Deep-Sea Research II 88-89 (2013) 7–13

Contents lists available at SciVerse ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

The impact of animal platforms on polar ocean observation

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ARTICLE INFO

Available online 16 July 2012

Keywords:
Oceanographic equipment
CTD profilers
Instrument platforms
Data collections
Data loggers
Ocean-ice–atmosphere system
Polar oceanography
Marine mammals

ABSTRACT

The polar seas play a critical role in the climate system, forming important links between all oceans and between the atmosphere and deep sea. In addition, they support vital and unique ecosystems containing important living resources. Yet despite their importance, the physical environment and ecosystems of the polar regions are still under-sampled and, as a result, relatively poorly understood. At the 1st Symposium on Biologging Science in Tokyo, 2003, I reported on the initiation of the first large scale deployment of newly developed ocean profiling tags that used marine mammals as observation platforms (the SEaOS project). I expressed the hope that this approach would provide a rich new source of oceanographic data, creating a "win/win" opportunity with tags not only providing new insights into the behaviour of the equipped animals but also dramatically increasing ocean data availability in general. Now, almost a decade later, this hope has been realized.

Instruments attached to animals have now delivered more than 270,000 CTD profiles, many from under-sampled parts of the polar regions where little or no oceanographic sampling had previously occurred. The data have been incorporated into global and regional models and have resulted in a range of publications on physical ocean processes as well as on the biology of the species that carried the tags. The magnitude of the contribution can be appreciated by querying the World Ocean Data Base (WOD). Animals have now provided approximately 70% of all oceanographic profiles south of 60°S and are beginning to have a similar impact in the Arctic. The geographical coverage of the animal data fills in large tracts of previously under represented sectors of the polar oceans. Animals also have provided data during the polar winter when no other sources were available. As a comparison, the almost 900,000 CTD profiles provided by the Argo Program are considered to have revolutionized our understanding of the physical function of the oceans. The contribution of animal-borne CTDs to the WOD is increasing rapidly and is likely also to have a major impact, especially in higher latitudes. Incorporating these data into models and analyses in the future will dramatically improve our understanding of global physical oceanography as well as our understanding of polar ecosystems.

1. Introduction

The polar seas form important links between all oceans and carry climate signals from one ocean basin to another. They form critical connections between the atmosphere and deep sea and thereby influence the capacity of oceans to store heat. They are sources of deep water formation and are important drivers of global circulation, which is a major determinant of planetary heat flow. This heat flow can in turn have a significant effect on global sea level. For example, the upwelling of warm deep water onto the Antarctic shelf has the potential to cause sea-level rise by speeding the melting and breakup of the ice shelves of western Antarctica, which in turn can accelerate the movement of terrestrial ice sheets (Thomas et al., 2004). The polar seas also support vital and unique ecosystems that contain important living resources that are increasingly open to exploitation. Detailed oceanographic information is necessary to develop an understanding of the links between ocean variability and ecosystem productivity and also to develop knowledge-based and effective resource management approaches.

Despite their critical role in our climate system and the general recognition of their extreme importance in global ecosystems, the physical environment and ecosystems of the polar regions are still under-sampled and hence, relatively poorly understood. At the 1st Symposium on Biologging Science in Tokyo 2003 (Fedak, 2004), I reported on the first use of an animal platform to collect ocean CTD profiles (Lydersen et al., 2002) and described the initiation of the first large-scale deployment of these novel ocean profiling tags on marine mammals (The SEaOS project, http://biology.st-and.ac.uk/seaos/index.html). This international project involved the deployment of more than 80 ocean-profiling instruments on Southern elephant seals from 4 major breeding colonies

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http://dx.doi.org/10.1016/j.dsr2.2012.07.007

on sub-Antarctic Islands in the Southern Ocean by French, Australian, US and UK teams (Biuw et al., 2007; Charrassin et al., 2008). SEaOS led to the development of a larger international project. This project, called MEOP (Marine Mammals Exploring the Oceans Pole to Pole http://www.meop.info/), was formed in 2006 as part of the International Polar Year and deployed instruments on pinnipeds in both the Arctic and Antarctic Seas.

At that meeting in Tokyo, I predicted that this approach would provide a rich new source of oceanographic data from poorly known areas of high-latitude oceans and in difficult to reach places under the pack ice and near-shore. I suggested that enlisting animals as observation platforms presented a "win/win" opportunity in that, not only would it provide essential new insights into the behaviour of the animals in relation to ocean features, but that it also would dramatically increase ocean data availability, effectively complementing the wealth of data from Argo floats and other more conventional sources (Fedak, 2004). This hope has been realized beyond my most optimistic expectations. Here, I report on the ocean data contributions made by animals carrying oceanographic profilers since I made that prediction and discuss the impact that the animal platform approach has had on polar ocean observation. This paper is not intended as a comprehensive review of published literature but rather as an overview of the rapid development over the intervening decade. My intention here is to convey, via a few examples, the scope of the contribution of the animal platform approach to available ocean data. The oceanographic papers cited are only a subset of the papers published using these tags and were chosen to illustrate the diversity of ways this approach is being used and point to its future potential.

2. Summary of methodology

Purpose-built satellite relay data loggers (CTD-SRDLs) were developed by the Sea Mammal Research Unit Instrumentation Group (SMRU-IG, Scotland) using a sensor package designed and manufactured by Valeport Ltd (UK). These instruments incorporate purpose-built conductivity/temperature/depth sensors and are small and robust enough to be attached to the fur of seals using rapidly setting glues (Fedak et al., 1983; Field et al., 2011). They collect CTD profiles that approach the accuracy of Argo profiling floats (http://www.argo.ucsd.edu/). The CTD-SRDLs use the Argos satellite (http://www.argos-system.org/) location and data transmission system (CLS-Argos) to relay several profiles each day. The profiles are collected during the animals' ascent to the surface from their deepest dives. When the animals reach the surface, the instruments transmit the highly compressed data under flexible programmatic control. These transmissions may be received by passing Argos satellites. The data are relayed to ground stations and forwarded to processing centres where the location from which the messages were sent is estimated using the Doppler shift information gathered from the received frequency of the transmission.

