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Terrestrial animals have a long history of being studied although have only relatively recently begun to detail due to the challenges involved in studying them. Compared to other marine species seabirds are relatively easy to study and are potentially sensitive to changes in the marine environment. As a result of this they are often used as bio-indicators. In the Southern Ocean a number of different devices created by a number of different manufacturers are used, with each type having advantages and disadvantages. When selecting a device to undertake a study it is therefore necessary to consider the biological question being asked, the size of the study species and the budget of the research. The data which is collected in these studies can be used for both conservation and fisheries management purposes and has been used so by the Commission for the Conservation of Antarctic Marine Living Resources. However, there are a number of ethical considerations to be taken into consideration, including the weight of the device and potential impacts upon breeding success. Tracking and monitoring technologies are continually being improved, allowing for increasingly complex biological questions to be answered, which allows for a greater understanding of the ecology of seabirds.

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Seabird tracking in the Southern Ocean

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Introduction

Overview of the development of tracking and monitoring

Tracking and monitoring in the past

Observing animals from a distance has a long history, going back to the the days of Aristotle (Ropert-Coudert & Wilson 2005). Terrestrial animals, being easier to study, have been monitored the longest. In addition to there are many species which are heavy enough to have been used in the earlier telemetry studies when the devices were much larger than they are now. Up until the early 1970s marine research on seabirds was ship-based (Ainley *et al*. 2012) as the birds spent long periods of time away from land and there was not any other viable option of studying them whilst they were at sea and away from colonies. As technology improved marine research became based around aerial studies and is now predominately land-based (Ainley *et al*. 2012). The first depth recorder was attached to a Weddell seal (*Leptonychotes weddellii)* in 1965 and the first seabird to be tagged was an emperor penguin (*Aptenodytes forsteri*) in 1971 (Wilson & Vandenabeele 2012)) which allowed researchers to begin to monitor these animals from longer distances. Before the 1990s there was very little information available about the activity and movement of seabirds at sea (Bost *et al.* 2008). The original studies had high rates of premature tag loss or failure (Hart & Hyrenbach 2009) which was a considerable limitation in early studies.

Fishes have longest tagging history of all the taxonomic groups which is due both to their commercial importance, but also the less strict permit requirements (Hazen *et al.*2012).

Technology made considerable advancement during the 1980s and 1990s, which had a dramatic impact on the way that tracking was undertaken. Satellite tracking began to be used in the 1980s (Hart & Hyrenbach 2009), and has been used now for more than 25 years as tool for research (Meyburg & Meyburg 2009). The availability of satellites to locate animals has allowed for more accurate locations to be gathered, thereby improving the quality of the research. However, in 1992 battery power was the only option for platform terminal transmitters (PTTs) (Meyburg & Meyburg 2009). This limited the length of studies and constrained the number of location fixes that could be recorded in order to conserve the battery power as long as possible (although solar-powered PTTS are now available) (Meyburg & Meyburg 2009). By the late 1980s technology had advanced to the stage that biologists were no longer designing their own devices, but leaving this to electronics engineers (Wilson & Vandenabeele 2012). This was due to the fact that the devices were becoming increasingly complicated to both design and build. Since the work of Jouventin and Weimerskirch in 1990 there has been a considerable increase in the use of satellite telemetry with >100 papers having been published since then (Burger & Shaffer 2008).

More recent advancements

Improvements are continually being made to the devices that are available. These improvements include: larger memory sizes (Bost *et al.* 2008; Boyd *et al*. 2004; Wilson & Vandenabeele 2012), lower power consumptions (Boyd *et al*. 2004) and more rapid acquisition rates (Bost *et al.* 2008). Devices are also continually being miniaturised (Barbraud *et al*. 2012; Bridge *et al*. 2011; Wilson & Vandenabeele 2012), providing much more accurate locations (Bridge *et al*. 2011) and collecting different types of data (Hart & Hyrenbach 2009; Sokolov 2011; Wilson & Vandenabeele 2012). The availability of solar power has contributed to tags becoming smaller (Burger & Shaffer 2008), which means that smaller species can be studied. The combination of all of these factors has resulted in more species to be studied, in greater depth with great accuracy and for longer periods of time.

