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CTD-SRDLs for
real-time
oceanographic data

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Technical Note: Animal-borne CTD-Satellite Relay Data Loggers for real-time oceanographic data collection

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Abstract

The increasing need for continuous monitoring of the world oceans has stimulated the development of a range of autonomous sampling platforms. One novel addition to these approaches is a small, relatively inexpensive data-relaying device that can be deployed on marine mammals to provide vertical oceanographic profiles throughout the upper 2000 m of the water column. When an animal dives, the CTD-Satellite Relay Data Logger (CTD-SRDL) records vertical profiles of temperature, conductivity and pressure. Data are compressed once the animal returns to the surface where it is located by, and relays data to, the Argos satellite system. The technical challenges met in the design of the CTD-SRDL are the maximising of energy efficiency by minimising size, whilst simultaneously maintaining the reliability of an instrument that cannot be recovered and is required to survive its lifetime attached to a marine mammal. The CTD-SRDLs record temperature and salinity with an accuracy of better than 0.005°C and 0.02 respectively. However, due to the limited availability of reference data for post-processing, data are often associated with slightly higher errors. The potential to collect large numbers of profiles cost-effectively makes data collection using CTD-SRDL technology particularly beneficial in regions where traditional oceanographic measurements are scarce. Depending on the CTD-SRDL configuration, it is possible to sample and transmit hydrographic profiles on a daily basis, providing valuable and often unique information for a real-time ocean observing system.

1 Introduction

One of the greatest impediments to our understanding of ocean processes is a lack of in situ data from remote regions. As a consequence, there is currently a lack of ability to detect and monitor changes in oceanographic conditions in some regions known to be important climatically, and a shortage of data with which to challenge and validate climate models. Understanding the ocean's role in the climate system

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requires sustained sampling of the time-varying oceanic storage of heat and freshwater (Roemmich et al., 2004; Quadfasel, 2005). While the former reveals how the ocean absorbs and redistributes heat from the atmosphere, the latter reflects variability in precipitation and evaporation through salinity anomalies, with the added complexity of anomalies due to sea ice and glacial ice-related processes in the polar regions.

The Global Ocean Observing System (GOOS) is designed to fulfill these requirements (Alverson, 2008a), and necessitated the creation of special profiling floats with which to observe the temperature and salinity of the world's oceans down to 2000 m depth. The broad-scale global array of profiling floats, known as Argo, has already grown to be a major component of GOOS. Deployments began in 2000 and, by the second half of 2007, 3000 floats were distributed over the global oceans. This array is providing about 100 000 hydrographic profiles and velocity measurements per year (Gould et al., 2004).

The Argo array is designed for broad-scale ocean sampling at spatial intervals of hundreds of kilometres, greater than the size of eddies and boundary currents (Roemmich et al., 2004). Although the profiling float has enormous potential for these broad-scale ocean observations, it does not provide a complete observational strategy (Alverson, 2008b). It is essential that parallel advances are made in the measurement of air-sea exchanges and small-scale sampling for estimation of lateral fluxes. It is necessary to sample at higher spatial resolution in a "line-sampling" mode (i.e. section-based data distribution), resolving eddies and boundary currents for flux calculations, and to sample from ocean boundary to ocean boundary for flux integration. Research vessels lend themselves to the line-sampling mode, as reflected in the data collection strategies and ocean heat/freshwater transport estimates from the World Ocean Circulation Experiment and other comparable programmes (e.g. Ganachaud and Wunsch, 2000).

In this paper, we discuss and present recent advances in a novel technique that complements well the existing observing systems. Autonomous CTD-Satellite Relay Data Loggers (CTD-SRDs) can be attached to marine animals, and report vertical profiles of conductivity, temperature and pressure to a maximum depth of around 2000 m (de-

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pending on species). The implementation of this technique has great potential to help populate remote and previously data-sparse regions (Fedak, 2004). Whilst the underlying concept is not new (Evans, 1970; Boehlert et al., 2001), CTD-SRDLs are the first instruments that record full temperature and conductivity profiles, and enable transmission of these data in near real-time. This latter functionality is a key requirement for a fully-enabled ocean observing system, while the ability to return salinity data (derived from temperature, conductivity and pressure) is especially important in regions where the water column structure is dominated by salinity changes, e.g. the polar and subpolar oceans. The information returned from CTD-SRDLs is relevant not only to the study of physical structures of the oceans (Lydersen et al., 2002; Boehme et al., 2008a,b; Costa et al., 2008; Charrassin et al., 2008; Roquet et al., 2009; Meredith et al., 2009), but can also be useful for studying the ecology of the carrying animals (Lydersen et al., 2002; Hooker and Boyd, 2003; Lydersen et al., 2004; Charrassin et al., 2004; Biuw et al., 2007).

