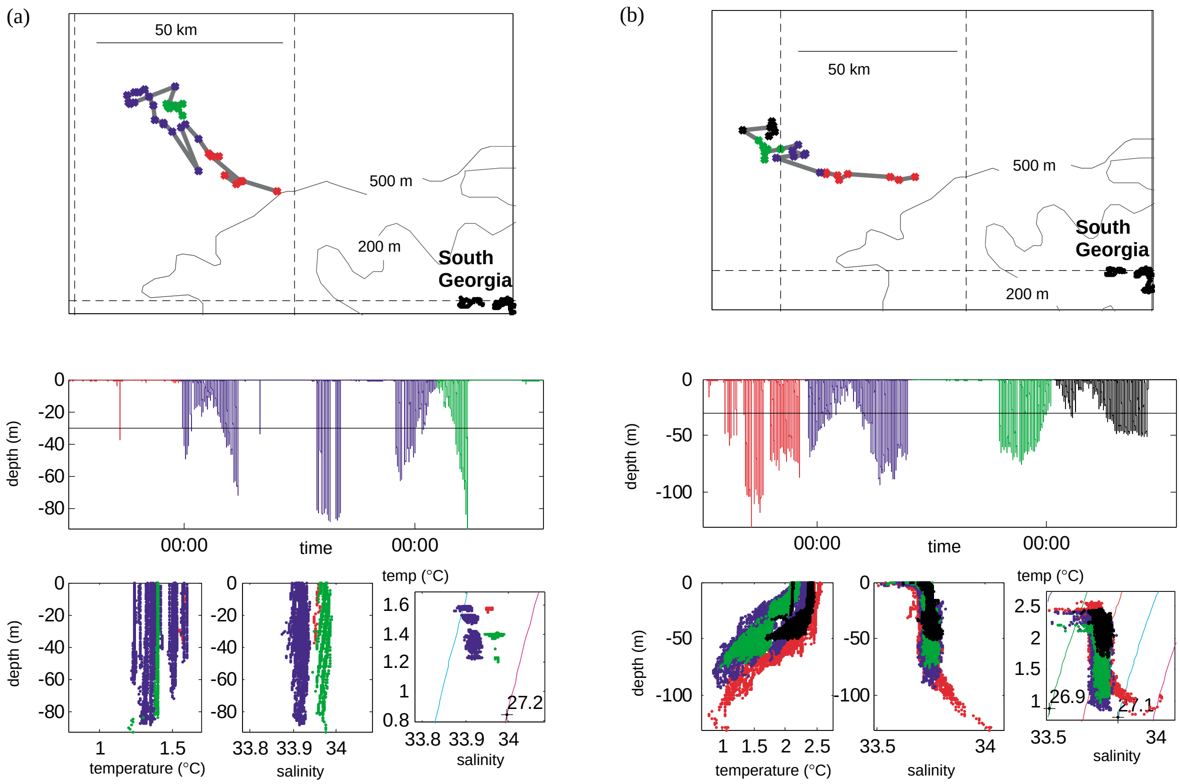

Fig. 6. Fine-scale variation in oceanographic features collected from two seals: the satellite track during data collection (above), the dive profile (middle) and plots of oceanographic features (below)—showing temperature variation with depth (left), salinity variation with depth (middle) and temperature–salinity plot (right). Isopycnals are marked in 0.1 kg m^{-3} intervals. Oceanographic characteristics are shown for descent portions of dives > 30 m (line marked on dive profile). The sections are coloured to differentiate oceanographic characteristics associated with different dives. These colours are also shown on the dive profile and the satellite track. (a) During deployment #4, the seal appeared to move between areas of two distinct salinities but varying temperatures with no distinct thermocline. (b) During deployment #8, the seal moved between different water masses over very short scales of time and space.

seals were exposed in the waters to the north of South Georgia. The salinity variation recorded here therefore appears to be accurate on a relative basis, if not on an absolute basis. Thus, results from the field trials presented here suggest that this system has potential for determining relative salinity variation in the waters in which marine mammals forage.

