



TITLE:

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AUTHOR(S):

Kishida, Narumi; Okuyama, Junichi; Arita, Mamiko;
Kume, Natsuki; Fujita, Kento; Nishizawa, Hideaki;
Torisawa, Shinsuke; Mitsunaga, Yasushi

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CASE REPORT

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A validation of abstracted dive profiles relayed via the Argos satellite system: a case study of a loggerhead turtle

Narumi Kishida¹, Junichi Okuyama^{2*}, Mamiko Arita¹, Natsuki Kume¹, Kento Fujita³, Hideaki Nishizawa³, Shinsuke Torisawa¹ and Yasushi Mitsunaga¹

Abstract

Satellite telemetry devices can record movement data of animals along with the environmental data. Such data are relayed remotely via satellite systems, but are constrained by the limited bandwidth availability. A satellite relay data logger (SRDL) that can abstract dive profiles and compress the data for transmission using a broken stick model (BSM) has been widely used in studies on dive behavior and physiology of marine animals. However, there is still uncertainty in the abstracted dive profiles. Here, we aimed to evaluate the certainty of abstracted dive profiles (via satellite communication) in terms of dive performance (dive depth, duration, and dive type) by comparing it with the actual dive data (from the retrieved tag) in a loggerhead turtle deployed with the SRDL throughout a 1.4-year foraging period. There was no significant difference in the maximum dive depth between the retrieved and satellite transmission data; however, there was a slight but significant difference in the dive duration. The dives from both datasets were classified into five types. Inconsistent dive classifications occurred in 1.7% of the data. There was no significant difference in the proportion of time spent diving between the retrieved and satellite transmission data for each type during the common recording period. In monthly scale comparisons, however, a significant difference was detected when the amount of data via satellite transmission was the smallest. Our results demonstrated that the dive data abstracted using BSM almost reconstructed the actual dive profiles with certainty in a loggerhead turtle, although slight inconsistencies were observed.

Keywords: Broken-stick model, *Caretta caretta*, Dive type, Dive classification, Dive profile, Satellite relay data logger, Sea turtle

Background

Central to many behavioral and ecological studies is the need to record the movement and performance of free-living animals. The challenge of making such measurements is particularly acute in marine environments, where animals are often submerged, making direct observations difficult. Consequently, animal-borne electronic

devices play a crucial role in marine vertebrate research. Although animal telemetry devices are able to record information at high temporal and spatial resolutions, in many cases, devices cannot be recovered, meaning that the data they collect must be transmitted using satellite communication or mobile telephone networks. The Argos satellite system (<https://www.argos-system.org/>) provides a satellite communication platform to obtain information from animals that move large distances and where instrument recovery is not possible. Thus, Argos satellite-linked archival animal telemetry devices have rapidly developed (e.g., pop-up satellite archival tags [1]

*Correspondence: okuyamajunichi@gmail.com

² Fisheries Technology Institute, Japan Fisheries Research and Education Agency, Fukai Ota 148, Ishigaki, Okinawa 907-0451, Japan
Full list of author information is available at the end of the article



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and satellite relay data loggers [2]). These tags can record behavioral and environmental information that the marine animals experienced during submergence such as depth, speed, temperature and conductivity, as well as location data.

Many air-breathing divers, such as marine mammals, birds, and turtles, spend a considerable amount of time underwater, performing functions such as traveling, foraging, and resting. To understand their ecology, one must study their dive behavior. A popular approach to the study of dive behavior is the classification of dive patterns based on the characteristics of dive parameters [3–7]. The identification of types of dive behavior is useful for comparing behavioral patterns and activity budgets between individuals and in different spatial and temporal contexts, providing an insight into their overall behavior [5].