While the measurements returned by CTD-SRDLs are neither regular in terms of spatial and temporal coverage (compared, for example, to satellite measurements of oceanographic fields), these studies provide valuable in situ information about the sub-surface structure of the ocean. The use of oceanic predators for remote data collection, although suffering from the inability to predetermine the locations of sample collection, can benefit from the ability of such predators to select foraging areas. Sampling is not uniform, but in many cases the predators act as “adaptive samplers” by targeting foraging areas, which are likely to coincide with many of the regions of most interest to biological and physical oceanographers (Ginet et al., 2001; Boehme et al., 2008b). Furthermore, migrations to and from these focal foraging areas are often highly directed, and regularly cross major ocean fronts, providing a combination of transect-type and mooring-like data (Boehme et al., 2008a,b; Costa et al., 2008; Meredith et al., 2009; Roquet et al., 2009). With careful selection of species, gender and age of the animals, as well as the geographic location and time of tagging, it is even possible to undertake focused, highly cost-effective oceanographic studies in regions that might

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be difficult, and therefore expensive to access in any other way (Nicholls et al., 2008).

2 Design

The series 9000 CTD-SRDL (Fig. 1) is designed and built at the NERC Sea Mammal Research Unit (SMRU), St Andrews, UK. It consists of a 401 MHz RF unit and antenna for data transfer via the Argos system, a lithium-ion D-cell battery and a Hitachi H8/3048 microprocessor programmed to act as the data logger, data compression tool and to schedule data transfer. The CTD sensor head is built and calibrated at Valeport Ltd, Devon, UK. Data from various sensors are collected when pre-programmed conditions of time and depth are met. Sampling algorithms onboard the CTD-SRDL detect the deepest point of a dive, and then begin rapidly sampling temperature, conductivity and pressure until the surface is reached. The limited Argos data bandwidth and energy constraints do not allow all data points to be transmitted. Therefore, a sub-set of pressure points with corresponding temperatures and conductivities are selected for transmission from these high-resolution data (see Sect. 4). Detailed data from the pressure sensor and information from a wet-dry sensor are collected and used to form detailed individual dive and haulout records along with synoptic summary records of animal behaviour (Fedak et al., 2002). Data are then stored in internal memory and transmitted at the surface via the Argos satellite system (Argos, 1996).

Potential effects on an animal's normal behaviour must be considered whenever an animal-borne instrument is designed. While the "rule of thumb" for complete instruments dictates that they weigh no more than 2–5% of the animal's total body weight (Cochran, 1980), subsequent studies have shown the importance of species-specific considerations. Aldrige and Brigham (1988) showed that adverse impacts from the weight of instruments should be examined not only for each species but also for size variations within each species if no such data from closely related species exist. The CTD-SRDL is designed to minimise any effects on an animal, i.e. shaped to minimise hydrodynamic drag. The outside dimensions are 12.0 cm length, 7.2 cm width and

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6.0 cm height (Fig. 1). The antenna length is 15 cm. The volume is about 254 cm^3 with a mass of $545 \pm 5 \text{ g}$ in air and $255 \pm 5 \text{ g}$ in sea water. The cross-sectional area is about 35 cm^2 . Referring to the “rule of thumb” for the animal’s total body weight, an instrumented animal should therefore have a minimum mass of 25 kg. CTD-SRDLs have been deployed on harbour, grey, hooded, harp, ringed, weddell, crabeater, northern and southern elephant seals, and also on california sea lions, and leatherback turtles, which are all substantially larger than the minimum required size. Due to animal behaviour, CTD-SRDLs must sometimes be attached to the head of an animal to increase the surface time sufficiently to make a transmission possible. In this case, the weight of the CTD-SRDL is of greater importance, because the head often needs to be accelerated in order to catch prey. Previous practical experience with CTD-SRDLs and data loggers of similar size and weight has showed no harm on a variety of animals (McMahon et al., 2008). Analyses on adult female southern elephant seals (250–800 kg) on Macquarie Island showed no measurable effect. For instance, females carrying tags gained the same weight over winter (and summer) as those not carrying tags (Hindell, personal communication, 2008).

3 Oceanographic sensors

The design requirements for a CTD sensor to be integrated into a small animal-borne instrument are particularly demanding. It has to use almost no power, be virtually indestructible, and yet be minimised in size and weight. This requires small, non-pumped sensors that are inevitably less accurate when compared to larger pumped CTD systems. A key issue was thus to determine the required accuracy of the oceanographic sensors to be useful for oceanography, and to incorporate these requirements into the design specifications. Recent studies show that mid-depth Southern Ocean temperatures have warmed by as much as 0.17°C since the 1950’s (Gille, 2002), but long-term changes in the deep ocean temperature are usually of the order of 0.01°C per decade (Zenk et al., 2003; Fukasawa et al., 2004). Recent examinations of sur-

