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Biologging Research in Japan

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1. Introduction

Recent years have brought us face-to-face with various ocean-related problems that demand resolution. Among them are responses to climate change, preservation of biodiversity, management of fishery resources, debris, and underwater noise. One tool that can help solve these problems is "biologging." Biologging is the practice of attaching devices to animals and recording how they live and information about their environments (Figure 1). The term "biologging" originated in Japan, being coined at the first International Bio-Logging Symposium in Tokyo in 2003. Biologging was defined at the symposium as the "investigation of phenomena in or around free-ranging organisms that are beyond the boundary of our visibility or experience" (Boyd et al. 2004). In this paper, I will discuss possibilities for using marine animals as "observation platforms" in Japan, the characteristics of biologging research undertaken by Japanese researchers thus far, and examples of how biologging in Japan is helping to solve ocean issues. I will then conclude by considering future prospects for biologging research.

Figure 1: An Antarctic fur seal with a biologging device

2. Possibilities for Using Marine Animals as "Observation Platforms" in Japan

With a long longitudinal length (approximately 1,500 km), the Japanese archipelago hosts diverse environments that have been subjected to various biologging studies. To date, biologging field studies of marine animals have been conducted in at least 56 locations in Japan (Figure 2), and at least 52 species of animals have been targeted. They include five mammal species, five bird species, two reptile species, 36 fish species, and four species of invertebrates (crabs and shrimps). These figures demonstrate how biologging research is being conducted extensively throughout Japan, and how its focus is not limited to any

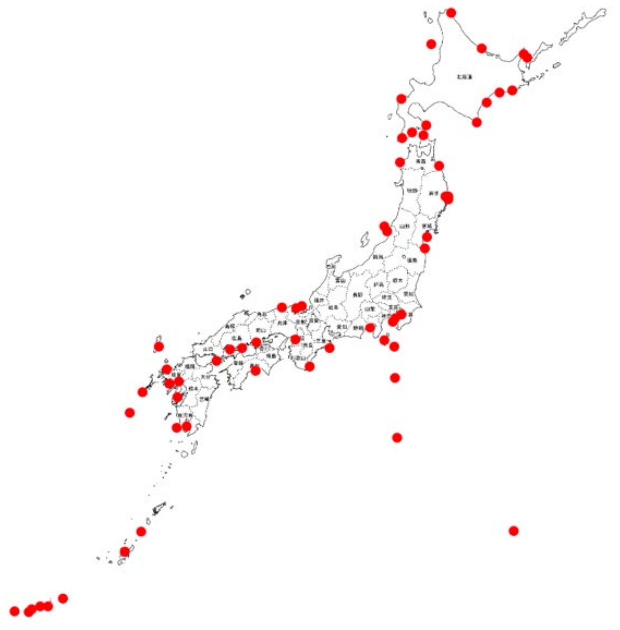

Figure 2: Biologging field studies targeting marine animals that were conducted in Japan (red dots). The figure shows how biologging has been used throughout Japan, from Hokkaido to Okinawa and the Ogasawara Islands.

particular sea areas or animals. Various marine animal species gather environmental data as they move about, without being confined to specific locations, and hence can become useful “observation platforms” in many areas of the country.

When using marine animals as platforms, it is important to have information on the ranges of their vertical and horizontal movement. The animal that typically comes to mind when considering vertical movement is the sperm whale, which dives to depths in excess of 1,000 meters (Amano and Yoshioka 2003, Aoki et al. 2007). However, many other species also come and go between the surface and depths ranging from around several tens to several hundreds of meters. They include the loggerhead turtle (which goes down to 340 meters; Narazaki et al. 2015), rhinoceros auklet (50 meters; Kato et al. 2003), whale shark (1,400 meters; Nakamura et al. 2020), and ocean sunfish (200 meters; Nakamura et al. 2015). As for horizontal movement, tracking records (based on straight-line distances after device attachment) have shown the streaked shearwater going 900 km in several days (Yoda et al. 2014), Pacific bluefin tuna going 1,400 km in 16 days (Itoh et al. 2003), chum salmon going 2,800 km in 2.5 months (Azumaya et al. 2016), and loggerhead turtles going 2,800 km in one year (Narazaki et al. 2015). Although it is not always possible to track these ranges, as there are differences among individuals in terms of diving depth and travel distance, animals that move extensively in vertical and horizontal directions can be useful as observation platforms.