Data relayed remotely via the Argos satellite system are constrained by the limited bandwidth availability. Therefore, dive behavior and physiology of marine animals has been studied based on abstracted dive data [7–10]. One of the novel data compression techniques is the broken stick model (BSM) implemented in a satellite relay data logger (SRDL, Sea Mammal Research Unit, UK). BSM can efficiently summarize the curvilinear shape of a dive using a piecewise linear shape with a small, fixed number of vertices or breakpoints [2, 11]. However, ignoring the uncertainty in BSM-derived abstracted dive profiles may lead to incorrect inferences if the BSM output has a substantial error [11]. To our knowledge, there have been only two empirical studies that validate the BSM-derived dive profiles by comparing them with the actual dive profiles of animals (leatherback turtle *Dermochelys coriacea* [12] and elephant seals *Mirounga angustirostris* and *M. leonina* [11]). Therefore, there is still room for verification of the certainty of abstracted dive profiles and the biological and ecological interpretation of dive behavior based on abstracted profiles for other animals.

In this study, we deployed the SRDL on a loggerhead turtle (*Caretta caretta*) to track her post-nesting migration and then physically retrieved the SRDL 2 years after the release. Thus, we obtained the actual dive profile from the retrieved tag in addition to the abstracted dive profile via satellite transmission from the same turtle for a period of approximately 1.4 years. We aimed to validate the following questions: (1) whether abstracted dive data correctly represented dive performance during the tracking period and (2) whether the dives were correctly classified to the same type between actual and abstracted data. We also sought to understand how the abstraction of dive profiles affected the biological and ecological interpretations of dive behavior in a loggerhead turtle.

Methods

This study was conducted on Okinoerabu Island, Kagoshima Prefecture, Japan (Fig. 1). We conducted a survey during the main nesting season (from the end of May to the middle of June) from 2015 to 2018. To examine the post-nesting foraging habitat of loggerhead females, satellite relay data loggers (SRDL, Sea Mammal Research Unit, UK) were deployed on eight nesting loggerhead turtles using epoxy putty, two-component epoxy resin, and glass fiber cloth (Konishi Co., Ltd. Osaka, Japan) after nesting [13]. A female turtle (straight carapace length of 91.5 cm) deployed with an SRDL and released at Wanjo Beach on June 27, 2016, was recaptured at the same beach on May 23, 2018. Thus, SRDL was physically retrieved. We then obtained the dive data of this turtle by directly downloading the retrieved tag data and also from the Argos satellite transmissions.

The turtle was tracked using an Argos satellite system from June 27, 2016, to November 14, 2017. She migrated from Okinoerabu Island to the East China Sea after her reproductive period and then stayed there until the battery of the SRDL expired.

During the tracking period, 2,293 dive data were obtained using an Argos satellite system. These dive data were reconstructed using the five most prominent points of inflection calculated using the BSM during each measured dive [2, 11]. The time and depth of these five points, together with the time of the end of the dive and the dive duration, were transmitted via the satellite during the deployment period. Data for individual dives were generated when the dive depth exceeded 3 m with a duration of >30 s. The raw data of dive depth and duration were assigned to one of unequal 64 bins (depth: 0–340 m, duration: 0–64,800 s) and sent as bin information. Therefore, the dive depth and duration data obtained via satellite transmission were reduced in resolution compared to the actual data from the retrieved tag. In this study, when the depth data assigned to a given bin was obtained, we used the center values of bins to calculate the statistical values (e.g., a depth data of 200–220 bin was regarded as a depth of 210 m).

The retrieved SRDL provided continuous depth and water temperature data recorded at 4-s intervals. In these data, a dive was defined as the one when the turtle submerged underwater deeper than 3 m for more than 30 s (the definition was the same as that for the satellite transmission data). From the retrieved SRDL, 30,074 dive data were obtained from July 9, 2016, to December 3, 2017. Dive data during the first 12 days from June 27, 2016, were not obtained because they were overwritten in the memory of the SRDL owing to the limitation of storage capacity.