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face and near-surface salinity changes showed that long-term changes of salinity were of the order of 0.02 per decade (Curry et al., 2003; Boyer et al., 2005). The salinity changes at greater depths are somewhat smaller in the order of 0.005–0.01 per decade (Meredith et al., 2008). To detect such small changes in the deep ocean, high accuracy measurements are necessary. Ship-based CTDs are traditionally used, but also Argo floats generally achieve these accuracies (Wong et al., 2003; Boehme and Send, 2005; Wong and Owens, 2009). Upper ocean changes are easier to detect (as shown above). Expendable bathythermographs (XBTs), which are traditionally used to provide very large numbers of in situ ocean temperature profiles have an accuracy of ± 0.02 to $\pm 0.1^\circ\text{C}$ (Boyd and Linzell, 1993; Lockheed Martin Sippican, Inc., 2009). Expendable CTDs (XCTDs) also record salinity with an accuracy of about 0.06 (Lockheed Martin Sippican, Inc., 2009), which is not accurate enough to detect the above-mentioned long-term changes in the upper ocean, but is sufficient to position strong gradients found at boundaries of eddies or across ocean fronts. Remote sensing plays an important part, when large areas need to be covered, e.g. sea surface temperature (SST) is routinely measured by satellite with an accuracy of 0.1 to 0.5°C and a spatial resolution between 1 and 50 km (McClain et al., 1985; Reynolds et al., 2005). Again, this is not sufficient to detect long term changes. Accordingly, in line with the magnitude of signals being measured and the capabilities of other complementary techniques, there is a requirement for CTD-SRDLs to provide data with proven accuracies of $\pm 0.01^\circ\text{C}$ for temperature and ± 0.02 for salinity to detect long-term changes in the upper to mid-depth ocean. While these sensor accuracies in themselves are quite easily achievable, they are substantially harder to attain in genuine deployments due to other requirements and the nature of the deployment.

The pressure sensor is incorporated in the CTD head of the CTD-SRDL (Fig. 1). This sensor consists of a Keller series-7 piezoresistive pressure transducer (Keller AG, CH) with a diameter of 15 mm. A high-sensitivity piezoresistive silicon chip is used for pressure sensing. The chip is protected from ambient influences by a stainless steel (316L) housing sealed with a concentrically corrugated diaphragm. The housing is

filled with silicone oil for the transfer of the pressure from the diaphragm to the sensing component. The fully welded housing is vacuum-tight. The pressure range given by the manufacturer is up to 2000 dbar with an accuracy of about 1% of the full-scale reading. However, comparisons with a SeaBird Electronics (SBE) 911plus CTD showed an accuracy of better than 0.25% of the actual reading (SMRU/BAS, unpublished data), i.e. better than 5 dbar at the full scale reading, while checks in the calibration lab at Valeport Ltd showed errors in the pressure reading of less than 1 dbar over the full range (Table 1). To account for any long-term drift, pressure readings are also taken, whenever the wet-dry sensor detects the surface and if an offset exists, pressure is reset to zero.

The CTD head is equipped with a Platinum Resistance Temperature Detector (PRT). The PRT works on the principle of resistance through a fine platinum wire as a function of temperature, e.g. the most common type (PT100) has a resistance of 100 ohms at 0°C and 138.4 ohms at 100°C. The probe is housed in a metal tube in front of the conductivity sensor (Fig. 1). Valeport Ltd. states an accuracy of better than $\pm 0.005^\circ\text{C}$. This was confirmed by post calibration checks done by Valeport Ltd. (Table 1) and by recalibrations at the calibration lab at the Naval Postgraduate School in Monterey, CA, USA, which also showed that the temperature readings are in general better than $\pm 0.002^\circ\text{C}$ (Fig. 2).

An inductive method was selected over an electrode cell to measure the conductivity of the seawater. This, and the titanium and ceramic construction, give improved durability and reduces the risk of sensor drift due to corrosion. Valeport Ltd. also developed a new digital measurement technique for the inductive sensor, resulting in a highly accurate sensor with much lower power consumption than traditional methods, and with much shorter sampling duration. One known feature of some inductive cells is that they compress slightly under pressure. This could result in a significant effect on the necessarily small bore of the inductive cell on the CTD-SRD. An inaccuracy of about $1\mu\text{m}$ in the bore would push the sensor out of specification. Again, the use of high strength ceramics in the construction mean that even at 2000 dbar pressure, the conductivity

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cell retains its shape sufficiently. Valeport Ltd. calibrates the conductivity sensor to an accuracy better than ± 0.01 mS/cm. Post-calibration checks at Valeport Ltd. show accuracies of about ± 0.005 mS/cm (Table 1). This would lead to an error in the derived salinity of ± 0.02 for the claimed accuracies and ± 0.01 with the measured accuracies.

5 These tests show that the accuracies of the temperature and the derived salinity before deployment in an undisturbed environment are better than the set requirements.