Bandwidth constraints imposed by both the animal's diving habits and CLS Argos requirements effectively limit the amount of data that can be sent. The instruments are controlled by software that allows flexible data reduction/compression approaches depending on the situation in which they are being used and the study objectives. This allows the devices to send the salient data features despite the bandwidth limitations. Profiles for the relevant deployments were reduced to sets of 17 depths with their associated temperatures (T) and salinities (S). These were chosen using a combination of 10 fixed depths (chosen depending on the maximum depth) and a set of 7 depths determined by a "broken stick method" as used with XBTDs (Rual, 1989). More detailed descriptions of the design of the instruments and the way they collect data are presented in Fedak et al. (2001, 2002) and Boehme et al. (2009).

In order to meet the demands of the physical oceanography community on data quality and specification, substantial effort has gone into characterising the precision, accuracy and stability of the CTD-SRDLs (Boehme et al., 2009; Roquet et al., 2011). These authors have shown that precision (repeatability) of measurements is better than 0.01 °C in temperature and 0.01 psu in salinity. Both papers suggest a general calibration procedure that can be applied on CTD-SRDLs that ideally involves performing a ship-based CTD comparison before the deployment on seals to correct for any depth-dependent T and S biases. This and other delayed mode quality controls can further correct for a salinity offset caused by distortions of the external field of the conductivity sensor by the proximity to the head of the seals. There are further details about the use of the tags on the following websites, including photos of how the tags are attached and links to an animation describing their operation (http://www.smru.st-and.ac.uk/protected/downloads.html; http://biology.st-and.ac.uk/seaos/; http://www.st-andrews.ac.uk/~savex/).

The data received by the Argos system are downloaded on a daily basis to servers at SMRU-IG where they are archived, decoded and stored in an Oracle database maintained (and backed-up) at SMRU. These data contain location and dive behaviour information as well as the CTD profiles and some diagnostics on instrument performance. Data are automatically processed into deployment specific Access files and made available to users via a dedicated web page (http://www.smru.st-and.ac.uk/protected/technical.html). In addition, once each day, the CTD profile data (with only limited quality control) are also transferred to the British Oceanographic Data Centre (BODC) from where it is picked up by the UK Met Office and transmitted via the World Meteorological Organization's Global Telecommunication System (GTS) to operational centres where it can be incorporated into a variety of ocean and weather models.

Further processing of the data, including more rigorous quality control and post-processing, is subsequently carried out by the individuals involved in the projects that deployed the tags or others granted access to the original data. In general, after post-processing and the initial use, the data are later made freely available via the World Ocean Data base (WOD; http://www.nodc.noaa.gov/OC5/WOD/pr_wod.html). The general ethos is that all of the data collected by the animals are made available each day via the GTS for operational use and are later made freely available to the broader ocean community as soon as it is feasible after further processing. A major effort to post-process all available CTD profiles from animal platforms using the best possible procedures is currently underway (Roquet et al., pers. comm.) More than 150,000 profiles have been post-processed so far, and should soon become available on the WOD website.

While the SMRU CTD-SRDLs are the only devices used on animals to provide profiles that include salinity, other tags used on a range of large marine animals have provided temperature/depth (T/D) information (also known as bathythermograph data). See Boehlert et al. (2001) and the TOPP website http://www.topp.org/. Simmons et al. (2009) and McMahon et al. (2005) provide information on the unique characteristics of these data and its quality. Much of the data from these tags have also been made available on the WOD (Boehlert et al., 2001; Robinson et al., 2012).

The data provided by animal-borne instruments is unlikely to equal the accuracy of traditional ship-based systems in the near future. Nor are such devices likely to deliver the detailed, data-rich profiles provided by Argo Floats because of energy and bandwidth constraints. But animal platforms can send several profiles each day, and because the travel rate of seals is typically no faster than 5 km/h, the spatial resolution of the data are often greater than any other ocean observing system. Furthermore, because seals often travel to areas that are difficult to reach logistically, and spend extended periods of time foraging within such areas, the animal-borne CTD-SRDLs can deliver data in near real time from these under-sampled regions. They can therefore play an essential and very much complementary role in strategic, cost-effective ocean observation systems, especially when used in combination with other approaches such as profiling floats, gliders, moored buoys etc.

3. Results

There are now over 1.4 million T/D or CTD profiles in the WOD from animal platforms (Fig. 1). These are all listed, somewhat confusingly, under the category "Autonomous Pinniped Bathythermographs (APB)" when in fact they are data of a mix of types from different instruments and several species. The majority are from instruments that provide only temperature and depth information and that were primarily designed to monitor animal behaviour (see Section 4 below). Despite making up only about 10% of these data, the profiles provided by animals equipped with CTD-SRDLs have had the greatest impact so far in the oceanographic literature, because they provide both salinity and temperature. It is these data that are the primary focus of this paper.

The CTD-SRDL data in the WOD make up only about half of the more than 270,000 CTD profiles obtained by this approach since 2004 (Fig. 2A), All, however, were made available on a daily basis as they were collected via the GTS. It is hoped that the remainder will be entered as post processing is completed. But even if we consider only the nearly 150,000 of these profiles already available from WOD as of June, 2012, the magnitude of the contribution of animal platform data is apparent, particularly in the Southern Ocean. Fig. 3 shows the location of CTD profiles available from all sources, colour coded by the type of platform that provided them. The red points that dominate the image are from Argo floats while the animal platform CTDs are shown in yellow. The magnitude of the data contribution of the Argo Program is apparent but the animal-borne profiles effectively complement the data collected by Argo and other sources, in that they are particularly dominant on the continental shelves, near coasts, and in the far south of the Southern Ocean where other data are scarce.