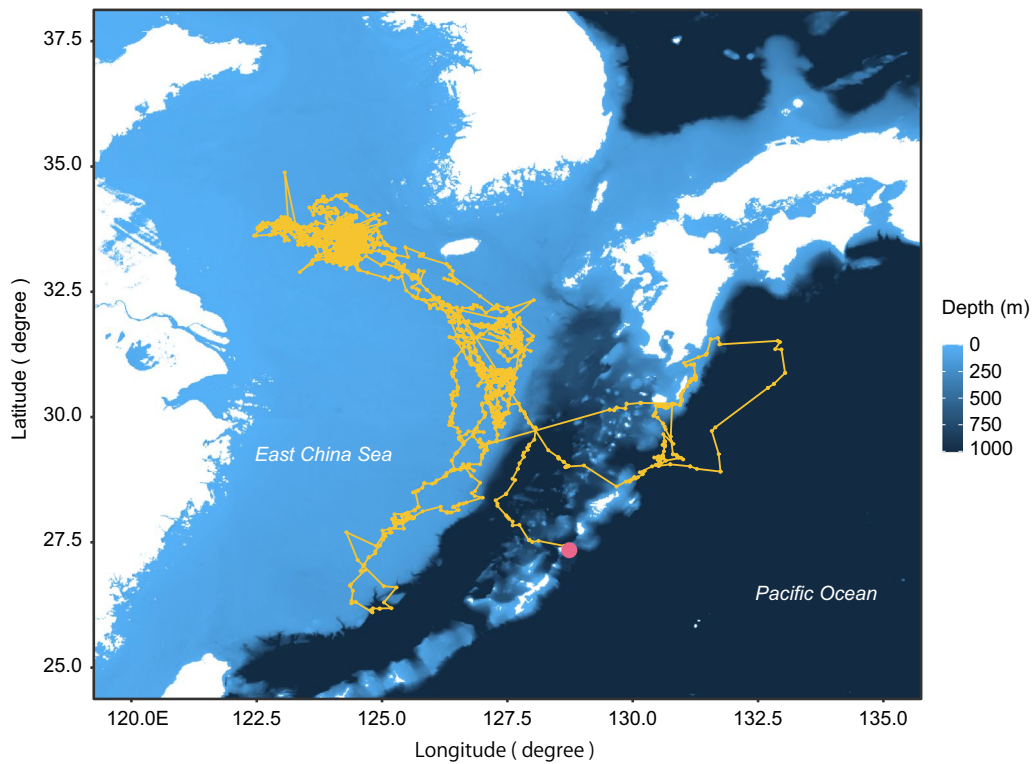


Fig. 1 A map of the study area. The yellow line represents the migration route of a female loggerhead turtle. The red circle represents the location of Okinoerabu Island

In this study, the dive data obtained via satellite transmissions and the retrieved tag was visually classified into five types based on the shape of the dive profile. The classification was based on previous studies investigating the dive behavior of loggerhead turtles (Fig. 2) [3, 6]. A Type

1 dive consists of descents, flats, and ascents, and is often associated with diving behaviors such as resting and foraging on the seafloor [3, 4, 10]. A Type 2 dive consists of a descending dive followed by an immediate ascent, which is often observed during migration and is considered