One disadvantage of a single bore inductive cell is the increased risk of interference of the external field of the sensor. During calibration tank experiments, we tested the CTD-SRDLs in different configurations to estimate possible effects on the salinity measurements (Fig. 3). During the first test, the CTD-SRDL was moved towards the calibration tank wall (non-conductive), with the bottom of the CTD-SRDL facing the wall. As the distance between the tank wall and the bottom of the CTD-SRDL was reduced, an effect on the derived salinity values became obvious at a distance shorter than 10 cm (Fig. 3). When the bottom of the CTD-SRDL was in contact with the tank wall, the salinity values were up to 0.075 too low. The CTD-SRDL was also turned in the tank, e.g. with the side of the instrument in contact with the wall. The effect on salinity was greatest when the inductive cell was in direct contact with the interference, with the resulting errors being up to 0.5 (Fig. 3). Interestingly, a second salinity test with the bottom of the CTD-SRDL touching the tank wall gave errors of around 0.01, much less than in the first test (Fig. 3). This, and the high magnitude of the errors, suggests that the conductivity sensor is highly sensitive to obstructions in the external field.

During deployment, CTD-SRDLs are sometimes attached to a plate with cable ties, with the plate already having been attached to the animal's fur. These configurations were also tested in the calibration tank experiments. Cable ties were placed around the CTD-SRDL in front and behind the conductive cell. These cable ties were seen to have a distinct effect on the conductivity reading (offset of order 0.05, Fig. 3) and hence should be avoided, or alternatively the data will need to be corrected before use. However, these calibration tests also suggest that even if no cable ties and/or plates are used, the proximity of the conductivity cell to the body or head of the animal,

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containing several tissues with different conductive or insulating properties, is likely to have an effect on the conductivity measurements. The salinity data will therefore have to be corrected accordingly.

4 Data compression and transmission

5 Animal telemetry is occupying a rapidly increasing fraction of Argos bandwidth, however the Argos system does have some drawbacks for telemetry from marine mammals. Transmitters that are certified to communicate with Argos must conform to very strict frequency tolerances. Individual messages (termed “uplinks”) may be up to 960 ms in duration and it takes 4 or more complete uplinks for the system to compute
10 a location and provide an estimated accuracy (Argos, 1996). This accuracy depends on the number of uplinks received, the temporal pattern of these receptions and the position of the satellite relative to the transmitter (Vincent et al., 2002). Uplinks may contain a maximum of 256 bits (32 bytes) per message in a rigid format and Argos sets a minimum interval of 40 s between transmissions (Argos, 1996). However, Argos
15 effectively limits the usable number of bits to 228, because 28 bits are now used for the PTT (Platform Transmitter Terminal) number.

These restrictions, combined with the fact that animals are only briefly and infrequently at the surface (for example, 10% of the time for elephant seals), place unusually tight limits on bandwidth. These and those limitations caused by energy constraints,
20 demand complex data collection software and extreme data compression, which in turn demand a sophisticated data collection platform. This bandwidth restriction is compounded by the fact that satellites are not always visible. However, the data transmission restrictions resulting from energy constraints and Argos restrictions do not interact in an additive way and steps taken to circumvent Argos limitations also serve
25 to help avoid energy constraints. Detailed descriptions of the collection and compression of behavioural data are given by Fedak et al. (2002); here, we concentrate on the hydrographic data compression. The design of the compression method of the CTD

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data is determined by the user and can be changed at any time before the deployment. Therefore, we describe the standard program that is used in most cases and is the default setup appropriate for general application.

The CTD-SRDL samples pressure every 4 s during a dive. At this point only the pressure sensor of the CTD head is utilised to minimise energy consumption. The deepest point of a dive is detected by analysing the trend provided by the pressure sensor. One day is divided into four 6-h periods in which one full CTD profile is recorded and if this deepest depth exceeds a pre-set value in a 6-h period, the CTD-SRDL switches to “sampling-mode”. This setting is chosen to ensure that the batteries last long enough to perform 4 CTD profiles a day, assuming a 12 month deployment with an average diving depth of 1000 m. On the ascent, the CTD-SRDL then begins sampling temperature, conductivity and pressure at 1 Hz until the surface is reached. From this full profile data, salinity is calculated. In doing so, a 1-s time lag (derived empirically) is applied to the conductivity readings to account for the different time constants between the temperature and conductivity sensors. While the conductivity time constant is instantaneous, the temperature sensors is afflicted with a time constant of about one second. Then, a 5-s median filter is applied to the temperature and salinity time series of that particular profile to remove any spikes, instead of a mean filter, which could introduce a bias. This 5-s median filter depends on any spikes to be shorter than two seconds (affecting two readings), but a longer filter would flatten the profile too much.