Tracking seabirds

Monitoring and tracking seabirds

There are many reasons why seabirds are monitored and used as indicators. A key factor is that of all marine organisms seabirds are the easiest to study (Wilson & Vandenabeele 2012). This is because they are a long-lived group with high levels of adult survival and recruitment which is progressive (Lewison *et al.* 2012). In addition to this they generally breed in colonies in coastal areas and normally are philopatric, particularly once they have been recruited to a particular colony (Lewison *et al.* 2012). This means that not only are long-term studies on individuals possible, but they can be fairly easy to locate, and re-locate in subsequent years. As a result of this our understanding of seabird foraging patterns is improving rapidly (Bost *et al.* 2008), which is also true for other areas of seabird ecology.

Seabirds are tracked for a number of reasons. These reasons include the fact that hey have a position in the upper part of the marine food web (Lewison *et al.* 2012) and many species undertake long-distance, polar-temperate migrations (Ballard *et al.* 2010). This means that they are a group which has a considerable influence (and can be influenced) within the marine ecosystem on a global scale. Therefore understanding their biology means that there can be an increased understanding of the structure and function of marine ecosystems. Studies of seabirds has, overall, revealed a wide range of different findings which include the remarkable flight capabilities and wide distributions (Adams & Flora 2010) of some species and variations in inter- and intra-specific foraging strategies (Quillfeldt *et al.* 2011). As a result of these studies the behaviour of seabirds is now much better understood (Hazen *et al*. 2012).

Seabirds as indicators

Seabirds have long been used as an indicator of the availability and distribution of resources (particularly by fishers), although this use has become more realised in recent times (Bost *et al.* 2008). This realisation has only occurred as the range of their distribution (seabirds being found in all oceanic systems including polar, tropical, coastal and pelagic) and the way that they interact within the marine ecosystem was not fully recognised that long ago (Lewison *et al.* 2012). What makes them good indicators is the fact that, potentially, they have high sensitivity to changes in the environment at different temporal scales (Bost *et al.* 2008) as well as being heavily dependent on marine resources (Bost *et al.* 2008; Oswald & Arnold 2012). Given all of these factors, especially their wide distribution and sensitivity to environmental change, seabirds can be 'the canary in the coalmine' and so be used to create system alerts that something is occurring before it otherwise would have been detected.

Devices being used in the Southern Ocean

Types of devices and manufacturers

A number of different devices have been used in the Southern Ocean in recent times including radio transmitters and radio receivers (Huin *et al.* 2000; Hahn *et al*. 2007; Lyver *et al.* 2010), geo-locaters/global location sensing (GLS) (Adams *et al*. 2009; Ballard *et al.* 2010; Phillips *et al*. 2005), global positioning system (GPS) (Masello *et al.* 2010), and PTTs (Erdmann *et al*. 2011; Jaeger *et al.* 2010; Phillips *et al.* 2005). The devices used in these studies have been manufactured by a number of different companies including Laschewskie-Siewers Telemetry Systems (Hahn & Reinhardt 2007), Lotek (Adams *et al*. 2009), British Antarctic Survey (Phillips *et al.* 2005) and Microwave Telemetry (Phillips *et al.* 2005) and Earth & Ocean Technologies (Quillfeldt *et al.* 2011).

Example studies in the Southern Ocean

A number of different types of studies have been done in the Southern Ocean from a regional level to large scale migrations. Examples of these studies are given below, which show the diversity of studies being done, but also some of the different technologies and methods which are used. During the austral winters of 2001 and 2002 in Marguerite Bay, Antarctica (on the Western Antarctic Peninsula) Erdmann *et al.* (2011) tracked a number of Adélie penguins (*Pygoscelis adeliae*) to determine their foraging locations. The penguins had a PTT tag weighing between 80-82g attached, and location fixes were obtained from the Argos satellite system. The study found that each of the tracked penguins (52 in total) had foraging areas which had little overlap. However, when there was heavier sea ice cover there was a higher degree of overlap in foraging areas for the female Adélies. The authors concluded that whilst bathymetry influenced the foraging areas of the penguins, sea ice was a much more important driving factor behind their foraging locations.

Phillips *et al.* (2005) undertook a study to investigate the migration and summer feeding of non-breeding black-browed albatrosses (*Thalassarche melanophrys*) from South Georgia. The study took place over three consecutive breeding seasons from 2001 to 2004. The birds were initially equipped with GLS loggers (Afanasyev 2004) which weighed 9g each. In the second year some of the birds also had a 17g radio transmitter attached and some also had a 30g satellite transmitters attached in addition to this. All three instruments together represented <2% of the adults body weight. This study found that this population has a strong degree of site fidelity, even though they travelled very long distances with one male reaching Australia. The population at South Georgia has been in decline since the mid 1970s with an annual decrease of >4% per year, which is mostly due to the interactions of this species with long-line fisheries.