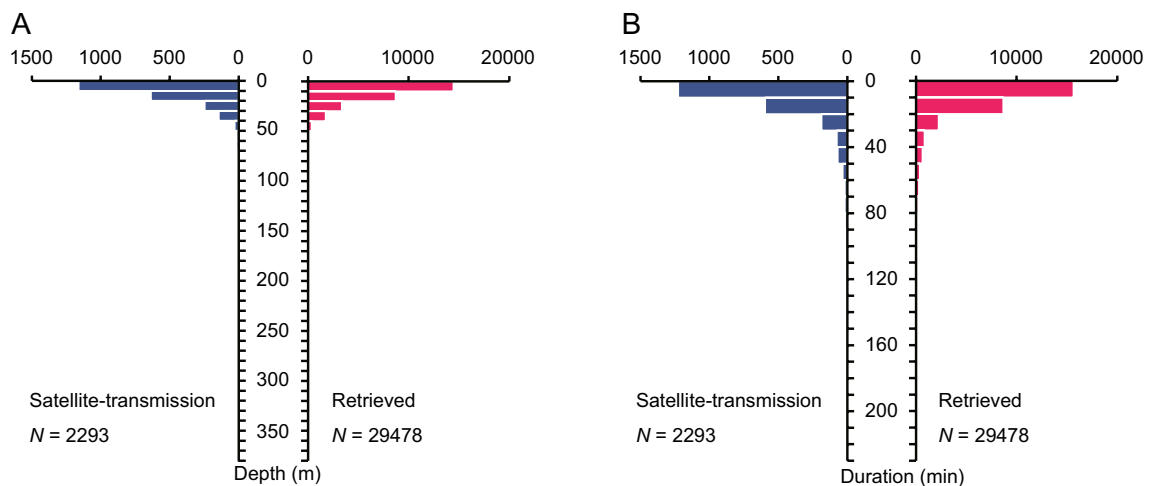


Fig. 2 Comparison of satellite transmissions and the retrieved dive data. A comparison of the maximum **A** dive depth and **B** dive duration between the satellite transmissions and the retrieved data from a loggerhead turtle

exploratory [3, 4]. A Type 3 dive consists of a descent, gradual ascent, and final ascent, and is often associated with resting or moving at the depth of neutral buoyancy [3, 4, 10]. A Type 4 dive represents a submergence shallower than 6 m [4]. A Type 5 dive refers to a W-shaped dive (a dive with up-and-down undulations in the bottom of the profile), which is considered to be associated with foraging and swimming in the water column in the middle layer [5, 7].

In this study, IGOR Pro ver. 6.1 (Wave Metrics, Inc., Lake Oswego, OR, USA) was used for dive data analysis. To investigate whether there was a difference in the dive patterns recorded between the satellite transmissions and the retrieved tag data, we examined the difference in the proportions of time spent performing each dive type using the χ^2 test. We also examined how accurately the five data points generated using BSM in the satellite transmission data represented the actual dive type. Thus, we extracted the same dives from satellite transmissions and the retrieved tag, and visually compared the dive types between them. Generalized linear modeling (GLM) with a gamma distribution and log link function was used to determine the differences in dive depth and duration between the retrieved tag and satellite transmission. The retrieved tag or satellite transmission was numerically converted using dummy variables (retrieved tag = 1, satellite transmission = 0), and then treated as explanatory variables. The significance of the regression coefficient was assessed using the *t*-test. The lme4 package in R ver. 3.52 (R Development Core Team 2018 [14]) was used to run the GLM analyses.

Results

The female loggerhead turtle tagged with the SRDL nested at Okinoerabu Island, Japan, in June 2016, and left the nesting place and departed for the East China Sea (Fig. 1). She stayed in the East China Sea for 2 years with seasonal migration; she stayed in the northern part of the East China Sea during summer and the southern part during winter [13]. Then, on May 23, 2018, she came back to her initial nesting place at Okinoerabu Island, Japan, for nesting. Thus, we physically retrieved the SRDL from her and obtained the dive data of this turtle by directly downloading it from the retrieved tag and also through the Argos satellite transmission. The SRDL recorded continuous depth and temperature data from July 9, 2016, to December 3, 2017, and sent dive data via satellite transmission from June 27, 2016, to November 14, 2017. Thus, we used both dive data recorded during the common recording period from July 9, 2016, to November 14, 2017, including 29,478 and 2,293 dive data from the retrieved tag and satellite transmission, respectively.

The maximum dive depth (mean \pm S.D.) in the data obtained via satellite transmission was 15.0 ± 17.4 m, with maximum and minimum values of 135.0 m and 3.5 m, respectively (Fig. 2A). Meanwhile, in the data from the retrieved tag, it was 14.7 ± 16.5 m, with maximum and minimum values of 379.5 m and 3.0 m, respectively (Fig. 2A). The GLM demonstrated that there was no significant difference in the data of the maximum dive depth obtained from the retrieved tag and those from the satellite transmissions ($df=31,770$, $t=-1.0$, $P=0.32$).

