Trends in tagging of marine mammals: a review of marine mammal biologging studies

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The number of scientific papers resulting from biologging instruments deployed on marine mammals is increasing as improved technologies result in smaller devices and improved sensor-, storage- and transmission capabilities. I undertook a comprehensive review of papers resulting from biologging deployments on free-ranging marine mammals between 1965 and 2013 (*n* = 620) to summarise where (e.g. on which species, as well as in which geographic areas) deployment efforts were focused, the impacts of the resulting papers, and where there are shortcomings in the literature. Species-, sex- and age-class biases were evident in terms of animals instrumented. Also, large proportions of the papers resulted from deployments on a small number of species (particularly among the pinnipeds) and were more often on adult females than other demographic classes. The mean impact of papers (as assessed using journal impact factors and numbers of citations) was consistent over time, and was influenced by the number of species studied, sample sizes and instrument capabilities. I found a paucity of papers addressing device influences on animals, as well as studies with explicit conservation and/or management implications. This review aims to increase awareness of marine mammal biologging data already collected, stimulate appropriate further studies, and encourage the reuse of existing data.

Keywords: animal-borne devices, cetaceans, pinnipeds, satellite tracking, time–depth recorders

Introduction

Biologging generally refers to the science associated with the use of animal-borne devices to gather information on the behaviour, movements and physiology of animals, and/or on the environments they use. Whereas the term itself was apparently coined around the International Symposium on Bio-Logging Science, held at the National Institute of Polar Research, Tokyo, in 2003 (Naito 2010), the science of biologging is somewhat older and is recognised to have started as early as the 1940s, when depth gauges were used on whales and seals (Scholander 1940). After Scholander, the earliest biologging devices used on marine animals are generally recognised to be the maximum-depth recorder (DeVries and Wohlschlag 1964) and time–depth recorders (Kooyman 1965), all of which were deployed on Weddell seals *Leptonychotes weddellii* (Evans et al. 2013).

Technological advances are increasingly allowing for the miniaturisation of devices, as well as the incorporation of more sophisticated sensors into animal-borne instruments. For example, the use of fast-loc GPS technology (e.g. Dragon et al. 2012a), accelerometers (Naito et al. 2010) and camera systems (e.g. Naito et al. 2013) is allowing more detailed and fine-scale assessments of marine animal movements and behaviour. Furthermore, the addition of various sensors to biologging instruments is contributing increasingly to our understanding of ocean physical properties (Fedak 2013) and how marine mammals adjust their behaviour in relation to them (e.g. McIntyre et al. 2011a; Jaud et al. 2012; Bestley et al. 2013). Although the technological advances are clear, it is of interest to know how these technologies are applied in scientific studies and what specific questions are being addressed.

Biologging devices are currently used in scientific studies of numerous taxa, including terrestrial mammals (e.g. Hetem et al. 2012; McFarland et al. 2013), reptiles (e.g. Dubois et al. 2009; Watanabe et al. 2013), birds (e.g. Dean et al. 2013; Phipps et al. 2013), fish (e.g. Bonfil et al. 2005; Yasuda et al. 2013) and even invertebrates (e.g. Stewart et al. 2012; Watts et al. 2012). Given the obvious difficulties in observing animals at sea directly, the use of biologging technologies is ideally suited for studies involving marine animals, particularly semi-aquatic species that haul out on land, thereby providing opportunities for the deployment of instruments. Marine biologists (and marine mammalogists in particular) are increasingly making use of biologging technology. This is exemplified by the study species reported in the titles and abstracts of presentations (*n* =

165) at the Fourth International Science Symposium on Bio-logging (held 14–18 March 2011 in Hobart, Australia), where 93% were marine species and 53% marine mammals (Program and Abstracts document; available at http://www.cmar.csiro.au/biologging4/documents/AbstractsandProgram_final.pdf).

Here, I review the scientific papers that have resulted from the deployment of animal-borne devices on free-ranging marine mammals between 1965 and 2013. I aim broadly to summarise where (e.g. which species and geographical area) the deployment efforts were focused, the impacts of these papers, and where there are gaps and shortcomings to be addressed in the future. I aim specifically to answer the following questions:

- What are the trends in publication numbers resulting from biologging deployments on marine mammals?
- Which groups and species have carried biologging devices most frequently, and for which species are there few or no publications from biologging deployments?
- In which geographic areas have biologging deployments on marine mammals been focused?
- What are the trends in numbers of devices deployed, types of devices deployed and types of data reported on from biologging deployments on marine mammals?
- What proportion of marine mammal biologging studies is of an applied nature with direct conservation and/or management implications?
- What are the research fields within which the resulting data have been used and where are the papers resulting from biologging deployments on marine mammals published?
- What are the trends in terms of the impact of these papers (as measured by journal impact factors and numbers of citations), and which factors (e.g. numbers of authors, numbers of devices deployed, instrument types, etc.) influence the overall impact of papers?

Material and methods

For this review I focused on scientific papers in peer-reviewed journals that used data obtained through the use of biologging techniques on free-ranging marine mammals. Analyses were restricted to papers published up to and including 2013, and excluded book chapters, conference abstracts and so-called ‘grey’ literature (e.g. government reports, etc.). I attempted to include as many papers as I could find in the review and hence selected literature search terms that ensured a broad scope. I used primarily the ISI Web of Science and Scopus databases to search for relevant papers using a variety of search terms that included (but were not restricted to): ‘biologging’, ‘time–depth recorder(s)’, ‘satellite tag(s)’, ‘Argos’, ‘GPS’, ‘geolocation’, ‘accelerometer(s)’, ‘telemetry’, ‘migration’, and ‘dive behaviour’. Relevant papers cited in papers identified were also searched for individually and included. I further undertook author searches in Scopus for authors known to have published relevant articles, and scanned through all their recorded papers for more papers to include. Whereas it is possible that some relevant literature remained undetected, it is probable that the number of omissions was small and that literature reviewed represented the bulk of the scientific papers published in the field of biologging deployments on marine mammals.

For each paper, I recorded the following parameters (when reported):

1. Year of publication.
2. Species, Family, Suborder and Order of marine mammals that carried instruments. Here, I followed the naming convention for species as published by the Society for Marine Mammalogy (Committee on Taxonomy 2013). I retained Pinnipedia in the analyses as a clade that included the families Odobenidae, Otariidae and Phocidae. Also, I retained Cetacea at the Order level, and recognised Mysticeti and Odentoceti at Suborder level.
3. The location where deployments were made. Where coordinates were not reported, but place names provided, I estimated coordinates of the tagging locations using Google Earth images (https://earth.google.com/; accessed during 2013).
4. The conservation status of all species that carried instruments (as defined by the IUCN Red List of Threatened Species™ website [http://iucnredlist.org, accessed 31 March 2013]). I did not consider the conservation status of local populations, but only the status at species- or subspecies level as indicated on the IUCN Red List of Threatened Species. A species was considered ‘threatened’ if classified as either ‘Critically Endangered’, ‘Endangered’ or ‘Vulnerable’. ‘Data Deficient’ or ‘Near Threatened’ species were not considered as threatened in this review.
5. The sex of instrumented animals.
6. The age class of instrumented animals. Here, the use of terms such as ‘juvenile’ and ‘subadult’ was not always consistent across papers. I therefore chose to distinguish only between ‘adult’ and ‘immature’ animals (where the immature grouping included animals referred to as juveniles, subadults and/or pups).
7. Instrument type deployed (see Table 1 for explanatory detail).
8. The number of animals that carried instruments.
9. The number of instrument deployments resulting in data reported in the paper. This number is referred to as the ‘number of successful devices’.
10. The type of outcome reported that resulted from biologging data (see Table 1 for further detail).
11. Whether or not the paper reported explicit resulting applications. Here, I considered as ‘applied’ those papers that clearly illustrated applications in terms of conservation or management (protected areas, fisheries, etc.). Papers that did not display obvious applications in terms of conservation or management, and papers that made only vague reference to applications (e.g. papers that stated only that the data generated had management/conservation implications but without making explicit recommendations in that regard), were classified as ‘non-applied’.
12. The journal where the paper was published.
13. The 5-year Impact Factor (ISI Web of Science) of the journal (or Impact Factor if no 5-year Impact Factor was available).
14. For studies published up to and including 2010, I further recorded the calculated impact of the paper as a function