This geographic complementarity is easily appreciated by examining the proportion of profiles delivered by animals in relation to data from all other sources by latitude (Fig. 4). In quantitative terms, animal platforms have provided about 70% of all oceanographic profiles available for the Southern Ocean south of 60 degrees. This proportion is likely to be an underestimate of the magnitude of their impact because many more profiles have been collected by animals in the region since then, but have not yet been entered in the WOD. While not evident in broad temporal overviews such as that in Fig. 3, it is also noteworthy that much of the data obtained using animal-borne platforms is collected during the winter months, when large areas of the Southern Ocean are covered in ice. Logistic difficulties make other methods (Argo floats, ships and gliders) difficult and more expensive during this time and this further enhances the value of the data collected by animals.

The method has not yet had so large an impact in the Arctic, but it certainly has the potential to produce one just as significant. The large, EU Damocles Project (http://www.damocles-eu.org/) demonstrated how a large international effort can overcome the logistic constraints of providing data from the Arctic Ocean. The deployments during the MEOP Project in the N. Atlantic on hooded seals have recently clearly demonstrated the potential contribution animal platforms could make in the Arctic as well (see Figs. 1 and 2B).

The use of animal platforms also presents opportunities for monitoring ocean conditions with finer temporal and spatial resolutions. An example of the increased resolution, particularly in austral winter months (May–Aug) of combining animal platform data with other sources is shown in Fig. 5 (Boehme et al.,

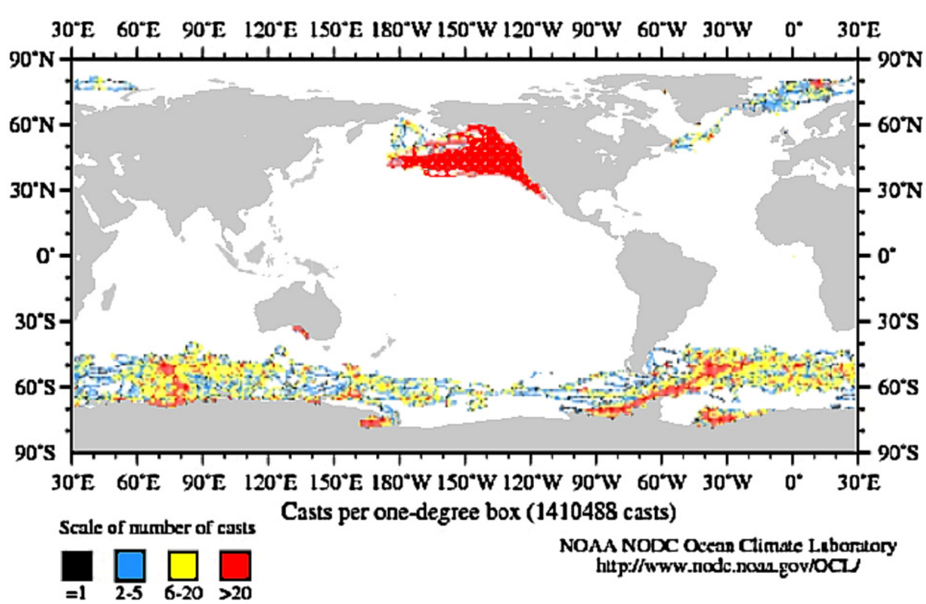

Fig. 1. The distribution of animal platform data taken from the web pages of the World Ocean Database. This map and animal platform data can be accessed from the WOD "Data sets & products" page http://www.nodc.noaa.gov/OC5/WOD/pr_wod.html and choosing "WODselect". After checking the "geographic coordinates" and "data set" tick-boxes, select "build a query". Then, after deselecting the "OSD" tick-box and ticking "Autonomous Pinniped Bathythermographs (APB)" choose "get an inventory". You will then get the option to either view the map as shown above or download the data. Note that data from other sources, such as Argo Floats, can also be seen and compared by selecting other sensor types in the list. It is also possible to select only data from tags that include both temperature and salinity by initially ticking the measured variables box and, after building a query, ticking all four temperature and salinity boxes.

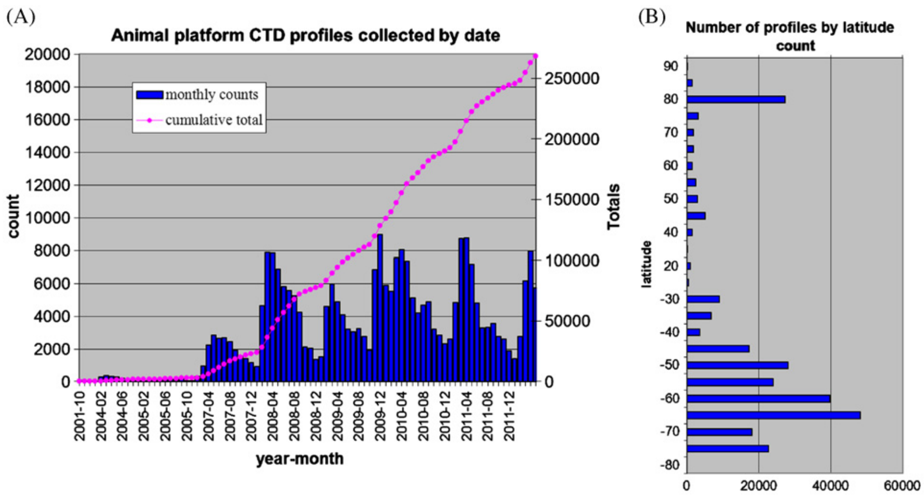

Fig. 2. The cumulative total (line) and monthly counts (bars) of ocean profiles obtained from animal platforms in the last decade (panel A) and the distribution of profiles by latitude (panel B). This contribution results from opportunistic deployments from programs funded by 10 different national funding bodies from 2001 through June, 2012. A running total of profiles distributed via the GTS can be obtained from http://www.smru.st-and.ac.uk/protected/meop/meop_gts_output.txt.