3. Characteristics of Biologging Research by Japanese Researchers

Here I briefly describe the devices used in biologging. A broad range of parameters is measurable with the devices used in current biologging. They include depth (pressure), swimming speed, acceleration, magnetism, horizontal position (Global Positioning System [GPS]), heart rate, environmental temperature, salinity (electrical conductivity), dissolved oxygen, illumination, sound, and images (cameras and echo-sounder) (Table 1). These devices have led to advancements in research on animal physiology and behavior and, further, made it possible to monitor the environments that animals encounter. The devices that are attached to animals are largely divided into two types: storage-type devices (data loggers) and transmitter-type devices (radio transmitters, sound wave transmitters, and satellite-compatible transmitters). Data loggers can record a vast amount of data, including video, sound, and acceleration. However, they must be recovered to obtain their stored data. On the other hand, transmitters need not be recovered to obtain their data, as the data are received as transmitted signals. However, the amount of information that can be transmitted using radio waves and sound waves is limited, making the acquisition of large amounts of information impossible. Thus, only simple parameters, such as water temperature and depth, are handled. There are devices that combine both the storage and transmission approaches, and it is possible to acquire data via radio waves or sound waves by using algorithms built into the device to convert, thin, and simplify large amounts of accumulated data. But even so, a far greater amount of information can be obtained when the device is recovered. Detailed descriptions of the devices used can be found in the books “Baiorogingu: Dobutsu-tachi no Fushigi ni Semaru" (Biologging: Probing the Mysteries of Animals) and “Baiorogingu 2: Dobutsu-tachi no Shirarezaru Sekai wo Saguru” (Biologging 2: Exploring the Hidden World of Animals). In reality, biologging done using a data logger is often called “biologging,” while that using a transmitter is often called “biotelemetry.” However, in this paper, I refer collectively to all methods that involve attaching a device to an animal as “biologging.”

Table 1: Examples of sensors built into biologging devices and obtainable information

Sensor	Information	What is learned
Pressure	Depth, altitude	Dive duration, dive depth, flight altitude
Temperature	Environmental temperature	Water temperature, air temperature, body temperature, stomach temperature
Acceleration	Acceleration	Movement, posture
Propeller	Speed against current	Swimming speed
Quantity of light	Environmental illuminance	Illuminance, sunshine duration, sunrise/sunset time, distribution of luminous prey, horizontal position information
Sound	Audible sounds, ultrasound	Sounds of calls, location of sound source, swimming speed, chewing sounds
Magnetism	Geomagnetism	Body orientation
Electric potential	Heartbeat, myoelectric activity, brainwaves	Heart rate, muscle activity, brain response to external stimuli, etc.
Video	Still images, video	Environment seen by the animal, feeding information, conditions of plastic garbage
GPS	Horizontal position	Horizontal position, speed of the ground
Electrical conductivity	Environmental salinity	Salinity
Blood	Blood	Blood hormones, blood oxygen level, etc.
Echo-sounder	Echo-sounder	Shadows of prey species
Dissolved oxygen	Environmental dissolved oxygen	Dissolved oxygen