In absolute terms, however, the effect of the individual animal on the logger may present the greatest difficulty in establishing accurate salinity values to a high precision. This could ultimately limit the utility of this type of instrument when carried by marine mammals. However, there are several potential ways to determine the extent of this offset and thus to calculate absolute salinity values, for example by simultaneous collection of data from two instruments in the same water mass: one predator-borne, and one suspended. With the set-up presented here, with data collection during 2 days of the foraging trip, this would be difficult. However, future improvements with increased memory and battery capacity (Sea Mammal Research Unit, unpublished data), together with a suspended salinity sensor at the exit and entry points for the seal, would relatively easily allow calibration at the start and end of each foraging trip. Regardless of this limitation, the results collected are still useful qualitatively, even if they are problematic in terms of absolute salinity measurement.

This study also suggested several features of the off-the-shelf unit which could be improved in future versions of CTD-loggers for deployment on marine mammals. Incorporation of the depth sensor alongside temperature and conductivity sensors would avoid the need for merging two data sets. Such merging based on independent clocks is unlikely to be perfect, and so will inevitably introduce slight hysteresis into the data set, although there may also be hysteresis caused by the sensor time lag (Fig. 4). In addition, the memory capacity of the CT-logger should be improved to enable sampling over an entire 7-day foraging trip. Battery power of the CT-logger would also need to be improved, and could be achieved by activating the sensors only immediately prior to sampling rather than continually. Lastly, the unit could be solid potted in epoxy to allow a more effective hydrodynamic shape and to ensure that the sensor orientation is fixed relative to the study animal.

The spurious readings from the conductivity sensor during the ascent portion of dives are probably caused by material intruding into the field of the conductivity sensor. It is possible that this was associated with the swimming motion of these seals. The descent and ascent of dives of several marine mammal species appear to differ in movement pattern, with a gliding phase during descent and an active swimming phase during ascent (Williams et al., 2000). Such an active swimming phase could interfere with the readings on the conductivity sensor to some extent. Alternatively, the presence of bubbles around the sensor could also cause the decreases observed. Bubbles have been noted in several of the images recorded by video systems attached to these seals (Hooker et al., 2002). These spurious readings do not present a large concern however, since they can be easily removed from the data set by restricting data to the descent portion of dives.

Therefore, despite these potential problems with the salinity readings recorded here, we have shown that data useful to both oceanographers and biologists can be collected with this type of instrument. The data collected in CTD-type casts showed a pattern that is typical of the upper 100 m of the water column in the region of South Georgia (Fig. 4; Brandon et al., 2000; Deacon, 1982; Priddle et al., 1986). Results over this scale allow an examination of fine-scale changes in water mass over time and space, and illustrate the changes in mixed layer depth and water column structure over scales of hours and tens of kilometres (Fig. 6).

As in this study, ship-based studies have suggested the existence of at least two different water masses in the region (Brandon et al., 2000; Priddle et al., 1986; Fig. 5b). The fact that data collected from instrumented seals showed the same general pattern of water mass structure as from ship-board surveys conducted in the region is extremely promising, particularly since these data were collected at a fraction of the cost of such a survey. This study was further able to investigate fine-scale variations in space and time, and showed the trend in movement of the front between two major water masses during the season (Fig. 5). Furthermore, fine-scale differences between water types are observed within 2-day deployments (Fig. 6). It therefore appears likely that continued collection and incorporation of data collected over extended timescales from marine predators such as these would allow a window into the temporal dynamics of small-scale oceanographic changes such as eddy formation and dissipation.

In summary, using this sensor type we have been able to collect temperature and salinity data of a quality suitable for oceanographic studies. However, we have shown how important it is to calibrate instruments such as this prior to field deployment, and this is likely to be particularly crucial in cases in which instruments are not recovered for post hoc calibration. This system has the potential to provide valuable environmental data to both biologists and oceanographers. In addition to providing environmental detail relevant to the interpretation of predator behaviour, in some circumstances predators like fur seals might be used to undertake oceanographic sampling that could complement oceanographic sampling by other methods (Boehlert et al., 2001; Hooker et al., 2000; Lydersen et al., 2002). The application of such technology to marine mammals which forage in certain areas or which regularly dive to depths of over 1000 m could be used to provide additional information about relatively inaccessible ocean areas.

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