Finally, a set of four 256 bit Argos messages is produced. One message contains a detailed dive summary. Another message comprises information about the cruise/haul-out pattern in the 6-h period (see Fedak et al., 2002, for more details), while the CTD data are compressed into two other messages. Only 17 representative depth points with corresponding temperature and salinity values are selected for transmission using a combination of 8 predefined depths, 7 inflection points, which are chosen via a broken-stick point selection algorithm (Fedak et al., 2002) and the extreme depths. The first message contains 8 fixed depth T/S pairs and the shallowest measurements. The second message contains 7 broken-stick and the deepest triplets. The fixed depth

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points are chosen according to the deepest point of the dive based on Table 2. The remaining seven points are selected between the fixed depth points based on the broken-stick method.

The standard software has a temperature range from -2°C to 30°C with a resolution of 0.10% of the temperature range of the specific profile, i.e. if the maximum and minimum temperatures within one profile are less than 10.24°C apart, then the resolution will be better than 0.01°C . Only the minimum and maximum temperatures are transmitted as full values while all intermediate values are associated to one of 10 bits, hence the resolution depends on the temperature range. This setup will thus produce a temperature resolution that will be better than the required accuracy in most of the high latitude oceans. The salinity range is 8.19, typically between 29 and 37 to be applicable in most of the world oceans. The resolution of the transmitted data points is about 0.39% of the salinity range of that specific profile, i.e. if the salinity range within the profile is less than 2.56, a resolution of better than 0.01 is achieved (8 bit resolution).

The compressed hydrographic and behavioural data are then transmitted during each surfacing of the seal. The CTD-SRDL antenna is oriented so as to be out of the water when the seal is at the surface (Fig. 1). The minimum interval between two successive messages has to be 40 s (Argos, 1996). However, sometimes the CTD-SRDL is underwater, because of waves or the animal's movements, so that the next transmission would not be received by a satellite, or would be delayed. The average surfacing time of e.g. an elephant seal is around 130 s, which would theoretically allow the CTD-SRDL to send 3 messages. Unfortunately, Argos satellites are not always available and the low power of the transmitter together with the small antenna result in messages not being received by the Argos satellite system. Due to its high compression, all bits in any one value are significant and receiving or decoding errors have a great impact. Such "flipped bits" can result in wrong values or, more significantly, can change the e.g. temperature range of a profile and therefore alter all temperature values. Therefore a pseudo-random method to schedule the transmission of an unbiased sample of stored profiles is used and some messages are received more than once,

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allowing to check and correct “flipped bits”. If, by chance, a CTD-SRDL is recovered at a later stage, all data collected for transmission, whether or not they were successfully relayed, can be downloaded. This data is compressed based on Table 2, but still in full resolution.

5 To quantify the impact of these transmission issues, data from more than 115 000 messages returned from CTD-SRDLs deployed on southern elephant seals during 2004 and 2005 were analysed (Fig. 4). For more than 75% of all surfacings, 2–3 messages were received (Fig. 4) resulting in about 2 CTD profiles on average per day. A third of this data might have only the seven or eight points of one message. The limited surface time also reduces the possibilities of a position fix by the Argos system, which requires at least 4 received messages (Argos, 1996). Only for less than 25% of all surfacings are four or more messages received and a position calculated (Fig. 4). Consequently, positions for some surfacings are determined using delayed mode auxiliary location processing, typically by removing locations requiring unrealistic swimming speeds for a given species. Further information on post-processing such data is given by McConnell et al. (1992) and Lonergan et al. (2009). The position of the CTD profile is then assumed to be between the framing surface positions, with the relative distances to each framing position determined by their relative times of occurrence. In general, the accuracy of the position for each CTD-SRDL profile is of the order of 2 km. This is less accurate than the position information typically associated with e.g. ship-based CTD profiles, but is entirely adequate for general open-ocean studies. There is currently much effort by animal biologists and statisticians to improve these position estimates using a variety of movement models and state-space approaches. Furthermore, since 2008 Argos provides error ellipsis estimates (major and minor axis lengths and orientations relative to North/South) for each position fix, and these will also be re-calculated and provided in delayed-time for past deployments. This will substantially improve the location error estimates, and lead to movement models with smaller uncertainty for interpolated positions such as those calculated for CTD profiles for the delayed-mode data.

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5 Field experiences and real-time data