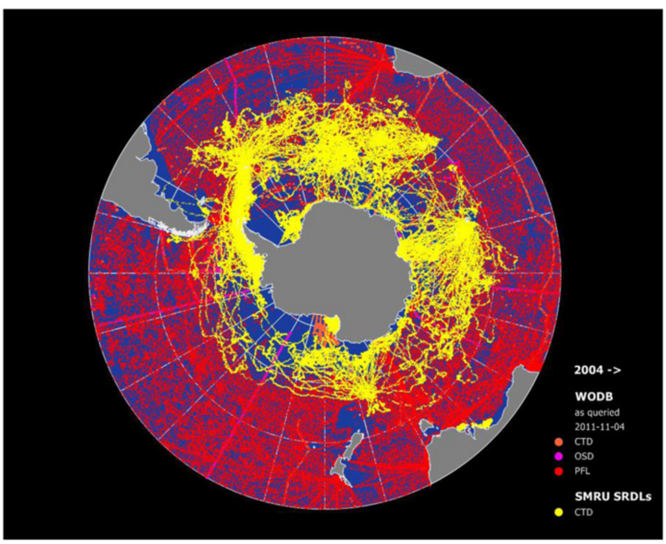

Fig. 3. Map showing the locations of Southern Ocean CTD profiles provided by seals. Each yellow dot indicates a single profile. Dots in other colours show the profiles from other sources in the WOD from other sources. PFL—Argo profiling floats, CTD—ship-based casts and OSD—ocean station data from discrete samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2008a). It is clear that both increased seasonal coverage and improved spatial resolution can be realized by strategically using complementary approaches.

4. Discussion

The need for ocean data has never been greater than it is at present, nor has the need been felt by a broader community. Data provided by animal platforms have already resulted in a range of publications on physical ocean processes as well as on the biology of the animals that carried the tags, and they have also been incorporated into global and regional databases and circulation models. Sampling devices placed on diving animals that frequently return to the surface, allowing the devices to relay data via satellite, can provide data from even remote regions quickly enough for operational use as well as be archived for additional post processing for general ocean modelling at both large and small scales. Therefore, the use of these data extends far beyond that of academic, geophysical study and ranges from weather and climate forecasting to management of civilian and military marine operations. Below I give examples of how the data from animal platforms have been used to both improve geographical coverage and/or spatial and temporal resolution, especially when used to compliment data from other sources.

In their paper with the ECCO-GODAE Consortium Members, Wunsch et al. (2009) discuss the importance of combining state of the art, global ocean circulation models with "complete" ocean data sets. They pointed out that questions about how the ocean will behave under a changing climate require continued observations along with interpretation using the best available theoretical tools. They singled out the importance of seal platform data in the Southern Ocean stating that, "because they are almost our only data sets from under the Antarctic sea ice…." and go on to say, "…they [the seals] perhaps represent the future, in which ever more species are used to obtain a truly global observation system".

Another global analysis incorporating data collected from southern elephant seals (*Mirounga leonina*) mapped frontal structure and sea ice formation rates around the entire Southern Ocean (Charrassin et al., 2008). The authors reported that the seal data provided a 30-fold increase in hydrographic profiles from the sea-ice zone, allowing the major fronts to be mapped south of 60°S and sea-ice formation rates to be inferred from changes in upper ocean salinity.

The relatively high resolution data provided by the animals, when combined with other data sources such as Argo floats, has allowed ocean frontal processes to be examined and understood at finer spatial scales. Boehme et al. (2008b) combined Argo data with that collected from southern elephant seals to provide a five-fold increase in the number of monthly profiles around South Georgia. This allowed the authors to increase the spatial resolution of their dataset by a factor of three and enabled them to investigate the monthly variability of all three major fronts within the Antarctic Circumpolar Current in the Atlantic part of the Southern Ocean. In another recent paper, Roquet et al. (2009) confirmed for the first time the existence of a strong permanent ACC front crossing the Kerguelen Plateau using fine-scale hydrographic measurements obtained by 8 different elephant seals equipped in 2004 at the Kerguelen Islands. Recently, Nøst et al. (2011) used more than 2000 CTD profiles collected by southern

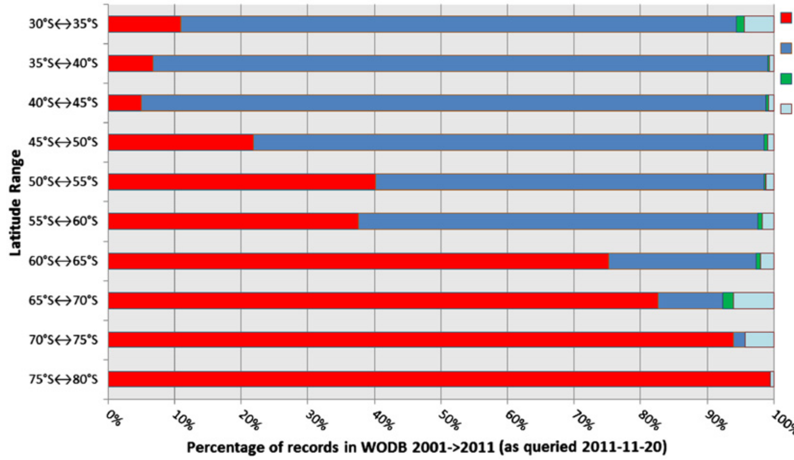

Fig. 4. The percentage of CTD profiles in the World Ocean Data base south of 30 degrees contributed by animal-borne CTD platforms (APB) profiling floats (PFL), moored buoys (OSD) and ships casts (CTD). Note the increasing importance of animal platforms in high latitude. A similar pattern is developing in high northern latitudes.