of the journal impact factor and the number of citations relative to the year it was published (i.e. impact = journal impact factor + (number of citations ∕ years since publication). Because some papers displayed a lag period whereby citations did not increase linearly over time (unpublished data), I included the journal impact factor in this calculation to provide a more representative indication of impact of recently published papers. I obtained citation numbers obtained from both ISI and Scopus, when available. Only citations recorded up to and displayed during the first two weeks of 2013 (up to and including 14 January) were included. When the citation numbers differed between the two databases, I recorded the higher of the two.

For comparative purposes, I also calculated the impact of a sample of papers making use of biologging data from animals other than marine mammals (n = 40). I conducted searches on Scopus using the search phrases 'biologging', 'bio-logging', 'wildlife tracking' and 'telemetry'. The 'telemetry' search was restricted to the research fields of Agricultural and Biological Sciences and Environmental Sciences. From the results for each search phrase, I selected 10 papers published between 1960 and 2010. Selection was done in a systematic fashion; all papers were ordered and numbered by date, before the oldest and youngest papers were selected, followed by eight additional papers separated by equal time intervals.

I investigated the relationships between the calculated impact of papers and other recorded parameters in a number of ways. Impact showed a skewed distribution due to the presence of a number of papers with comparatively high impact (Impact <10: n = 387; Impact 10–19.9: n = 36; Impact 20–29.9: n = 4; Impact 30–39.9: n = 4; Impact 40–49.9: n = 2; Impact >70: n = 1). I therefore assessed relationships between parameters and the impact of papers at two different levels. Firstly, I investigated relationships between the impact of medium-impact papers (Impact <10) and parameters using standard parametric statistics (ANOVA, t-test and regression). Secondly, I assessed relationships between the frequency of high-impact papers (Impact ≥ 10) and parameters using Fisher's exact test, χ^2 tests, and *post hoc* Marascuilo procedures. Continuous variables were grouped into appropriate categories for assessing their relationships with the frequency of high-impact papers using k-means cluster analyses. All statistical procedures were undertaken in the R programming environment (R Version 2.15.2; R Core Team 2012) and statistical significance was set at $p < 0.05$. Mean and SD values are reported unless otherwise stated.

Results

Instrumented species

I recorded a total of 620 papers that used data obtained from biologging instruments deployed on marine mammals between 1965 and 2013 (see Supplementary Material [available online] for complete bibliography). Papers were published in a total of 113 different journals, although four journals accounted for 41% of all papers published – *Marine Ecology Progress Series* (75), *Marine Mammal Science* (68), *Polar Biology* (62) and *Canadian Journal of Zoology* (54) (see Supplementary Figure S1 [available online]).

Data obtained from deployments on phocids were most often reported (in 355 papers), followed by data from otariids (190), odontocetes (101), mysticetes (51), polar bears (13), sirenians (8), odobenids (7) and sea otters (5). The sum of these papers (730) exceeded the total number of papers considered (620) because several papers reported data from multiple families and/or suborders.

Within the group of papers reporting data from biologging instruments deployed on phocids, 80% reported results obtained from the five species most often used to carry devices (southern elephant seals *Mirounga leonina*; Weddell seals *Leptonychotes weddellii*; northern elephant seals *Mirounga angustirostris*; harbour seals *Phoca vitulina*; and grey seals *Halichoerus grypus*) (Figure 1a). Among the Otariidae, Antarctic fur seals *Arctocephalus gazella* were by far the most often reported as study species, followed by northern fur seals *Callorhinus ursinus*, New Zealand sea lions *Phocarctos hookeri*, Steller sea lions *Eumatopias jubatus*, and California sea lions *Zalophus californianus* (Figure 1b). Blue- *Balaenoptera musculus*, humpback- *Megaptera novaeangliae*, fin- *Balaenoptera physalus* and bowhead whales *Balaena mysticetus* were most often reported to carry biologging instruments among mysticetes (Figure 2a). Narwhals *Monodon monoceros*,

Table 1: Summary information regarding the instrument type and outcome reported as recorded for each paper

Parameter	Levels/groupings (one, or any combination)
Instrument type	Acoustic (environmental acoustics and/or acoustics emanating from the tagged animals) Camera (still or video imagery) Environment (*in situ* measures of temperature, conductivity and/or fluorescence) Physiological (e.g. heart rate, body temperature, electrocardiogram [ECG], etc.) Dive behaviour (e.g. time–depth recorders, accelerometers, speed sensors, etc.) Location (e.g. platform transmitting terminal [PTT], global positioning system [GPS], geolocation, etc.). Very-high-frequency (VHF) transmitters were considered only if used for tracking purposes, and not for device retrieval
Outcome reported	Acoustics At-sea dive behaviour (e.g. time–depth profiles, travel speed, etc.) At-sea location information Device influence (e.g. on behaviour, condition or survival of study animals, or other ecological impacts) Method (e.g. statistical analyses, tag technological improvements, etc.) Oceanography Physiology

belugas *Delphinapterus leucas* and sperm whales *Physeter macrocephalus* were most often used to carry biologging instruments among odontocetes, together resulting in 41% of all papers reporting results from odontocetes (Figure 2b). Of all papers assessed, 144 reported results obtained from species classified as threatened by the IUCN Red List. Of these, five papers included results from Critically Endangered species, 52 from Endangered species and 86 from Vulnerable species.

All pinniped species, except for one otariid- and two phocid species, were represented in the dataset (see Supplementary Table S1 [available online]). I did not find any papers resulting from biologging deployments on *Arctocephalus phillippii* (Juan Fernández- *A. philippii phillippii* or Guadalupe fur seals *A. p. townsendi*). Neither did I find any papers reporting biologging results from Caspian seals *Pusa caspica*, nor ribbon seals *Histriophoca fasciata*. Cetaceans were less well represented and I found data reported from deployments made on only 31 species of cetaceans out of a potential 90 currently recognised species (see Supplementary Table S1). The trend in numbers of papers published per year showed an exponential increase, starting in the early 1990s (Figure 3).