CTD-SRDLs have been deployed on a variety of species for more than 5 years now, and have delivered very large quantities of behavioural and oceanographic data. For example, the international “Southern Elephantseals as Oceanographic Samplers” (SEaOS) project collected more than 22 000 oceanographic profiles over 3 years in the Southern Ocean, and these represented a major addition to the World Ocean Database. Such datasets were usually received in near real-time during the deployment, with data analysed afterwards. Since recalibrations of the sensors are generally not possible, data quality has to be examined in an indirect way. Due to their similar nature to Argo float data, CTD-SRDL data are usually checked using methods similar to those used in the Argo community (Wong et al., 2003; Boehme and Send, 2005; Wong and Owens, 2009). Such post-deployment quality control adds uncertainty to the dataset, which is typically of order 0.005 in salinity, but can be higher (up to 0.1) in data sparse regions or regions of high variability in water mass properties (Wong et al., 2003; Boehme, 2004; Boehme and Send, 2005). Boehme et al. (2008a) and Nicholls et al. (2008) found similar results for their datasets, with errors of $\pm 0.005^{\circ}\text{C}$ in temperature and 0.02 in salinity, while Roquet et al. (2009) assumed an accuracy of $\pm 0.03^{\circ}\text{C}$ in temperature and 0.1 in salinity after post-deployment corrections. However, not all studies used the same version of the CTD sensor head and results can therefore differ. Generally, the salinity data collected during a CTD-SRDL deployment are too high when compared with ship-based measurements or climatology (Fig. 5). This may be caused by the aforementioned effect of the animal’s head on the inductive field of the conductivity sensor (Fig. 1). In case of CTD-SRDLs deployed on southern elephant seals, with the instruments glued to the fur on the head close to the upper neck region, the derived salinities generally have offsets between -0.3 and 0 in salinity (Fig. 5). However, this shows that the CTD-SRDL data can be reliably corrected using methods developed by the Argo community.

Since 2004 French collaborators in the SEaOS project deliver their CTD data to the

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French data center CORIOLIS in near real-time. However, since July 2008, a system has been operating to forward CTD-SRDL data to the Global Telecommunication System (GTS) in near-real time, from where it is distributed to data centres requiring rapid delivery data for numerical weather and ocean forecasting purposes. The “Marine Mammals Exploring the Oceans Pole to Pole”¹ (MEOP) project (involving 10 nations: Norway, UK, France, USA, Australia, Brazil, South Africa, Germany, Canada, Greenland) was the first to take the opportunity to provide CTD-SRDL data via the GTS, and produced up to 200 CTD profiles daily north of 60° N and south of 40° S during the International Polar Year (since July 2008). To ensure the highest possible data quality, simple checks can be performed before data are placed on the GTS. Here, the most important part is the determination of the “head-effect” on the conductivity measurements and its correction in the real-time data stream. Usually, a time series of measurements is needed to be compared with climatology to calculate instrument specific corrections, but a general correction in the order of -0.1 could be employed from the start (Fig. 5).

6 Summary and conclusions

We have outlined an innovative approach to the collection of oceanographic data that has proven particularly useful in remote, previously inaccessible parts of the oceans. Accurate satellite positioning of diving marine animals, relatively high-accuracy sensors, and the potential to collect large numbers of profiles cost-effectively in near real-time make these studies particularly important in regions where traditional oceanographic measurements are scarce.

The uniqueness of the series 9000 CTD-SRDL lies in its data collection, processing and transmissions strategies, and we have demonstrated that such animal-borne sensors have the potential to provide very large quantities of oceanographic measurements of usable quality in near real-time, down to depths up to 2000 m. The CTD-

¹<http://dev.meop.npolar.no/en/index.html>

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SRDLs record temperature with an accuracy of better than 0.005°C, however, due to the limited availability of reference data for post-processing, data are often associated with an error of 0.005–0.01°C. Salinity measurements are in general accurate to better than 0.02, but have an associated offset of the order of 0.1 during the actual deployment due to the effect of the seal's head and body onto the inductive field. The salinity data therefore need post-processing for delayed-mode quality control, but a correction can be used to produce a real-time data correction to enhance the rapid delivery data.

Depending on the CTD-SRDL configuration, it is possible to sample and transmit hydrographic profiles on a daily basis. The CTD-SRDL is therefore intrinsically an eddy-resolving line-mode device, rather than a broad-scale one delivering quasi-randomly scattered data. The natural niche for CTD-SRDLs in the observing system is in complementary measurements of boundary currents, ocean fronts and of property fluxes across lines (Boehme et al., 2008b), as well as coverage of undersampled ocean regions (Charrassin et al., 2008; Nicholls et al., 2008). They are thus a powerful complement to existing hydrographic sampling methods, and their utility will increase in the future as data quality improves further. Other enhancements will include different parameters that can be measured: a fluorometer is currently under development for incorporation into the existing CTD-SRDL package, and other sensors will be developed subsequently. Additional sensors would mean more data and new methods for relaying data from remote places and increasing the bandwidth are investigated, but energy constraints are still the all limiting factor. However, such developments will further enhance the contribution of the CTD-SRDL to the Global Ocean Observing Systems.

Acknowledgements. We would like to thank the Sea Mammal Research Unit Instrumentation Group for their endless work to improve their instruments. A special thanks to the staff and engineers of Valeport Ltd. for their help in designing the oceanographic sensors for the Sea Mammal Research Unit Instrumentation Group. The Naval Postgraduate School in Monterey, CA, USA, provided their calibration facilities for testing of CTD-SRDLs. Funding for instrument development was provided by the National Oceanographic Partnership Program Office of Naval Research. This research was funded by the Natural Environment Research Council (NERC) grants NE/E018289/1 and NER/D/S/2002/00426 and a NERC Co-operative Award in Science

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Fig. 1. Picture of a CTD-Satellite Relay Data Logger (CTD-SRDL) with antenna (1), temperature probe (2), inductive cell (3), pressure sensor (not visible) (4), battery (5), communications port (6) and wet-dry sensor (7). *Insert:* CTD-SRDL deployed on a southern elephant seal.