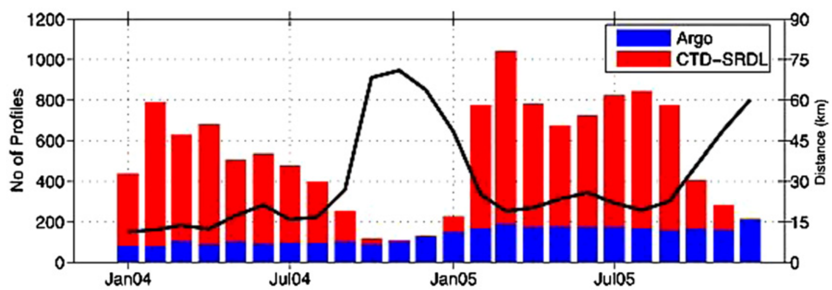

Fig. 5. Monthly number of South Atlantic hydrographic profiles (bars) and mean distance between neighbouring profiles (line) from the combined Argo/SRDL data set (Boehme et al., 2008b). Decreased oceanographic resolution (increased average distance between profiles) in the Austral Spring and Summer is due to seal haulout behaviour during this time when elephant seals spend much of their time on land to breed and moult.

elephant seals, many obtained during the polar winter in the eastern Weddell Sea, together with profiles obtained by drilling through the 395 m of ice on the Fimbul Ice Shelf to show how the cross-shelf exchange can be mediated by modified waters in the Antarctic Slope Front, and suggested that this process may be sufficient to cause basal melting of Antarctic ice shelves.

Data from another Antarctic species, the Weddell seal (*Leptonychotes weddelli*) (Nicholls et al., 2008), has been used to obtain data from the southern Weddell Sea continental shelf. These data allowed the authors to describe the full depth flow of water onto the shelf via a sill at the shelf break (74°S 44°W) and show that the warmth from the core of the flow was able to maintain the surface mixed layer above the freezing point, which resulted in a band of reduced ice-production. They noted the difficulty in getting winter data in any other way. A southern elephant seal has even been used as a " biological mooring" (Meredith et al., 2011). A particular seal had a preferred location close to the shelf break to the northeast of the South Orkney Islands where it spent 8 months diving to near the sea bed. The Eulerian nature of the data permitted the creation of a time series of potential temperature, salinity and potential density for the upper ocean near the Islands from March to November, 2007, which was used by the authors in combination with data from Argo and other sources to estimate local sea ice production and the impact of advection upon it.

Animal platform data have also been used to analyse transient local events. Padman et al. (2012) used opportunistically available data collected by instruments on several species of Antarctic seals to examine how the hydrography around the Wilkins Ice Shelf contributed to its break-up in 2008–2009. In another study, the diving behaviour of the seals was even used to make inferences about the bathymetry of under-sampled areas on the continental shelf of the Western Antarctic Peninsula (Padman et al., 2010). They produced a map of "seal-derived bathymetry" including "soundings" as deep as 2000 m.

The value of a strategic approach to ocean observation, and the benefits of the use of animal platforms in the Southern Ocean, have been clearly expressed in the SOOS (Southern Ocean Observing System) document published by the Scientific Committee on Antarctic Research (Rintoul et al., 2012). A clear example of how the animal platform data can provide a strategically important addition to studies of Southern Ocean dynamics and their effect on ice shelves is provided by Hattermann et al. (2012). They used a combination of 3 moorings with ice-base and sea bed current metres, ship based CTD casts and over a thousand CTD casts from elephant seals over two years to examine the mechanisms that deliver heat to the Fimbul Ice shelf. Their data indicated relatively low temperatures under the shelf and suggested less basal melting than predicted by current ocean models.

Strategically combining observational approaches can be equally useful in the Arctic. In a very effective use of animal-borne platforms, Straneo et al. (2010) used temperature records from CTD-SRDLs mounted on hooded seals in combination with ship and mooring data to examine melting at the ice–ocean interface around the Sermilik Fjord in East Greenland. The seal data were important to their analysis because they confirmed the year-round presence of subtropical water (STW) on the shelf and showed that the along-shore winds and deep channels stretching across the shelf are instrumental in driving STW into the Fjord where it can interact with the ice sheet. In another Arctic study, Grist et al. (2011) noted that, "Between 2004 and 2008, marine mammal mounted sensors increased the number of profiles [of high latitude Atlantic boundary currents] in the region fivefold, providing much improved coverage in the formerly data-sparse shelf regions.''

While the data collected by animals have found a wide variety of uses for oceanographic studies, it is also important to remember that the in-situ oceanographic information that the tags collect has improved our understanding of the habitat requirements of the animals themselves. With the instruments simultaneously collecting both ocean profiles and diving behaviour on board the animals, authors have been able to link foraging behaviour and changes in the animal's body condition directly to oceanographic conditions (Bailleul et al., 2007, 2010; Biuw et al., 2007, 2010; Dragon et al., 2010; Simmons et al., 2007). This linkage is critical to understanding the biology of the animals and shows clearly how including animals in the armoury of ocean observation techniques creates a win/win situation for biologists, oceanographers and even the animals themselves, in that the approach generates a better understanding of their habitat requirements and should facilitate more effective conservation.