Spatial distribution of deployments

Results were reported from biologging deployments made in close proximity to all continents and showed a wide distribution (Figure 4). The distribution included the coastlines of all continents, and many island groups with high densities are evident along the east and west coasts of North

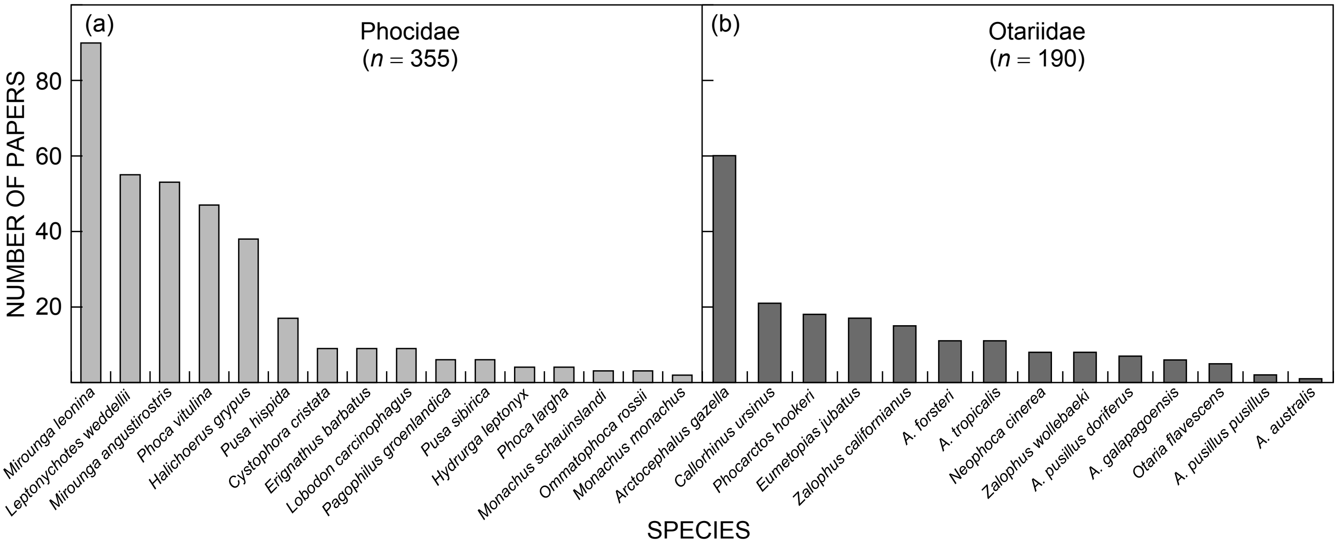

Figure 1: Number of papers resulting from biologging deployments on individual species of (a) Phocidae and (b) Otariidae

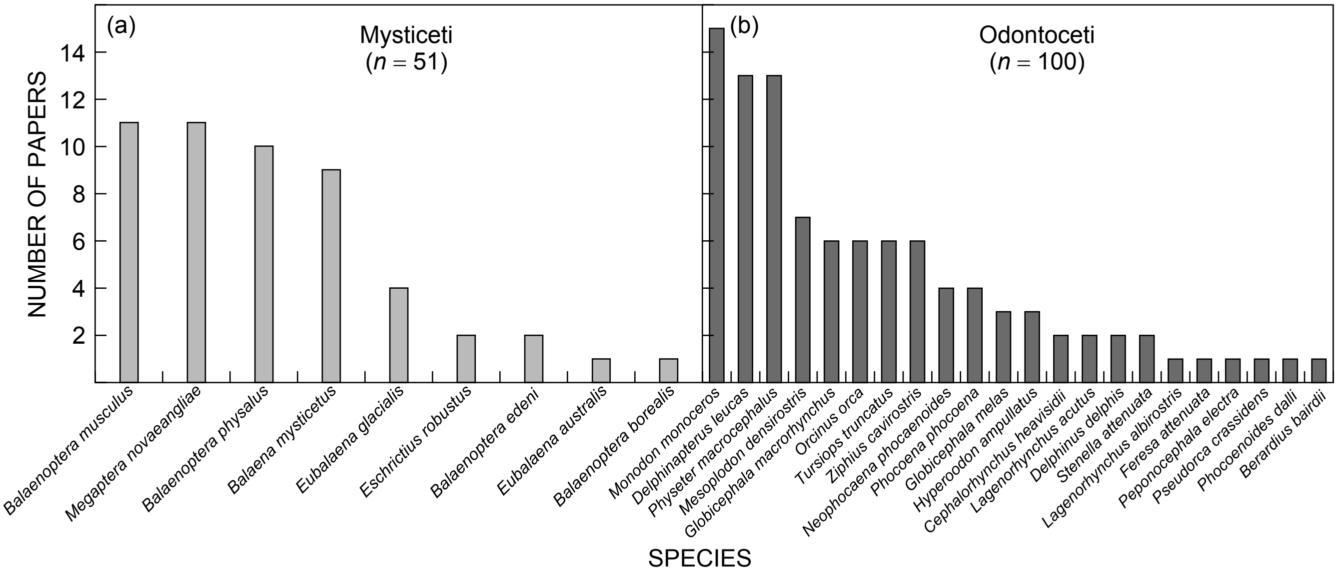

Figure 2: Number of papers resulting from biologging deployments on individual species of (a) Mysticeti and (b) Odontoceti

America, as well as north-western Europe. Other areas where high numbers of papers reported results include the western Antarctic Peninsula, eastern Australia and many of the sub-Antarctic islands. I found no papers that reported biologging results from deployments made on the east coast of Africa, the Middle East, southern Asia, or the west coast of South America.

Applied vs non-applied

I classified 15.3% of all papers as applied. Papers resulting from deployments on threatened species had a higher likelihood of being classified as applied than studies that involved deployments on species not considered threatened ($\chi^2 = 26.23$, df = 1, $p < 0.001$). There was no significant difference in impact between applied papers and those classified as non-applied (Wilcoxon test: $W = 11\ 379$, $p = 0.85$). An increasing trend in the proportion of papers classified as applied from the mid-1990s was evident, and these made up 29% of all biologging papers on free-ranging marine mammals recorded for 2013 (Figure 5).

Age- and sex classes

Most papers reported results obtained from deployments made only on adult animals ($n = 272$), followed by a combination of adults and immature animals ($n = 98$) and then immature animals only ($n = 95$). Results obtained from

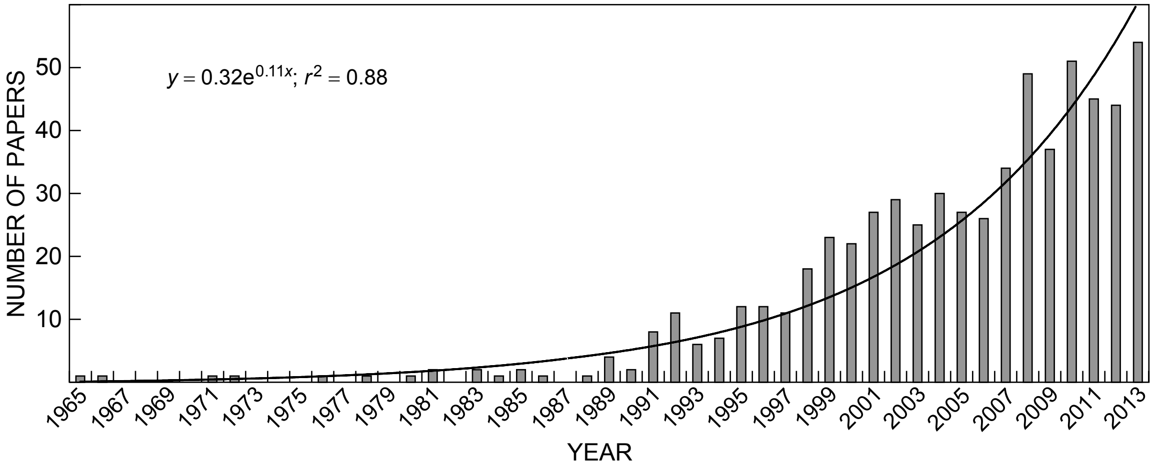

Figure 3: Exponential trend over time in number of papers that reported results obtained from biologging deployments on free-ranging marine mammals, 1965–2013