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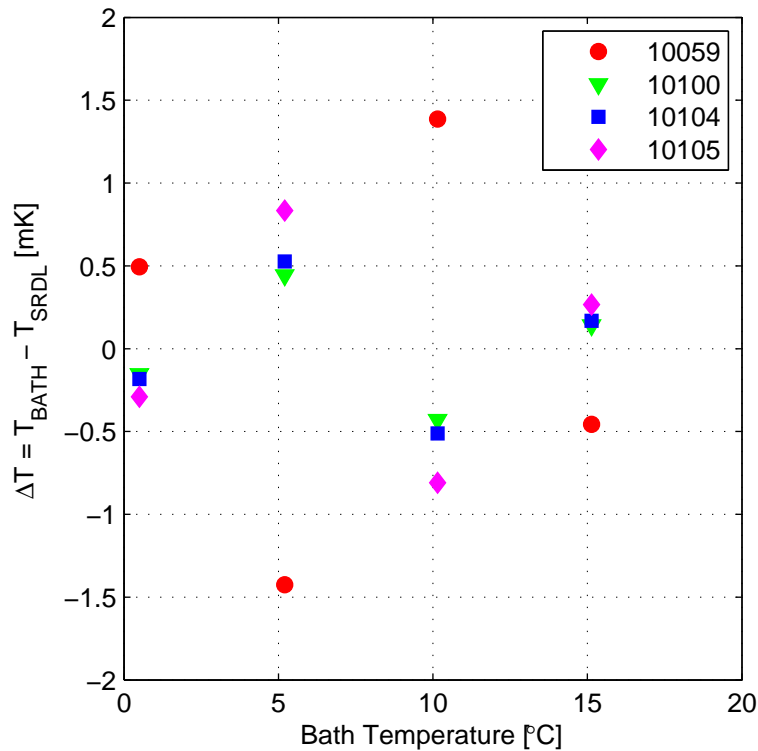


Fig. 2. Temperature differences between four controlled temperature baths and measurements from four CTD-SRDLs (colorcoded).

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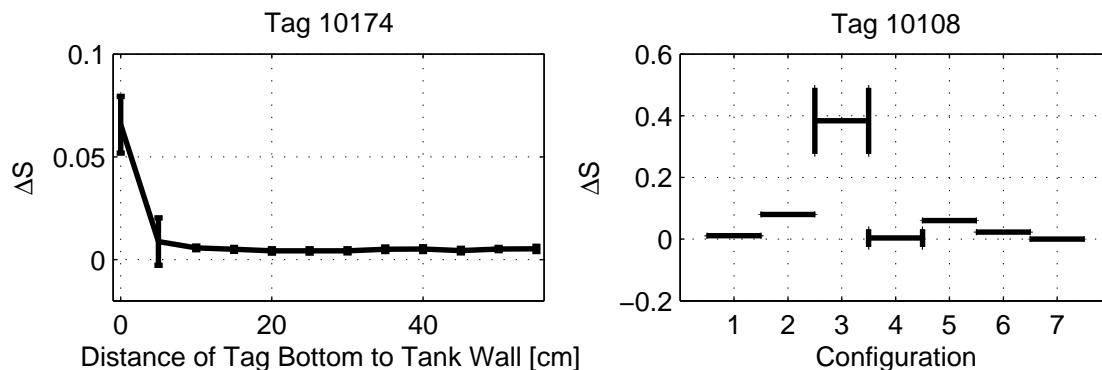


Fig. 3. External field effect on salinity. *Left:* Differences between the bath salinity and CTD-SRDL data. A CTD-SRDL was moved towards a wall of the calibration tank. The bottom of the CTD-SRDL was facing the wall. *Right:* The effect on CTD-SRDL salinity error using different deployment configurations: bottom at wall(1), side at wall (2), conductivity cell at wall (3), random movement (4), different cable tie configurations (5 and 6), no movements in the middle of the tank (7).