While this paper has concentrated on the use of animals to gather conventional CTD profiles and focuses on the impact of these data on ocean observation in polar seas, it is important to emphasise that a variety of other sorts of tags have been attached to animals that also collect in-situ temperature data. In particular, the TOPP project has deployed more than 4000 tags of a variety of types on 23 species of fish, birds, turtles and marine mammals, some of which delivered in-situ temperature data (Block et al., 2011). Some of these instruments were the CTD-SRDLs discussed here but many were of other sorts that, in addition to location and behavioural data, collected temperature/depth readings. Some were archival tags, which record data that is only made available some time after recovery of the instruments. Others relayed data if and when animals surfaced or once the tag was released to float to the surface, when information previously collected over extended periods of time was transmitted. The tags often obtained locations using sophisticated geolocation algorithms using threshold light levels recorded by the tags to infer sunrise, sunset and local noon. These were used in combination with sea surface temperature to estimate location (Hill, 1994). Locations obtained in this way are less accurate than those obtained by ARGOS or GPS but due to the large number of positions obtained and the use of state-space models and effective filters, the quality of locations was improved and its uncertainty estimated. The temperature sensors in tags from some manufactures are of a similar quality as those of XBTs. See ''supplementary information'' in the Nature web site for the Block et al. (2011) paper for details. Efforts are underway to make these data available via the WOD through cooperation with the NOAA US Integrated Ocean Observing System (IOOS) through its Animal Telemetry Network or ATN (http://www.ioos.gov/observing/animal_telemetry/welcome.html).

The variety of instruments attached to animals, when considered along with their differing sensor characteristics, the accuracy of their associated locations and the mode of delivery of their data, present challenges for the assimilation of such data into standard ocean data bases and models. However, while these data sets can be complex, variable in quality and may not always be suitable for climatology and modelling purposes, their geographic and temporal scope and their very fine spatial and temporal resolution make them uniquely valuable for understanding the distribution of the animals that carry them and also for specific oceanographic purposes e.g., determining water column structure, mixed layer depth, identification of water mass boundaries etc. (Bograd et al., 2010; McMahon et al., 2005). These data clearly have value that will increasingly be realized as the data assimilation challenges are met (see Moustahfid et al., 2011).

5. Concluding remarks

The examples presented here support the idea that animals can provide a significant and useful source of oceanographic data in a very cost effective way. Since the start of the Argo Float project in 1999, autonomous profiling floats have revolutionized ocean monitoring and have delivered nearly 1,000,000 salinity/temperature/depth CTD profiles. However, even with the wealth of Argo float data now available, important ocean areas remain un- or under-sampled. Data from these areas are increasingly being seen as critical in climate and weather forecasting and are necessary to facilitate safe and responsible management and exploitation of polar regions, especially as new marine biological and energy resources are being sought. New and effective observing strategies and data sources are increasingly needed to fill the need for increased coverage. It is now clear that animal platforms can play an essential role in such strategic, ocean observation systems. Incorporating data from them into models and using them in analyses in the future can dramatically improve our understanding of global physical ocean processes and dynamics as well as our understanding of polar ecosystems.

It seems likely therefore that the rate of dataflow from animal platforms will increase rapidly over the coming years. There are a number of national and international polar ocean and ice programs underway or under development using animal platforms. The approach is becoming increasingly used in the Artic and its importance in the Southern Ocean is also likely to rise as a result of other international projects such as Australian Animal Tagging and Monitoring System (AATAMS), part of the larger Australian Integrated Marine Observing System (IMOS, http://www.ioos.gov/observing/animal_telemetry/welcome.html). Additional programs are planned in the Arctic and Antarctic to study areas of deep water formation near shore. Others studies are planned to examine heat flow from water masses near or under ice shelves that constrain important land-based glacier systems that have the potential to significantly affect sea level. Furthermore, additional sensors that can be attached to CTD-SRDLs are presently in use and others are being developed, which may expand their utility. Deployed tags are currently providing fluorimeter data (Charrassin et al., 2010) and oxygen profiles. All this points to greater data flow in the future.

If we are to extract the maximum benefit of the approach, there is a clear necessity to make high quality, error checked data easily and freely available. The operational oceanography community needs the data in near real time; the broader ocean community needs data in post-processed, higher quality form over the longer term. There is also a need to ensure that the data remain available indefinitely with effective archiving. Following the lead of the Argo Program, efforts are being made to set up a streamlined system of real-time data quality control, delivery and management linking the data decoding process carried out at the SMRU Instrumentation Group and its distribution and archiving by the British Ocean Data Centre. But while there is a detailed plan for this delivery system, the resources needed to set it up and get it working are not yet fully in place.

Acknowledgments

The deployment of ocean profilers on marine mammals was supported by Grants in 10 countries. See http://biology.st-andrews.ac.uk/seaos/ and http://www.meop.info/en/partners/ for a list of participating organizations. The author was supported by the Natural Environment research Council Grants NE/G014833/1, NE/E018289/1 and NER/DS/2002/00426. The partnership between animals and oceanographers would not have been possible without the skill and imagination of the SMRU Instrumentation Group and the support of National Oceanographic Partnership Program of the US Office of Naval Research and the Sloan Foundation. I would like to thank the entire SEaOS and MEOP teams for making the collection of this unique set of data happen.

References

Bailleul, F., Charrassin, J.B., Monestiez, P., Roquet, F., Biuw, M., Guinet, C., 2007. Successful foraging zones of southern elephant seals from the Kerguelen Islands in relation to oceanographic conditions. Philos. Trans. R. Soc. B—Biol. Sci. 362, 2169–2181.

Bailleul, F., Cotte, C., Guinet, C., 2010. Mesoscale eddies as foraging area of a deep-diving predator, the southern elephant seal. Mar. Ecol. Prog. Ser. 408, 251–264.