Among the outcomes of Japanese biologging research, one that deserves particular attention is the world's first use of acceleration sensors to shed light on animal behavior (Tanaka et al. 2001, Yoda et al. 2001, Sato et al. 2002). Acceleration is normally recorded at a sampling interval of 10-100 Hz (10-100 times per second) or higher, which makes it possible to ascertain animals' detailed movements. Acceleration recordings include static acceleration (low-frequency component), which varies with posture angle and other forms of inclination, and dynamic acceleration (high-frequency component), which varies with fin and head movements. From the low-frequency component, it is possible to determine the conditions of standing or lying down, posture when lying down (e.g., facedown, faceup, sideways), and, in the case of diving animals, the body axis angle when diving or surfacing. Obtained information is also used to understand resting behavior (Yoda et al. 2001, Mitani et al. 2010, Watanabe et al. 2015). The high-frequency component is used to identify fin and wing movements (Tanaka et al. 2001, Sato et al. 2002, Sato et al. 2003, Watanuki et al. 2003, Aoki et al. 2012, Narazaki et al. 2013). From the movements of the fins and wings, it is possible to estimate the amount of energy consumed for swimming and flying (Sato et al. 2013), and from the frequency of stroking during diving, it is possible to estimate the animal's body condition (which here refers to "state of health," as a fatter animal is considered to be a healthier animal) (Sato et al. 2003, Watanabe et al. 2006, Adachi et al. 2014, Narazaki et al. 2018, Aoki et al. 2021). Furthermore, events in the animal's predation are detected from rapid movements of the head and mandible as well as violent movements of the entire body (Suzuki et al. 2009, Naito et al. 2009, Iwata et al. 2012). Because the amount of acceleration data obtained is enormous, a tool for analyzing acceleration called "Ethographer" was developed specifically for biologging data analysis (Sakamoto et al. 2009). Ethographer is a macro program that operates on the numerical analysis software IGOR PRO (WaveMetrics, Oregon, USA). It can classify animal behavior into swimming, feeding, resting, flying, walking, and other activities based on information on the period and intensity of acceleration at an arbitrary time scale (such as every second). Heretofore, long-term recording of acceleration with short sampling intervals has been difficult due to the limited amount of data that devices can store. To solve this problem, a device was developed that records as events only specific signals measured by an acceleration sensor. It successfully records animal predation events over periods of several months (Naito et al. 2013).

Many studies are also conducted using video. In studies of feeding, video can record direct evidence of what an animal feeds upon as well as how much it eats and how it eats. As examples, video has shown whales plunging into schools of krill (Akiyama et al. 2019), penguins pecking at krill one by one (Watanabe et al. 2013), seals feeding on copepods (zooplankton) and small fish (Watanabe et al. 2020), sea turtles catching jellyfish (Narazaki et al. 2013), sharks chasing fur seals (Watanabe et al. 2019), and seabirds being fed by humans (Yoda et al. 2012). Because wild animals rarely show themselves resting in a vulnerable state, observing their resting behavior has been problematic. However, here too, video is proving useful in understanding the resting behavior of wild animals. For instance, video has captured sea turtles resting on the seafloor (Fukuoka et al. 2016) and whales resting underwater rather than on the surface (Iwata et al. 2021). Video is a powerful tool for revealing the ecology of various animals. However, recording times are currently limited to between a few hours to a dozen hours due to limitations of battery capacity. Thus, as in other areas, the development of devices capable of long-term recording will be welcomed in efforts to visually monitor ocean environments.

In the ways described above, the use of acceleration sensors and video has shed light on the complex ecology of marine animals. Information on feeding hotspots and habitats is important for conservation in the conduct of such human activities as fishing and ocean development. Obtaining information on the resting habits of marine animals, in particular, is difficult with methods other than biologging, and consequently such information tends to be scarce. It is therefore anticipated that more and more information will be collected through biologging in the future. Understanding the ecology of marine animals will lead to better conservation of marine ecosystems, which in turn will lead to the resolution of ocean issues.

4. Examples of How Biologging in Japan is Helping to Solve Ocean Issues

In the discussion above, I described how shedding light on animal ecology through biologging leads to better conservation of marine ecosystems. In this section, I will introduce efforts to monitor the ocean’s physical environment and to monitor marine debris, including plastics, as examples of research in Japan through which biologging has made direct contributions to the resolution of ocean issues.