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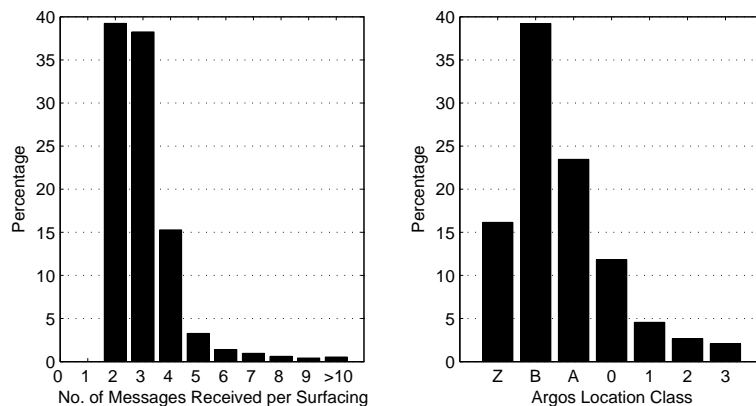


Fig. 4. Percentage of Argos messages received for each surfacing (left) and the Argos location class for each calculated position (right). The position accuracy is: 3 (<250 m), 2 (<500 m), 1 (<1500 m), 0 (>1500 m), A (three messages received), B (two messages received), Z (no position fix). Data are from CTD-SRDLs south of 40° S.

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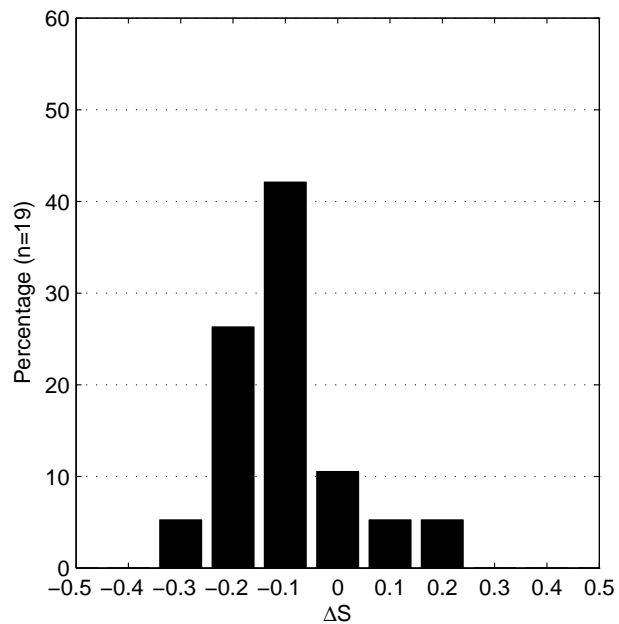


Fig. 5. Salinity differences between historical salinity data and CTD-SRDL data.

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Table 1. Summary of calibration checks done by Valeport Ltd, Devon, UK. 10 CTD-SRDLs were calibrated and then re-tested against one known temperature and salinity and against a range of pressures from 0 dbar to 2000 dbar in December 2007.

| SRDL ID | Maximum error in temperature [mK] | Maximum error in conductivity [10^{-3} mS/cm] | Maximum error in pressure [dbar] |
|---------|-----------------------------------|--------------------------------------------------|----------------------------------|
| 10 857 | 0 | 4 | 0.214 |
| 10 859 | 2 | 1 | 0.180 |
| 10 851 | 3 | 6 | 0.616 |
| 10 854 | 2 | 3 | 0.861 |
| 10 849 | 1 | 9 | 0.415 |
| 10 847 | 2 | 2 | 0.491 |
| 10 853 | 1 | 8 | 0.071 |
| 10 850 | 2 | 9 | 0.575 |
| 10 861 | 3 | 5 | 0.405 |
| 10 848 | 2 | 2 | 0.612 |
| Mean | 1.800 | 4.900 | 0.444 |
| Std | 0.919 | 2.998 | 0.239 |
| Max | 3.000 | 9.000 | 0.861 |

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Table 2. Fixed depth points transmitted depending on dive depth. All points are transmitted within one Argos message, except the one in brackets, which will be send together with the broken-stick depths.

| Pressure | Fixed depths used | | | | | | | | | |
|-----------|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 10 dbar | X | X | X | X | X | X | X | X | X | |
| 14 dbar | X | | | | | | | | | |
| 20 dbar | X | X | X | X | X | X | X | (X) | (X) | |
| 26 dbar | X | | | | | | | | | |
| 30 dbar | X | X | X | X | (X) | | | | | |
| 36 dbar | (X) | | | | | | | | | |
| 40 dbar | X | X | X | | | | | | | |
| 50 dbar | X | X | X | X | X | X | X | X | X | X |
| 60 dbar | | X | (X) | | | | | | | |
| 80 dbar | | (X) | | (X) | | | | | | |
| 100 dbar | | X | X | X | X | X | X | X | X | X |
| 150 dbar | | | X | X | X | (X) | | | | |
| 200 dbar | | | | X | X | X | X | X | X | |
| 300 dbar | | | | | X | X | X | X | X | (X) |
| 400 dbar | | | | | | X | (X) | | | |
| 500 dbar | | | | | | | X | X | X | |
| 750 dbar | | | | | | | | X | X | X |
| 1000 dbar | | | | | | | | | X | X |
| 1500 dbar | | | | | | | | | | X |

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