Biuw, M., Boehme, L., Guinet, C., Hindell, M., Costa, D., Charrassin, J.B., Roquet, F., Bailleul, F., Meredith, M., Thorpe, S., Tremblay, Y., McDonald, B., Park, Y.H., Rintoul, S.R., Bindoff, N., Goebel, M., Crocker, D., Lovell, P., Nicholson, J., Monks, F., Fedak, M.A., 2007. Variations in behavior and condition of a Southern Ocean top predator in relation to in situ oceanographic conditions. Proc. Natl. Acad. Sci. USA 104, 13705–13710.

Biuw, M., Nøst, O.A., Stien, A., Zhou, Q., Lydersen, C., et al., 2010. Effects of hydrographic variability on the spatial, seasonal and diel diving patterns of southern elephant seals in the Eastern Weddell Sea. Plos One 5 (11), e13816. http://dx.doi.org/10.1371/journal.pone.0013816.

Block, B.A., Jonsen, I.D., Jorgensen, S.J., Winship, A.J., Shaffer, S.A., Bograd, S.J., Hazen, E.L., Foley, D.G., Breed, G.A., Harrison, A.L., Ganong, J.E., Swithenbank, A., Castleton, M., Dewar, H., Mate, B.R., Shillinger, G.L., Schaefer, K.M., Benson, S.R., Weise, M.J., Henry, R.W., Costa, D.P., 2011. Tracking apex marine predator movements in a dynamic ocean. Nature 475, 86–90.

Boehlert, G.W., Costa, D.P., Crocker, D.E., Green, P., O'Brien, T., Levitus, S., Le Boeuf, B.J., 2001. Autonomous pinniped environmental samplers: using instrumented animals as oceanographic data collectors. J. Atmos. Oceanic Technol. 18, 1882–1893.

Boehme, L., Lovell, P., Biuw, M., Roquet, F., Nicholson, J., Thorpe, S.E., Meredith, M.P., Fedak, M., 2009. Technical note: animal-borne CTD-satellite relay data loggers for real-time oceanographic data collection. Ocean Sci. 5, 685–695.

Boehme, L., Meredith, M.P., Thorpe, S.E., Biuw, M., Fedak, M., 2008a. Antarctic circumpolar current frontal system in the South Atlantic: monitoring using merged Argo and animal-borne sensor data. J. Geophys. Res.—Oceans 113 (C9), C09012. 19 pp.

Boehme, L., Thorpe, S.E., Biuw, M., Fedak, M., Meredith, M.P., 2008b. Monitoring Drake Passage with elephant seals: frontal structures and snapshots of transport. Limnol. Oceanogr. 53, 2350–2360.

Bograd, S.J., Block, B.A., Costa, D.P., Godley, B.J., 2010. Biologging technologies: new tools for conservation. Introduction. Endangered Species Res. 10, 1–7.

Charrassin, J.-B., Roquet, F., et al., 2010. New insights into Southern Ocean physical and biological processes revealed by instrumented elephant seals. In: Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society.

Charrassin, J.B., Hindell, M., Rintoul, S.R., Roquet, F., Sokolov, S., Biuw, M., Costa, D., Boehme, L., Lovell, P., Coleman, R., Timmermann, R., Meijers, A., Meredith, M., Park, Y.H., Bailleul, F., Goebel, M., Tremblay, Y., Bost, C.A., McMahon, C.R., Field, I.C., Fedak, M.A., Guinet, C., 2008. Southern Ocean frontal structure and sea-ice formation rates revealed by elephant seals. Proc. Natl. Acad. Sci. USA 105, 11634–11639.

Dragon, A.-C., Monestiez, P., Bar-Hen, A., Guinet, C., 2010. Linking foraging behaviour to physical oceanographic structures: southern elephant seals and mesoscale eddies east of Kerguelen Islands. Prog. Oceanogr. 87, 61–71.

Fedak, M., Lovell, P., McConnell, B., Hunter, C., 2002. Overcoming the constraints of long range radio telemetry from animals: getting more useful data from smaller packages. Integrative Comp. Biol. 42, 3–10.

Fedak, M.A., 2004. Marine animals as platforms for oceanographic sampling: a "win/win"situation for biology and operational oceanography. Mem. Natl. Inst. Polar Res. 58, 133–147.

Fedak, M.A., Anderson, S.S., Curry, M.G., 1983. Attachment of a radio tag to the fur of seals. J. Zool. 200, 298–300.

Fedak, M.A., Lovell, P., Grant, S.M., 2001. Two approaches to compressing and interpreting time-depth information as collected by time-depth recorders and satellite-linked data recorders. Mar. Mamm. Sci. 17, 94–110.

Field, I.C., Harcourt, R.G., Boehme, L., Bruyn, P.J.N.d., Charrassin, J.-B., McMahon, C.R., Bester, M.N., Fedak, M.A., Hindell, M.A., 2011. Refining instrument attachment on phocid seals. Mar. Mamm. Sci 28(3), E325–E332 [http://dx.doi.org/10.1111/j.1748-7692.2011.00519.].

Grist, J.P., Josey, S.A., Boehme, L., Meredith, M.P., Davidson, F.J.M., Stenson, G.B., Hammill, M.O., 2011. Temperature signature of high latitude Atlantic boundary currents revealed by marine mammal-borne sensor and Argo data. Geophys. Res. Lett. 38 (L15601), 6 pp., http://dx.doi.org/10.1029/2011GL048204.

Hattermann, T., Nøst, O.A., Lilly, J.M., Smedsrud, L.H. Two years of oceanic 29 observations below the Fimbul Ice Shelf, Antarctica. Geophys. Res. Lett. 39, in press http://dx.doi.org/10.1029/2012GL051012.

Hill, R.D., 1994. Theory of geolocation by light levels. In: Le Boeuf, B.J, Laws, R.M. (Eds.), Elephant Seals: Population Ecology, Behavior and Physiology. University of California Press, Berkeley, pp. 227–236.