To accurately grasp the changes in marine environments that are associated with climate change, it is necessary to monitor the various physical environments of the ocean in as many regions as possible. The conventional methods for observing the ocean's physical environments have involved using observation vessels, satellites, and drifting buoys. While observation vessels can acquire various parameters and detailed data, they are costly and have difficulty conducting continuous observations in terms of space and time. Satellites have the advantage of being able to acquire planar, wide-area data. However, they can only measure data on the surface of the water and have difficulty acquiring underwater data. And drifting buoys can acquire a broad range of data, but their observations of sea areas are dependent on the vagaries of the current. In recent years, biologging has been shown throughout the world to be a powerful tool for monitoring the ocean’s physical environment

(Harcourt et al. 2019). Biologging's advantages include the ability to obtain continuous data spatiotemporally in both horizontal and vertical directions, and the ability to acquire data in areas that are difficult for ships to reach, such as those directly under typhoons and in areas of sea ice. On the other hand, disadvantages include the fact that obtainable data are animal-dependent, and that few continuous surveys conducted over several years exist. Examples of biologging in Japan include observations using seabirds and sea turtles as platforms.

Attaching GPS data loggers to streaked shearwaters, a species of seabird, can identify their paths as they drift on the ocean's surface. This information is being used to estimate the direction and speed of ocean currents of the surrounding surface (Yoda et al. 2014). Currents that were estimated from such drifting paths matched well with those observed by observation vessels, and medium-sized eddies that were estimated from the drifting paths matched with those estimated from satellite data (Yoda et al. 2014). Furthermore, it has been demonstrated that inputting seabird drift paths and cargo ship navigation records into an ocean current prediction model improves the accuracy of ocean current predictions (Miyazawa et al. 2015). The streaked shearwaters' flight speeds can be calculated from locational information obtained from their GPS data loggers. From this, the direction and speed of the sea winds that the birds experienced are estimated based on the assumption that their flight speed is influenced by wind relative to their direction of travel (Yonehara et al. 2016). Wind directions and speeds estimated from the flight of streaked shearwaters are shown to have a strong correlation with satellite-estimated wind information (Yonehara et al. 2016). Surface currents and sea winds estimated from the path data of seabirds can provide information at detailed time scales that cannot be obtained by satellites (which conduct observations several times a day). Additionally, satellite-based observations face the challenge of being unable to estimate sea winds within 100 km of coasts because rocks and other features near coasts scatter radio waves (Pickett et al. 2003). Thus, it is hoped that seabirds will come to serve as observation platforms that supplement conventional ocean observation data.

In a study that attached satellite-compatible transmitters to loggerhead turtles that visit the Sanriku coast, observations of location, depth, and water temperature were made for a maximum of 403 days. The loggerhead turtles swam as many as 2,600 km or more to the east from their release site, demonstrating the potential for wide-area marine environmental monitoring by sea turtles (Narazaki et al. 2015). In a study using similar data, assimilating data for vertical profiles of water temperature obtained from sea turtles into a prediction model provided a more accurate picture of ocean conditions in the Oyashio-Kuroshio confluence (Miyazawa et al. 2019). It is suggested that the results will be useful in predicting typhoon paths (Domingues et al. 2019). In an example of research conducted outside of Japan, it was shown that inputting data from olive ridley sea turtles in West Papua, Indonesia, into seasonal prediction simulations improves the accuracy of seawater temperature fluctuation predictions several months into the future (Doi et al. 2019). Globally, most of the oceanographic observations conducted using animals as platforms have targeted polar and cold regions; such observations tend not to be conducted in tropical and temperate regions (Harcourt et al. 2019). One possible reason for this is that the model animal for use as an animal platform in such observations is the seal (Boehlert et al. 2001, Fedak 2004, Biuw et al. 2007, Charrassin et al. 2008, Ohshima et al. 2013). Sea turtles have a wide three-dimensional behavioral range that extends both horizontally and vertically, and they are expected to play a more active role as a model animal platform for oceanographic observations in tropical and temperate zones.