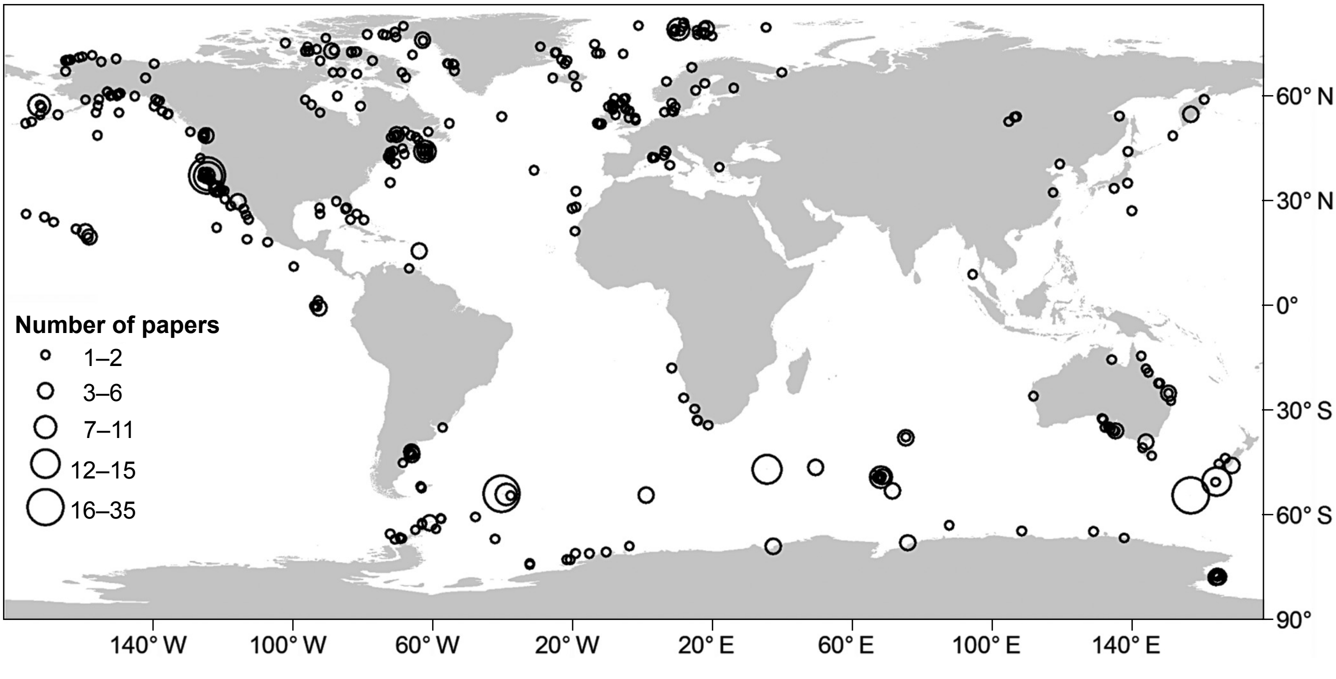

Figure 4: The number of papers per approximate location of reported biologging deployments on free-ranging marine mammals (1965–2013)

deployments made only on female animals were reported in 217 papers, whereas 54 papers resulted from deployments made only on male animals, and 233 from deployments made on animals of both sexes. Among papers that reported results from adult animals ($n = 355$), there was significant bias in favour of females, with fewer papers reporting results from adult males ($n = 126$) than would have been expected from a 50:50 ratio ($\chi^2 = 11.68$, $p < 0.001$).

Impact

The mean impact of all papers assessed was 6.3 (SD 6.1; median = 5). I found no trend over time in the impact of papers ($y = -0.08x + 157$; $r^2 = 0.004$, $F_{1,430} = 2.63$, $p = 0.12$). Similarly, when considering medium-impact papers alone, no trend in impact was evident over time ($y = 0.01x - 7.8$; $r^2 = -0.002$, $F_{1,383} = 0.14$, $p = 0.71$). However, there was an increase in the frequency of high-impact papers over time (Figure 6). The mean impact of the 40 papers examined that used biologging data from animals other than marine mammals was 6.3 (SD 7.4; median = 4.9) and did not differ significantly from marine mammal papers ($W = 8\,104$, $p = 0.516$).

Numbers of species

Most papers reported results from biologging deployments on a single species (single species, $n = 572$; multiple species, $n = 48$), and the maximum number of species included in a paper was 17. Medium-impact papers resulting from deployments on multiple species did not have a different impact compared to single-species papers ($W = 3\,238.5$, $p = 0.137$). However, papers reporting results from multiple species showed a higher frequency of high-impact papers compared to single-species papers (Fisher's exact test: odds ratio = 4.44, $p < 0.001$).

Numbers of devices deployed

Where reported, the median number of devices deployed in studies was 15 (range: 1–297). The median number of successful devices was 12 (range: 1–509). Various papers

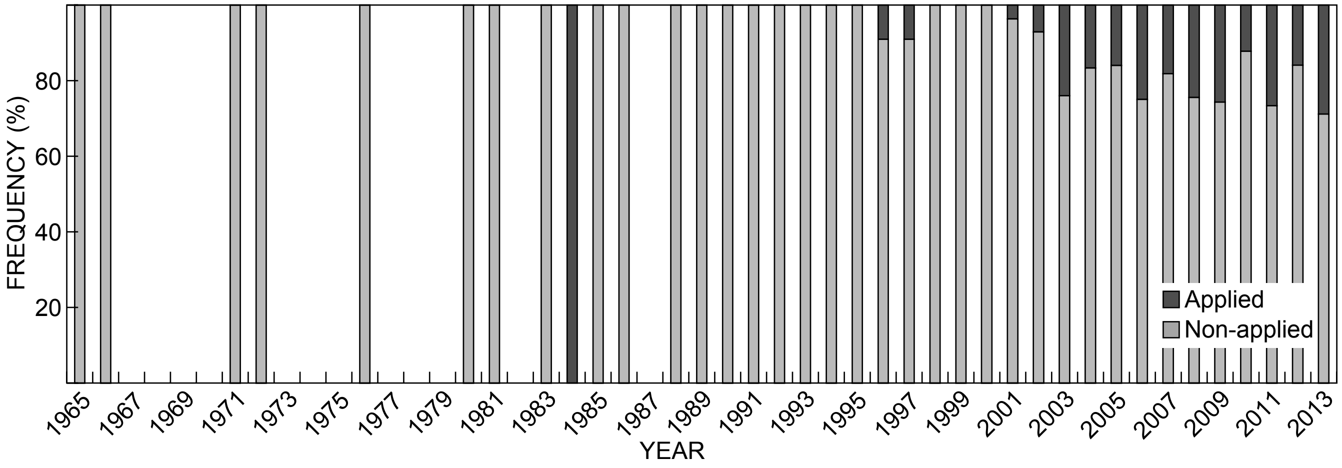

Figure 5: Variation over time in the proportions of applied and non-applied marine mammal biologging papers, 1965–2013