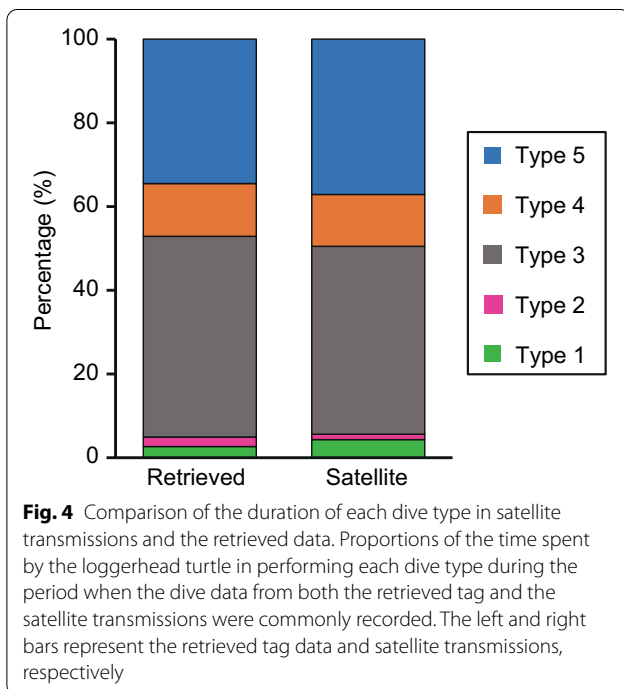
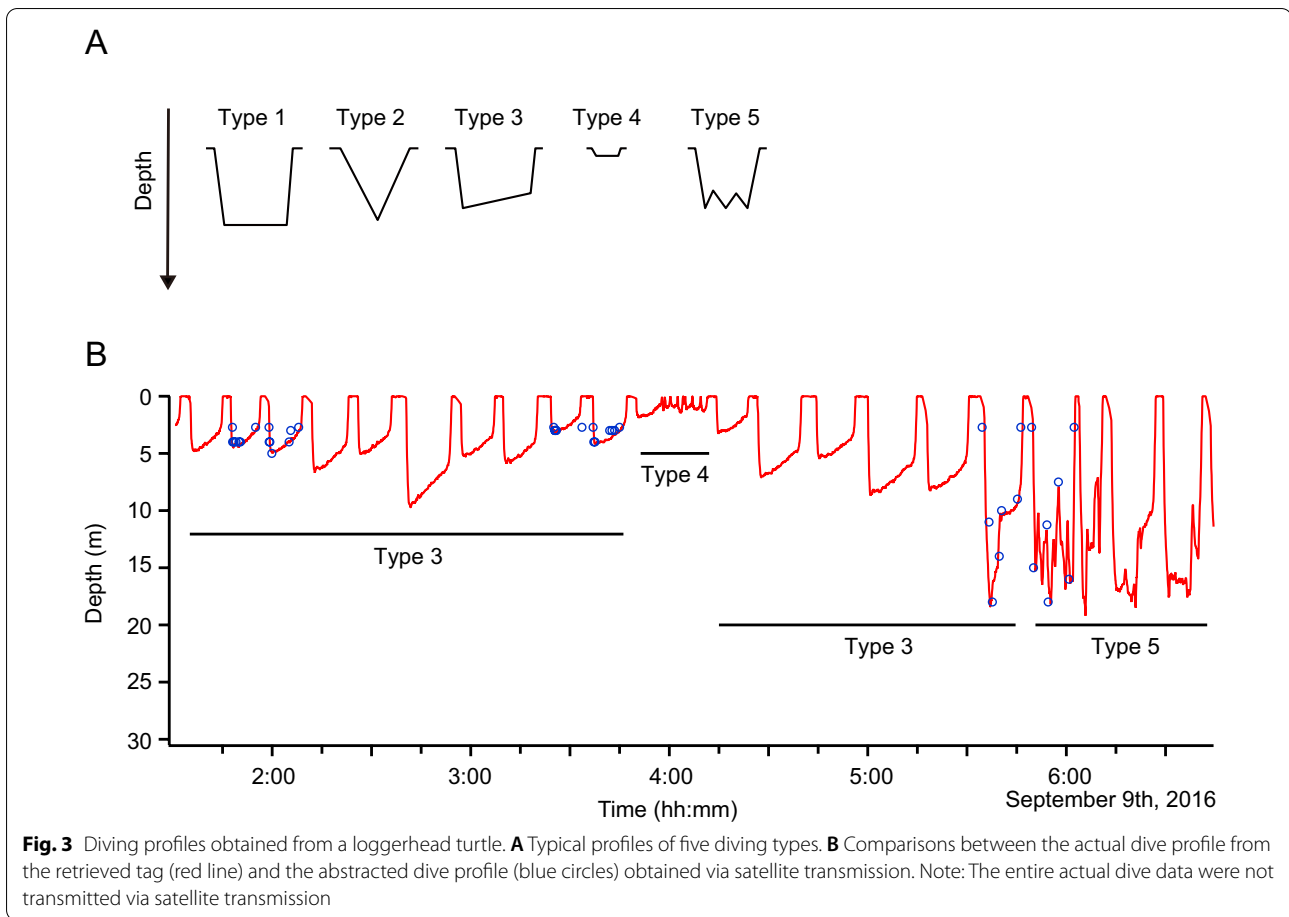
Dive duration (mean \pm S.D.) in the data from satellite transmission was 15.6 ± 23.0 min, with maximum and minimum values of 230 min and 0.6 min, respectively (Fig. 2B). Meanwhile, in the data from the retrieved tag, it was 13.8 ± 18.1 min with maximum and minimum values 221.6 min and 0.5 min, respectively (Fig. 2B). The GLM showed that there was a slight but significant difference in the dive duration data obtained from the retrieved tag and those from the satellite transmissions ($df=31,770$, $t=-4.43$, $P<0.001$).