Due to their small size species such as terns are often tracked using geo-location. A study by Egevang *et al.* (2010) monitored the migration of Arctic terns (*Sterna paradisaea*) using miniature archival light loggers (Mk14 geo-locators, British Antarctic Survey) which had a mass of 1.4 g. The results of this study showed that this species may have the longest migration route of any animal. The locations returned from the devices showed that this species travels from Greenland and Iceland down to the Southern Ocean during the northern winter, although there are some variations in the routes taken by different individuals.

Devices showing promise in other regions

Radar prototypes which are small enough to be used on birds are currently being tested by the University of Oklahoma (Bridge *et al*. 2011). In 2012 Chilson *et al.* published a paper on using radar to investigate ecology as well as the abundance and aerial movement of animals, including the nocturnal migration of birds in spring. This method of tracking uses weather radars, but with the weather data removed so that only biological data remains. Species can be differentiated by the rate that they flap their wings, which is affected by a number of factors including their size, mass, wing span and wing area. Whilst this method is not practical for some species (such as those which move in small groups or individually), for species which travel in larger groups this type of tracking shows a lot of promise. This is because it would allow for species to be tracked from long distances, whilst still having fairly good accuracy.

Choosing the best device

Advantages and disadvantages of different devices

Each type of device has advantages and disadvantages which are based on the accuracy, cost and size of the device. In many cases the mass of the battery determines the size of the tag (Bridge *et al*. 2011). The advantages and disadvantages of the devices that are (or could be) used in the Southern Ocean are listed below.

- Radio transmitters and radio receivers can use VHF (very high frequency) or UHF (ultra high frequency) (Meyburg & Meyburg 2009) and has followed the use of leg and flipper bands (mark-recapture studies) (Hazen *et al*. 2012)

Advantages:

Some versions are very small (Bridge *et al*. 2011) and Lotek has made one <0.20g which can be used on insects. They are also relatively cheap (between $150- $300 each), but require transmitters to be bought (as a one-off implementation) which can cost several thousand dollars (Bridge *et al.* 2011). VHF has a positional accuracy of at least 5°, although this can be reduced if the bird is directly observed (Meyburg & Meyburg 2009). The lack of seawater penetration by radar can be used as an easy way to determine dive/pause intervals in seabirds (Wilson & Vandenabeele 2012).

Disadvantages:

It is limited by the number of (stationary) receivers in place which means that it also (cannot be used for tracking migratory birds over long distances (Bridge *et al*. 2011). This device also requires 'line of site' for recordings to be made and it cannot be used in the sea as radio waves are not able to be transmitted through the seawater (Wilson & Vandenabeele 2012), which limits its application.

- GLS/geo-location tags, which use diel patterns to determine location (Burger & Shaffer 2008).

Advantages:

These tags use little power, have very small batteries and therefore tiny tags are available (Burger & Shaffer 2008) with some available being <1g (e.g. Biotrack geo-locators by Sirtrack)). Larger tags can be used to collect information for two-10 years and latitude calculations can be improved if sea surface temperatures are also recorded (Burger & Shaffer 2008). They are relatively cheap and cost between $25-400 (Bridge *et al*. 2011). These devices can be attached to a leg band which avoids problem of instrument loss during moult (Shaffer *et al*. 2005).

Disadvantages:

They have low resolution, with a mean error of 185-200km according Burger & Shaffer (2008) and about 200km latitude and 50km longitude according to Bridge *et al*. (2011). The tag needs to be recovered for the data (Bridge *et al*. 2011) which means that it has to be possible to re-capture the seabirds at the end of the study. While retrieving devices is relatively easy for colonial birds, getting to the colonies can be logistically challenging (and expensive) in the Southern Ocean. There are also issues with operating in high latitudes due to extra long hours of daylight or darkness (Meyburg & Meyburg 2009) which limits the operational area during throughout some time periods.

- PTT and GPS tags both use satellites to provide location fixes.