In recent years, marine pollution caused by plastic and other debris has been a matter of concern (Jambeck et al. 2015). Methods for surveying marine debris include visual observations from ships (Barnes and Milner 2005, Ryan et al. 2009), observations by submersible (Galgani et al. 1996, Barnes et al. 2009, Chiba et al. 2018), and collection using towed nets (Barnes et al. 2009, Ryan et al. 2009). Visual observations are made on the ocean's surface, while submersibles are mainly used on the seafloor. Although towed nets can be used for observations from the surface down to the seafloor, they can only be used at one depth zone at a time and therefore require a considerable amount of labor. Ascertaining trash drifting in the water (i.e., the space between the surface and the seafloor) is difficult using conventional observation methods, which makes it necessary to find a more effective observation method. Sea turtles are animals that breathe on the surface and feed and rest in the water or on the seabed. Given these characteristics, attaching biologging devices to them to observe marine debris is a conceivable approach. In fact, in a study that involved attaching video cameras to sea turtles, plastic bags were recorded drifting in the water as many as 46 times in 113 hours of filming time (Fukuoka et al. 2016). This suggests that sea turtles and other diving air-breathing animals (i.e., marine mammals and seabirds) can serve as useful platforms for surveying trash distributed vertically from the surface down to the seafloor. The study also revealed differences in animal species' responses to trash, showing that green turtles, which feed mainly on algae, mistakenly ate plastic bags, while loggerhead turtles, which prey on jellyfish and other moving things, passed by plastic bags without eating them (Fukuoka et al. 2016). Trash in the ocean has been reported to affect many marine organisms, including higher-order predators (Gall and Thompson 2015). Clarifying each animal species' reaction to trash is necessary if we are to properly understand the impact of trash in marine ecosystems. Biologging-based observations are an effective means toward this end.

5. Future Prospects for Biologging Research

Biologging is useful for more than just the activities mentioned above—namely, elucidating the ecology of animals, monitoring the physical environment of the ocean, and surveying marine debris. It also plays a role in the monitoring of toxic chemical pollutants (Ito et al. 2013), in the gathering of information on fish ecology that is necessary for fishery resource management (Tomiyasu et al. 2018), and in countermeasures against fishery damage (Masubuchi et al. 2019). Thus, we are beginning to see biologging's usefulness in solving various ocean-related issues. As the next step, we must share biologging data in order to enhance biologging's effectiveness in solving such issues.

By collecting and analyzing data from multiple animal species, biologging research has led to the discovery of laws regarding marine animals' movement abilities in general and to the identification of animals that deviate from those laws (Sato et al. 2007, Watanabe et al. 2011). Moreover, as was mentioned in the preceding section, incorporating biologging data into models for predicting the physical environments of the ocean can increase the precision of ocean current predictions and provide a more accurate understanding of ocean conditions (Miyazawa et al. 2015, Miyazawa et al. 2019). Studies such as those mentioned here have demonstrated that sharing and integrating biologging data can produce new results, regardless of the field. To share, integrate, and otherwise use biologging data effectively, it will be necessary to know what data exist and where they exist. A database of biologging data would be useful in this respect. At present, Movebank is the world's largest biologging database (Campbell et al. 2016). Movebank is a vast database into which movement data for over 1,000 animal species are registered. However, it has only one data category, which consists of horizontal movement data, such as GPS data. Other databases also exist, but their coverage is confined to particular regions, such as Europe or the United States (Campbell et al. 2016). What is needed now is a database without limitations on the information that can be registered. To address this need, the Sasakawa Peace Foundation's Ocean Policy Research Institute is preparing a new database of biologging data and plans to make a trial version available on its website. Although the database places no restrictions on animal species, measurement items, or survey locations, it currently contains only information from field surveys conducted by Japanese researchers. Thus far, biologging contributions toward resolving marine issues have been in a spot-by-spot manner focused on specific survey areas.

Human beings must address ocean-related issues on a global scale. A study focused on Antarctica's Ross Sea—the world's largest marine reserve—collected and analyzed biologging data for more than 4,000 individuals belonging to 17 species of higher-order ocean predators (marine mammals and seabirds) living in Antarctica from sources around the world. Its findings demonstrated that the established marine reserve and the animals' habitats overlap, thereby pointing to the value of the marine reserve that is currently being proposed (Hindell et al. 2020). The Ocean Policy Research Institute will strive to gather global information into its new database so as to promote research of this kind.

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