Lydersen, C., Nost, O.A., Lovell, P., McConnell, B.J., Gammelsrod, T., Hunter, C., Fedak, M.A., Kovacs, K.M., 2002. Salinity and temperature structure of a freezing Arctic fjord—monitored by white whales (*Delphinapterus leucas*). Geophys. Res. Lett. 29 (2119) 4 pp., 10.1029/2002GL015462.

McMahon, C.R., Autret, E., Houghton, J.D.R., Lovell, P., Myers, A.E., Hays, G.C., 2005. Animal-borne sensors successfully capture the real-time thermal properties of ocean basins. Limnol. Oceanogr.—Methods 3, 392–398.

Meredith, M.P., Nicholls, K.W., Renfrew, I.A., Boehme, L., Biuw, M., Fedak, M., 2011. Seasonal evolution of the upper-ocean adjacent to the South Orkney Islands, Southern Ocean: results from a "lazy biological mooring". Deep-Sea Res. 58, 1569–1579.

Moustahfid, H.C., Grimes, J., et al., 2011. Toward a National Animal Telemetry Observing Network (ATN) for our Oceans, Coasts and Great Lakes: Workshop Synthesis Report. US IOOS Workshop, March 2011. U.S Department of Commerce, N.T.M.N., Santa Cruz, California, pp. 51.

Nicholls, K.W., Boehme, L., Biuw, M., Fedak, M.A., 2008. Wintertime ocean conditions over the southern Weddell Sea continental shelf, Antarctica. Geophys. Res. Lett. 35 (L21605), 5 pp., http://dx.doi.org/10.1029/2008GL035742.

Nøst, O.A., Biuw, M., Tverberg, V., Lydersen, C., Hattermann, T., Zhou, Q., Smedsrud, L.H., Kovacs, K.M., 2011. Eddy overturning of the Antarctic Slope Front controls glacial melting in the Eastern Weddell Sea. J. Geophys. Res. 116, C11014.

Padman, L., Costa, D.P., Bolmer, S.T., Goebel, M.E., Huckstadt, L.A., Jenkins, A., McDonald, B.I., Shoosmith, D.R., 2010. Seals map bathymetry of the Antarctic continental shelf. Geophys. Res. Lett. 37 (L21601), 5 pp., http://dx.doi.org/10.1029/2010GL044921.

Padman, L., Costa, D.P., Dinniman, M.S., Fricker, H.A., Goebel, M.E., Huckstadt, L.A., Humbert, A., Joughin, I., Lenaerts, J.T.M., Ligtenberg, S.R.M., Scambos, T., van den Broeke, M.R., 2012. Oceanic controls on the mass balance of Wilkins Ice Shelf, Antarctica. J. Geophys. Res.—Oceans 117.

Rintoul, S.R., Sparrow, M., Meredith, M.P., Wadley, V., Speer, K., Hofmann, E., Summerhayes, C., Urban, E., Bellerby, R. (Eds.), 2012. SCAR, Cambridge. (pp. 74).

Robinson, P.W., Costa, D.P., Crocker, D.E., Gallo-Reynoso, J.P., Champagne, C.D., Fowler, M.A., Goetsch, C., Goetz, K.T., Hassrick, J.L., Hückstädt, L.A., Kuhn, C.E., Maresh, J.L., Maxwell, S.M., McDonald, B.I., Peterson, S.H., Simmons, S.E., Teutschel, N.M., Villegas-Amtmann, S., Yoda, K., 2012. Foraging behavior and success of a mesopelagic predator in the Northeast Pacific Ocean: insights from a data-rich species, the northern elephant seal. Plos One 7, e36728.

Roquet, F., Charrassin, J.B., Marchand, S., Boehme, L., Fedak, M., Reverdin, G., Guinet, C., 2011. Delayed-mode calibration of hydrographic data obtained from animal-borne satellite relay data loggers. J. Atmos. Oceanic Technol. 28, 787–801.

Roquet, F., Park, Y.H., Guinet, C., Bailleul, F., Charrassin, J.B., 2009. Observations of the Fawn Trough Current over the Kerguelen Plateau from instrumented elephant seals. J. Mar. Syst. 78, 377–393.

Rual P. 1989. For a better XBT bathy4message: on4board quality control, plus a new data reduction method. In: Picaut, J., Lukas, R., Delcroiz, T. (Eds.), Proceedings of Western Pacific International Meeting and Workshop on Toga COARE. Nouméa, New Caledonia, May 24430, 1989.

Simmons, S.E., Crocker, D.E., Kudela, R.M., Costa, D.P., 2007. Linking foraging behaviour of the northern elephant seal with oceanography and bathymetry at mesoscales. Mar. Ecol. Prog. Ser. 346, 265–275.

Simmons, S.E., Tremblay, Y., Costa, D.P., 2009. Pinnipeds as ocean-temperature samplers: calibrations, validations, and data quality. Limnol. Oceanogr.—Methods 7, 648–656.

Straneo, F., Hamilton, G.S., Sutherland, D.A., Stearns, L.A., Davidson, F., Hammill, M.O., Stenson, G.B., Rosing-Asvid, A., 2010. Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland. Nat. Geosci. 3, 182–186.

Thomas, R., Rignot, E., Casassa, G., Kanagaratnam, P., Acuña, C., Akins, T., Brecher, H., Frederick, E., Gogineni, P., Krabill, W., Manizade, S., Ramamoorthy, H., Rivera, A., Russell, R., Sonntag, J., Swift, R., Yungel, J., Zwally, J., 2004. Accelerated sea-level rise from West Antarctica. Science 306, 255–258.

Wunsch, C., Heimbach, P., Ponte, R.M., Fukumori, I., Members, E.-G.C., 2009. The global general circulation of the ocean estimated by the ecco-consortium. Oceanography 22, 88–103.