Advantages:

Satellite tags are now miniaturised and can provide high levels of accuracy for some species (Bridge *et al*. 2011), with the accuracy normally around 1-3km and can provide as many as 20 fixes a day from Argos satellites (Burger & Shaffer 2008), which use Doppler fixes (Meyburg & Meyburg 2009). GPS fixes are more accurate (to within metres of the actual location (Burger & Shaffer 2008; Wilson & Vandenabeele 2012). These tags can be as light as 5g and last 2-5 years (Microwave Telemetry) and some versions are being made which use solar power (e.g. Microwave Telemetry and North Star) which means a smaller battery size. This is useful in studies where the tag might be difficult or impossible to recover (Burger & Shaffer 2008). Due to the high level of accuracy GPS stags are good for tracking fine scale movements (Burger & Shaffer 2008).

Disadvantages:

The use of tags which use Argos data channels are expensive, at around US$2500 per device according to Adams *et al*.(2009) or up to nearly US$4000 each through Microwave Telemetry. They also have high power requirements, which means that they need a large battery (Bridge *et al*. 2011), which limits which species they can be used on. Solar powered devices are limited in the number of transmissions as they are in the high latitude regions during winter (Meyburg & Meyburg 2009) (which is an issue to consider for the Southern Ocean).

Trade-offs

Choosing the right tag can be difficult as the websites do not always advertise all of the necessary information including price, size and device specifications. Many devices allow flexibility in the number of fixes per day (e.g. Microwave Telemetry's PTT 100s; Lotek's GPS Bug; North Star's PTTs). Which device (and fix/sample intervals) is chosen depends on:

- The biological question/s being asked (including spatial and temporal scales)
- The size and weight of the species being studied
- The budget

Sometimes tags are used in conjunction as this can help improve accuracy, or because one tag alone lacks the capacity to record the necessary data. In addition to any tagging Meyburg and Meyburg (2009) suggest that ringing the seabirds (an extra cost) so that they can later be identified if the tag falls off or the seabird manages to chew off the attachment (and so the device can be lost).

Using data for conservation and management

Tracking and monitoring studies can reveal a considerable amount of information about not only what seabirds eat but where and when. This information is important as a major population regulator for sea birds is food availability, especially for species and populations which are not under high predation pressure (Hahn & Reinhardt 2007). This information combined with fisheries data can provide insights into potential overlaps between the consumer groups (human fisheries and seabirds). For example some species including macaroni (*Eudyptes chrysolphus*) and gentoo (*Pygoscelis papua*) penguins and 'imperial' shag (*Phalacrocorax* spp.) feed on the juveniles of commercially fished species (Ainley & Blight 2008). Therefore the population dynamics and behaviour of these species can influence, and be influenced by the commercial fishery. In addition to this the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) using seabirds including Adélie penguins, Cape petrels (*Daption capense*) and black-browed albatross as indicators for the CCAMLR Ecosystem Monitoring Program (CEMP) (CCAMLR 2012).

In the past (and at present in some regions) this relationship is not fully understood.
By-catch from fisheries is one of several anthropogenic disturbances that have the potential to impact upon seabird populations (Lewison *et al*. 2005). This has been shown through the interaction of albatrosses and petrels with the long-line fishery, and the subsequent dramatic population declines in these species. While this issue has been dealt with through mitigation measures in CCAMLR as well as the creation of the Agreement on the Conservation of Albatrosses and Petrels (ACAP) to deal with birds outside the Antarctic area, this emphasises the need for better understanding of seabirds and fisheries management in the Southern Ocean. This will help to ensure that the effects of overlaps (or potential overlaps) of target species and areas between seabirds and fisheries can be mitigated or avoided.

Conclusions

Technology gaps and challenges

Whilst technology has advanced a long way, particularly in the last 50 years or so, there are still areas which could be improved. Some studies (e.g. Ballard *et al.* 2010; Hart & Hyrenbach 2009; Phillips *et al.* 2005; Quillfeldt *et al.* 2012) use more than one tag during a study, sometimes with individuals carrying more than one tag. If tag technology could be improved so that single tags could integrate more sensors this would reduce the need for this (and reduce handling times as well).

Challenges that remain include increasing battery life, minimising devices size and mass and to “develop inexpensive silicon-based technologies (ASIC)”, increase transmission rate of data to satellites, reduce geo-location errors, develop other types of methods for data recovery and improve methods for inferring behaviour from tag data (Bograd *et al.* 2010). One of the ways that devices could be miniaturised further is by reducing battery size (as batteries are often the largest part of the device (Bridge *et al*. 2011; Wilson & Vandenabeele 2012)). Continuing to miniaturise tags is important as currently only 150 of the 10,000 known bird species are large enough to have PTTs attached (which currently have a minimum size of 5g) (Meyburg & Meyburg 2009). Linking tracking data with environmental data still remains a challenge (Adams & Flora 2010), as does concurrently advancing the tag technology and tag size (Hazen *et al*. 2012).