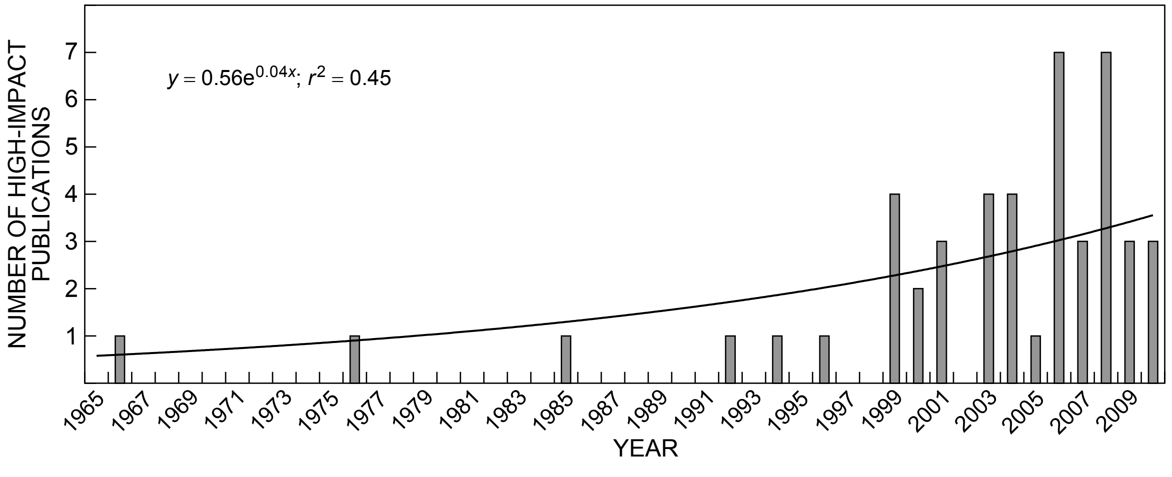

Figure 6: Exponential trend over time in number of high-impact papers that resulted from biologging deployments on marine mammals, 1965–2010. High-impact papers were defined as papers with impact values ≥10

reported only one or other of these quantities, which explains why the upper range limit of the former was lower than that of the latter. There was an increasing trend over time in both the number of devices deployed ($y = 1.01x - 2003$; $r^2 = 0.03$, $F_{1,441} = 14.44$, $p < 0.001$), as well as the number of successful devices ($y = 1.03x - 2036$; $r^2 = 0.02$, $F_{1,488} = 11.14$, $p < 0.001$) (Supplementary Figure S2 [available online]).

There were weak, but significant, positive relationships between the impact of medium-impact papers and the number of devices deployed ($y = 0.02x + 4.37$; $r^2 = 0.07$, $F_{1,312} = 22.7$, $p < 0.001$), as well as the number of successful devices ($y = 0.01x + 4.59$; $r^2 = 0.03$, $F_{1,332} = 12.7$, $p < 0.001$).

There was a significant difference in the frequencies of high-impact papers between identified clusters of the numbers of deployed devices ($\chi^2 = 21.07$, df = 3, $p < 0.001$). The *post hoc* Marascuilo procedure revealed a significantly higher frequency of high-impact papers among papers reporting on 51–120 deployed devices, when compared to other clusters (Table 2). Similarly, there was a significant difference in frequencies of high-impact papers between identified clusters of the numbers of successful devices ($\chi^2 = 23.05$, df = 3, $p < 0.001$). The cluster of papers reporting on data from 38 to 86 deployments had a significantly higher frequency of high-impact papers, when compared to clusters with fewer deployments (Table 2). I detected no significant difference in the frequency of high-impact papers between the cluster of 38–86 deployments and the cluster containing papers reporting data from more than 86 devices.

Instrument types

Instrument types (or combinations of instrument types) deployed were most often capable of providing both spatial location as well as some type of dive behavioural data (e.g. time–depth information) ($n = 210$). This was followed by deployments capable of returning location information only ($n = 182$); dive behavioural data only ($n = 125$); or a combination of spatial, behavioural and *in situ* environmental data ($n = 56$). All other instrument types (or combinations) were used in <20 papers. Numbers of papers using instruments capable of providing location information (also in combination with behavioural data, as well as in combination with behavioural and environmental data) showed an increasing trend over time (Figure 7). However, the sole use of instruments capable of obtaining only dive behavioural data showed a peak between 1998 and 2001, and appears to be decreasing (Figure 7).

Table 2: Results from *post hoc* Marascuilo procedures on the frequencies of clusters of high-impact papers. Papers were grouped according to reported numbers of instrument deployments (clusters identified by *k*-means clustering)

Cluster (number of devices)	High-impact papers (%)	Comparison	Significance
Devices deployed			
C1 ($n = 1–18$)	5.97	C2:C4	ns
C2 ($n = 19–50$)	6	C1:C2	ns
C3 ($n = 51–120$)	29.41	C2:C3	$p < 0.05$
C4 ($n > 120$)	0	C1:C3	$p < 0.05$
		C1:C4	$p < 0.05$
		C3:C4	$p < 0.05$
Devices returning data used for paper			
C1 ($n = 1–13$)	8.25	C1:C2	ns
C2 ($n = 14–37$)	6.3	C2:C4	ns
C3 ($n = 38–86$)	32.56	C1:C4	ns
C4 ($n > 86$)	20	C3:C4	ns
		C1:C3	$p < 0.05$
		C2:C3	$p < 0.05$

ns = not significant

A type-II ANOVA revealed a statistically significant difference in impact between papers reporting results from the various instrument-type categories ($F_{5,404} = 3.81$, $p = 0.002$). A multiple comparisons test (Tukey contrasts, implemented using the *multcomp* package – Hothorn et al. [2008]) revealed that papers using instruments capable of providing only spatial location data had significantly lower impact than papers using instruments (or combinations of instruments) capable of providing spatial location and dive behavioural data (Figure 8). Papers that used instruments capable of also recording *in situ* environmental variables (in addition to spatial and behavioural data) also had significantly higher impact than papers using spatial location only data (Figure 8). There were no other significant differences in impact between instrument types. I found no evidence for differences in the frequency of high-impact papers between papers reporting from the six instrument-type categories most often reported ($\chi^2 = 9.82$, df = 5, $p = 0.08$).

Outcome type

Papers that included animal behaviour (see Table 1 for definitions) outcomes were most numerous ($n = 382$) followed by papers that reported spatial movement outcomes ($n = 325$), methods ($n = 67$), oceanography ($n = 25$), physiology ($n = 24$) and device influence (14). Eight papers addressed device influence on pinnipeds (e.g. Heaslip and Hooker 2008; McMahon et al. 2008; Field et al. 2012), whereas six addressed device influence on cetaceans. Papers addressing device influence on cetaceans mostly reported only immediate behavioural responses to deployments (e.g. Watkins 1981; Watkins and Tyack 1991; Hanson and Baird 1998; Schneider et al. 1998), whereas one paper reported tissue healing around attachment sites (Sonne et al. 2012) and one reported on the survival of tagged individuals (Mizroch et al. 2011). I found no evidence for differences in the impact of medium-impact papers between types of outcome reported (ANOVA: $F_{11,373} = 1.7$, $p = 0.07$). Also, there was no evidence for an influence of outcome type on the frequency of high-impact papers ($\chi^2 = 4.65$, df = 5, $p = 0.46$).

Discussion

Which marine mammals are instrumented?

This review illustrates firstly the dramatic increase since the 1990s in the number of scientific papers resulting from biologging deployments on marine mammals. Given the technological advances in biologging instruments of this time period (Ropert-Coudert and Wilson 2005; Evans et al. 2013), this outcome is not surprising. The distribution of biologging papers was biased firstly towards pinnipeds,

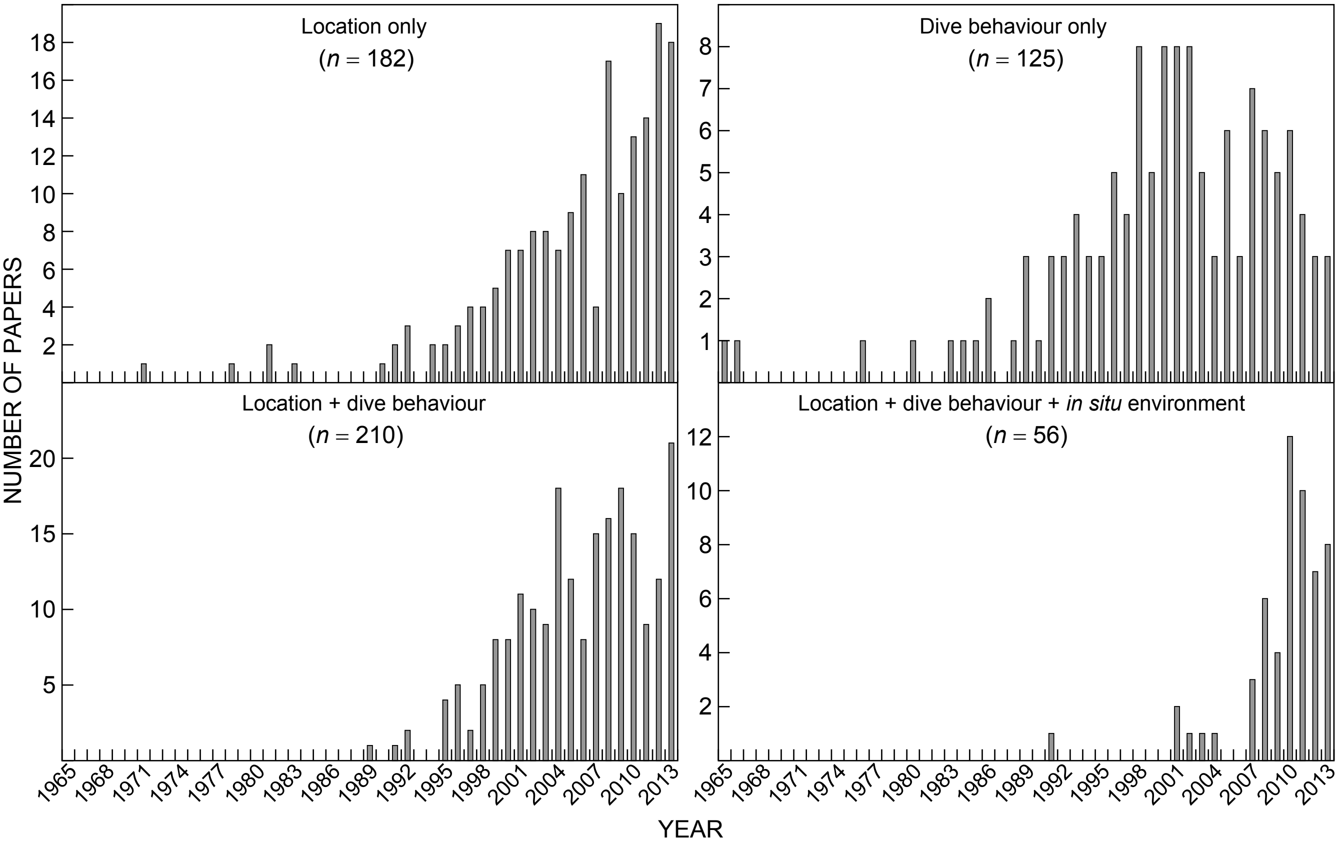

Figure 7: Variation over time in number of publications that reported results according to instrument type and/or combination of instrument type used, 1965–2013

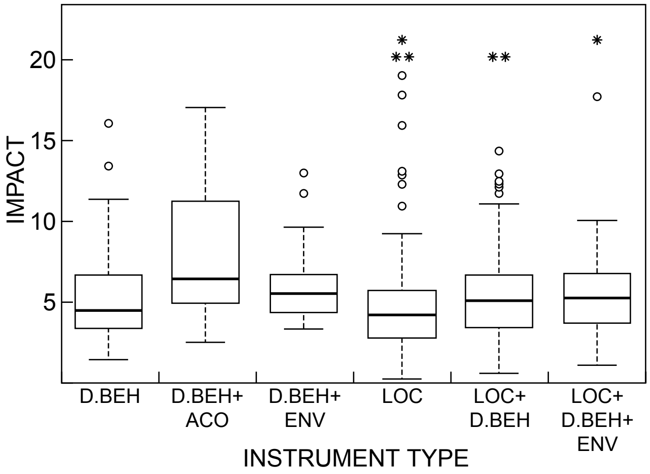

Figure 8: Box-and-whisker plot indicating differences in impact of medium-impact papers between instrument types used. D.BEH = dive behaviour only; D.BEH+ACO = dive behaviour + acoustics; D.BEH+ENV = dive behaviour + *in situ* environment; LOC = spatial location only; LOC+D.BEH = spatial location + dive behaviour; LOC+D.BEH+ENV = spatial location + dive behaviour + *in situ* environment. Bold line = median, box = 25th and 75th percentiles, points = outliers, whiskers = 1.5 times the interquartile range, or the maximum value (when there are no outliers). Statistical significance is indicated as follows: *$p \leq 0.05$, **$p \leq 0.005$

and secondly to a comparatively small number of species (specifically southern elephant seals and Antarctic fur seals). The distribution of biologging papers on marine mammal groups other than the Phocidae and Otariidae (walruses, cetaceans, polar bears and sea otters) was more even, with 13 species each presented in six or more papers, whereas 22 species contributed to the remaining 51 papers. An earlier review of tracking and dive behaviour studies of marine mammals suggested that only 13.3% of the available data were generated by cetaceans (Shaffer and Costa 2006). While the current review still indicates a comparative paucity in biologging studies on cetaceans (particularly when considering the higher diversity of cetaceans compared with pinnipeds), it also suggests a relative increase in the study effort on cetaceans through the use of biologging during the past eight years. A major limitation in the use of biologging instruments on cetaceans has been attachment techniques (Hooker and Baird 2001). These obvious additional difficulties in locating and attaching devices to exclusively aquatic marine mammals (compared with marine mammals that haul out onto land) explains the differences in numbers of publications between the seals and groups such as the cetaceans. Current attachment techniques for cetaceans include the use of stainless steel barbs designed to penetrate the blubber of study animals (e.g. Minimikawa et al. 2007; Andrews et al. 2008) or potentially less-invasive suction-cups for shorter-term deployments (e.g. Amano and Yoshioka 2003; O'Malley Miller et al. 2010). Scientists generally rely on either capturing smaller cetaceans (e.g. Lydersen et al. 2002) or remotely deploying instruments using tagging poles (e.g. Davis et al. 2007), cross-bows (e.g. Mate et al. 2011), firearms (e.g. Tyack et al. 2011) or air guns (Heide-Jørgensen et al. 2001). Whereas the practicality, effectiveness and safety of available attachment techniques seems to remain a challenge, the increasing trends in publications for Odontoceti and Mysticeti suggest that these limitations are being overcome.