Tag attachment is also not straightforward. This is because the supplier manufacturers do not supply the attachment equipment, such as glues, bands, cable ties and in some cases three or more different companies are involved in supplying the equipment to attach the tag (as is the case with Ballard *et al.* (2010)). Having the manufactures supply the attachment equipment may not be the solution as the engineers designing the devices may not be familiar with the species that are being studied. However, a more centralised system for obtaining the different equipment involved may be a potential solution to this if such a system is not already in place.

Research and knowledge gaps

Whilst our knowledge and understanding of seabirds has increased dramatically, particularly in the last few decades, there is still much that is not known or understood fully. This includes the relationships between foraging behaviour of seabirds and the density and availability of their prey (Bost *et al.* 2008). There are still gaps in our understanding of seabird ecology (Hazen *et al*. 2012), some gaps which need further tag improvement before they can be filled, particularly in regards to smaller species. Some of the many questions that still need to be answered in terms of conservation and management for seabirds were outlined in Lewison *et al. (*2012). These questions were grouped into six categories including: population dynamics, at-sea spatial ecology, and trophic direct effects of fisheries. Lewison *et al.* (2012) do not prioritise the questions that they have outlined in their paper, but some of the questions in their paper include: What is the form and importance of population structure?; how can we address knowledge gaps in at-sea distribution?; and “what are the roles of seabirds in communities and food webs?

Ethical considerations

Factors to be considered

In terms of studying seabirds, particularly in regards to device attachment, there are a number of ethical considerations to take into account. Considerations for tag attachment should include how they can compromise (or change) the seabirds' behaviour, physiology or energetics (Vandenableele *et al.* 2013). Some of the ways that the seabird can be negatively affected is through impacts on swimming ability (for penguins) (Lyver *et al.* 2010) and loss of streamlining (which increases energy expenditure) (Vandenableele *et al.* 2013) and an altered centre of mass (Adams *et al*. 2009). These impacts can also impact upon breeding success (Lyver *et al.* 2010). Adams *et al*. (2009) found that the attachment of tags on sooty shearwaters (*Puffinus griseus*) negatively impacted on the breeding success of this species, including a decline in survival rates and an increase in the likelihood of longer trip durations and desertion of nests. Assessing the risks of the potential impacts of tag attachment during studies is a key issue as most studies are done during the breeding season.

The 3% rule and its limitations

The relation of the device's weight to the seabird's total weight also needs to be considered. Phillips *et al.* (2003) (in Adams *et al*. 2009) advised that device weight should not exceed 3% of the body mass of breeding procellariiform seabirds (e.g. albatrosses and giant petrels). A study by Vandenableele *et al.* (2013) found that overall studies did adhere to the '3% rule'. The weight limit however is not consistently applied with some authors (e.g. Bridge *et al*. 2011) referring to it as the 3-5% rule. Given that the study by Adams *et al*. (2009) found that even tags less than 3% of a seabirds weight (in this case a sooty shearwater) can still have a negative impact, whilst other studies have reported no impact (Phillips *et al.* 2005, on black-browed albatrosses), this issue needs to be carefully considered.

It is possible that the weight of tag depends on the size of the bird being studied with large birds being less susceptible to the additional weight than smaller birds are. It may be that the rule varies between species, in which case further research, is needed. However, it should be noted that Wilson and Culik (1992) (in Adams *et al.* 2009) concluded after their study that streamlining was more important for penguins than mass (Adams *et al*. 2009). Therefore it is very possible that there is no absolute rule for maximum weight of a device, but that the size may need to be determined on a case-to-case basis.

The future

Tags are continuingly being made smaller with, larger memory sizes, lower power consumption, more sensors, higher accuracy in location fixes, data collected and cheaper technology. More questions and uncertainties are being addressed which is helping to fill in the knowledge gaps which is improving the way that conservation and management can happen. In terms of ethics, while there is some evidence that seabirds can be negatively impacted by attached devices, the benefits of the research need to be taken into consideration. However, improving satellite technology is resulting in tags that are increasingly less intrusive and have longer ranges and duration which reduces both human and tag impacts upon seabirds.

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