Among the pinnipeds, elephant seals are considered ideal animals to carry biologging instruments, given their large size (Le Boeuf and Laws 1994), long-distance migrations (Hindell and McMahon 2000; McIntyre et al. 2011b), extreme dive behaviour (McIntyre et al. 2010a) and high fidelity to haulout locations (Hofmeyr et al. 2012). It is therefore not surprising that so many studies have used elephant seals to carry biologging instruments. The high number of papers on Antarctic fur seals largely emanates from intensive study efforts carried out at Bird Island, South Georgia (e.g. Boyd et al. 1995; Staniland et al. 2007), and the Kerguelen Islands (e.g. Bonadonna et al. 2001; Lea et al. 2002).

Biologging instrument deployments were heavily biased towards adult female animals, and the results reported here illustrate the relative paucity of biologging data obtained from immature animals, as well as adult males. A similar bias has been described for satellite telemetry data specifically from pinnipeds (Hart and Hyrenbach 2009) and attributed to both ecological and logistical biases. For example, female central-place foragers tend to return reliably to land in order to attend to nursing pups (Hoelzel 2009), whereas (larger) male animals tend to be less predictable and can be more difficult to immobilise safely for instrument deployments (Ramdohr et al. 2001; Geschke and Chilvers 2009). Such bias in information in favour of one demographic group provides obvious limits to interpretation of data pertaining to the behaviour of the instrumented species, particularly in the many species that exhibit sexual- and/or age-related segregation in behaviour and habitat use patterns (e.g. Field et al. 2005; McIntyre et al. 2010b; Leung et al. 2012).

Instrument types

Instrument types (or combinations thereof) used in the studies assessed here most often provided location and dive behavioural data. These were often combinations of satellite transmitters and time–depth recorders. Time–depth recorders were among the first instruments used in animal-borne deployments on marine mammals (Kooyman 1965). Such recorders are still in use in many studies (e.g. Bodkin et al. 2012; Dragon et al. 2012b), although instrument sizes have decreased relative to early models, storage capacities have increased and sensor accuracies have improved. The use of satellite-linked instruments to obtain location data is comparatively new (compared to logging instruments such as time–depth recorders), and some of the first studies to make use of such technology on free-ranging marine mammals were published in the late 1980s/early 1990s. These studies include the tracking of harbour seals in the 1980s (e.g. Stewart et al. 1989), grey-, ringed- and elephant seals in the early 1990s (e.g. Heide-Jørgensen et al. 1992; McConnell et al. 1992a, 1992b) and bottlenose dolphins in the early 1990s (e.g. Mate et al. 1995). Satellite-linked instruments traditionally used Service Argos to obtain location estimates. This technology is now often combined with, or even replaced by, the use of GPS technology to obtain more-accurate position estimates for tracked marine mammals (e.g. Costa et al. 2010; Dragon et al. 2012b).

The continuing increase of papers that report data from devices that provide only spatial data can mostly be attributed to the increasing number of papers that report results from satellite tags deployed on cetaceans. For example, of the 22 papers using location-only instruments published in 2012, 11 resulted from deployments on cetaceans (e.g. Gales et al. 2012; Lydersen et al. 2012; Woodworth et al. 2012). This trend can be expected to change in the future, as improvements in attachment techniques and decreased instrument sizes will allow for the incorporation of additional sensor packages on devices suitable for cetacean deployments (e.g. Laidre et al. 2010), resulting in the replacement of location-only instruments with location/dive behaviour- and location/dive behaviour/*in situ* environmental instruments.

My interpretation of the prevalence of various instrument types is likely to contain some bias due to authors not reporting the full capabilities of instruments deployed. For instance, whereas modern time–depth recorders often also measure *in situ* water temperature, this capability was not necessarily mentioned if the authors reported results of the time–depth data only. I therefore expect, for example, that the trend in papers using dive behaviour-only instruments (Figure 7) may be an under-representation of the decline in use of dive behaviour-only instruments. Similarly, the increase of papers reporting data obtained from devices capable of also measuring *in situ* environmental variables (Figure 7) is likely to be more pronounced than is reported here.

Scientific impact

The impacts of marine mammal biologging papers were very similar to those of biologging papers resulting from other taxa. Despite the rapidly increasing numbers of publications, there was no clear trend in the impact of papers over time, other than an increasing frequency of high-impact papers. This stability in impact may be due to consistency of overall quality and visibility of papers, or alternatively to the increasing numbers of papers themselves sustaining impact levels of other marine mammal biologging papers through citations (i.e. through a positive feedback). The results reported here suggest that the impact of papers is influenced by numbers of species studied, sample sizes, and to a limited extent the capabilities of devices used.

The influences of number of species and sample size on the impacts of papers were not surprising. Papers that reported data from multiple taxa tended to be either: (1) of broad relevance to entire ecosystems (e.g. Block et al. 2011); (2) fundamental to the understanding of movement and behavioural traits (e.g. Sato et al. 2007; Sims et al. 2008; Watanabe et al. 2011); (3) of a comparative nature (e.g. Schreer et al. 2001); or (4) illustrative of broadly-applicable methods (e.g. Freitas et al. 2008). The likely influence of larger sample sizes on the citation frequency of papers has previously been acknowledged (Padial et al. 2010), and furthermore is illustrated for medical papers (Kostoff 2007). These results therefore highlight the influence of sample size on the impact of papers, even when sample size ranges are within ranges typical for ecological studies.

Addressing possible adverse instrument effects

I recorded only 14 papers with explicit aims to address instrument and/or instrument deployment influences on the study animals and/or the marine environment. This includes only those papers with assessment of deployment influences as a central aim, and not necessarily all papers that incidentally reported such an influence (or lack thereof). I also excluded papers reporting results from captive environments or papers based on modelling exercises solely; the inclusion of such papers (e.g. Pavlov et al. 2007) and other unpublished research (e.g. Hanson 2001) would have increased the number of papers addressing device influences on animals. The need for more studies assessing device impacts has also been recognised by other authors (Wilson and McMahon 2006; Hart and Hyrenbach 2009; McMahon et al. 2011). Godfrey and Bryan (2003) reported – from an analysis of radio-tracking papers of various taxa – that only 4.5% of mammal studies (including terrestrial mammals) explicitly assessed tag effects on study animals. Interestingly, 61% of these studies reported substantial tagging effects, thereby further illustrating the need for more information on potential tagging impacts. McMahon et al. (2011) summarised potential negative effects of biologging devices either in association with capture (e.g. stress, anaesthesia side-effects, etc.), device types (e.g. inducing drag, attracting predators, etc.), attachment method (e.g. generation of excessive heat by glues) or timing/duration of attachment (which may have an influence during breeding seasons, etc.). Nevertheless, whereas some assessments have shown no consequences of instrument attachment in terms of long-term survival (e.g. McMahon et al. 2008), the results of this review illustrate a paucity of studies quantifying the influences of biologging devices on the energetics, fitness and survival of free-ranging animals that are used to carry instruments. This field of investigation, therefore, apparently remains an important one that requires more focus in order to ensure the ethical use of biologging instruments.

Outcomes and subject categories – are researchers optimising the output generated?

Papers mostly reported outcomes that were classified either as animal dive behaviour or spatial movement. Similarly, Hart and Hyrenbach (2009) reported that the largest proportions of papers resulting from satellite tracking of marine mammals focused on the movements and habitats of animals, with other topics addressed in fewer papers. The dominance of behaviour and spatial movement papers mirrors the use of instrument types, which were dominated by devices capable of recording this type of information.

Although not explicitly reflected in the results, single datasets were frequently used to produce various papers, whereby authors either used different methods to analyse data or used previously collected data to address new questions. Furthermore, a number of papers assembled various datasets in order to answer questions related either to various species (e.g. Sims et al. 2008; Watanabe et al. 2011), areas used by multiple animals (e.g. Block et al. 2011) or inter-population differences in behaviour (e.g. James et al. 2012). McMahon et al. (2011) advocated the so-called ‘three Rs’ in biologging studies, suggesting that researchers should: (1) reduce the numbers of animals instrumented (although maintaining statistically relevant numbers); (2) refine procedures to minimise pain and stress; and (3) replace experiments involving animals with *in vitro* models as far as possible. I suggest the inclusion of a ‘fourth R’, namely recycling of available data. Of course, technological improvements allow for answering new questions, and therefore require new deployments of suitable instruments, and in some cases ongoing deployments of appropriate devices are pursued in the context of long-term monitoring programmes (e.g. Bester et al. 2011). However, there is a substantial amount of marine mammal biologging data among researchers across the world that could support new research.

Shaffer and Costa (2006) suggested the need for a common repository where marine mammal tracking- and dive behaviour data can be stored and made available for wider use within the marine mammal community. Efforts to store data appropriately and make them more widely available have been ongoing during recent years and are the subject of various online initiatives (e.g. Australian Antarctic Data Centre [https://data.aad.gov.au/]; PANGAEA [Diepenbroek et al. 2002]; SCAR-MarBIN [http://www.scarmarbin.be/index.php]). This review, and the associated bibliography (see online Supplementary Material), aims to increase further the awareness of data already collected by marine mammal researchers, as well as other scientists (e.g. oceanographers) who are interested in using data obtained from biologging instruments on marine mammals. An increased awareness of the data that have been collected, coupled with appropriate data storage and increased data availability, can not only assist in answering additional interesting questions, but can also reduce the need for additional deployments.

Biologging and conservation/management

Marine mammals are a comparatively poorly known group, facing high threat levels (Schipper et al. 2008), and biologging studies have the potential to inform numerous conservation and management actions. The potential benefits of using biologging instruments in animal conservation research are many (see review by Cooke 2008). These include the potential to inform assessments of animal distributions, emigration behaviour, reproductive potential, mortality rates, and habitat use. The results presented here show that biologging deployments have been concentrated at higher latitudes, particularly along the North American and northern European coastlines, as well as the sub-Antarctic islands and the Antarctic continent (Figure 4). This is similar to the distribution reported by Shaffer and Costa (2006), who noted a paucity of marine mammal tracking- and dive behaviour studies in mid-latitudes, and closer to the equator. Whereas high numbers of globally threatened marine mammal species occur at high northern latitudes, the distributions of data-deficient species, as well as those threatened by accidental mortality (e.g. fisheries interactions, etc.) are concentrated at the equator and mid-latitudes (Schipper et al. 2008). This indicates a substantial spatial mismatch, with the exception of the Australian coastline, between the general use of biologging technologies on marine mammals and the spatial areas where such information is most likely to inform conservation and/or management actions. Furthermore, only a small proportion of studies reported explicit conservation and/or management implications (15.3%), despite numerous papers stating that their results have either management or conservation implications, but without providing specific detail. This proportion did show signs of a clear increase over time, however, from the early 2000s onwards. Two caveats associated with the interpretation of these data, as well as the lack of papers on a number of species (see below), are (i) the exclusion of literature other than peer-reviewed journal articles and (ii) the possible omission of relevant peer-reviewed literature in languages other than English. I excluded from the review documents that formed part of the so-called ‘grey literature’ (e.g. policy documents, reports, etc.), and the inclusion of such documents would likely have increased the number of cases where biologging information has been applied in conservation and management actions.

I did not find any publications resulting from biologging deployments on Juan Fernandez fur seals, Guadalupe fur seals, Caspian seals or ribbon seals. However, biologging investigations have been undertaken on at least some of these species without resulting in (English language) peer-reviewed papers (e.g. Osman 2008). All of these species are potentially of some conservation concern – both fur seal species are currently listed as Near Threatened on the IUCN Red List, Caspian seals as Endangered and ribbon seals as Data Deficient. Caspian seal populations have experienced decreases exceeding 70% over the past three generations, apparently due to excessive hunting (Harkonen et al. 2008), disease outbreaks (Kuiken et al. 2006), and possible negative effects associated with environmental contaminants (Watanabe et al. 1999). I further did not find biologging papers on a number of threatened cetacean species. Examples here include the Critically Endangered vaquita *Phocoena sinus* and the Endangered Ganges river dolphin *Platanista gangetica*. Although conservation science could potentially benefit from reliable habitat-use information from animal-attached devices, difficulty in the deployment of such devices on timid animals such as vaquitas is acknowledged (Morrel 2008). In such cases, alternative technologies are increasingly being used to obtain population and movement estimates of animals (Dalton 2008; Sasaki-Yamamoto et al. 2013).

Overall, the results presented here suggest that a comparatively small proportion of biologging studies on marine mammals are clearly of an applied nature, despite the non-specific claims of many papers to the contrary, and that the use of biologging technologies is still under-represented in conservation and management science. There is therefore a need to further develop study designs to deliver research outputs useful to marine mammal conservation practitioners and other decision makers. This accords with the suggestions of others to increase the applicability of conservation-related research for the advancement of specific conservation goals (e.g. Laurance et al. 2012).

In conclusion, numbers of scientific papers resulting from the deployment of biologging instruments on marine mammals are increasing rapidly. This review has illustrated how such papers are distributed between species, geographical areas, instrument types, journals and outcome categories. The scientific impact of marine mammal biologging papers appears to be relatively stable, although increases in the number of very high-impact papers are evident. There is a clear bias, with regard to species, age class and sex, in terms of data reported and this can be expected to limit the inferences obtainable from the available data. This review has also identified a paucity both of biologging papers with explicit management and/or conservation implications, and of papers aiming to quantify instrument deployment influences on study animals and their environments. It is hoped that the review will increase awareness of existing biologging data from marine mammals, encourage additional use of such data (e.g. through meta-analyses) and lead to the increased application of biologging studies for conservation and management purposes.

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