The dives from both datasets were classified into five types (Fig. 3) based on previous studies (see [Methods](#)). There was no significant difference between the retrieved and satellite transmission data in the proportion of time spent performing each dive type during the common recording period (χ^2 test, $df=4$, $\chi^2=1.52$, $P=0.822$; Fig. 4).

Month-by-month comparisons of the proportion of time spent performing each dive type demonstrated that there were no significant differences between the proportions from the retrieved and satellite transmission data in all months except June 2017 (χ^2 test, $df=4$, $\chi^2=19.6$, $P<0.001$, Fig. 5). A significant difference was observed when the number of data points obtained via satellite transmission was the smallest (Fig. 5).

Pairwise comparison of the dive type for the dives commonly recorded in both retrieved and satellite transmission data demonstrated that 2254 dives (98.3%) were classified as the same dive type, but 39 dives (1.7%) were classified as different types. The classification of different dive types is summarized in Table 1, and the comparisons of dive profiles classified into different types are shown in Fig. 6. The most frequent cases were the ones where Type 5 dive in the retrieved data was classified as Type 3 dive in the satellite transmission data (22 of 39 dives, case A, Fig. 6A), followed by Type 2 being classified as Type 3 (8 of 39, case B, Fig. 6B), and Type 3 being classified as Type 5 (5 of 39, case C, Fig. 6C).

In case A (Table 1, Fig. 6A), up-and-down undulations were observed at the bottom of the actual dive profile in the retrieved data; thus, it was classified as Type 5, but such undulations were not reconstructed in the satellite transmission data, resulting in classification as Type 3.



Similarly, non-reconstruction of the bottom undulation resulted in the classification of Type 5 in the retrieved data to Type 2 in the satellite transmission data (Case D in Table 1, Fig. 6D). In case B, straight surfacing from the bottom was observed in the retrieved data (Type 2), but there were some breakpoints in the ascent phase in the satellite transmission data, which looked like the gradual ascent of Type 3 (Fig. 6B). In case C, the instantaneous up-and-down movements during the gradual ascent in the actual profile caused a wobble shape in the bottom phase of the profile in the satellite transmission data, giving an appearance of the characteristic pattern of Type 5 (Fig. 6C). In case E, the actual dive profile had an intermediate characteristic between Type 2 and Type 3, forming V-shaped submergence with a gradual ascent. The gradual ascent occurred at a depth above 3 m and, thus, was not reflected in the abstracted dive profile obtained from the satellite transmission data (Fig. 6E).

Discussion

This study compared the outputs between abstracted dive data obtained via satellite transmission and actual dive data from a retrieved tag and evaluated the certainty

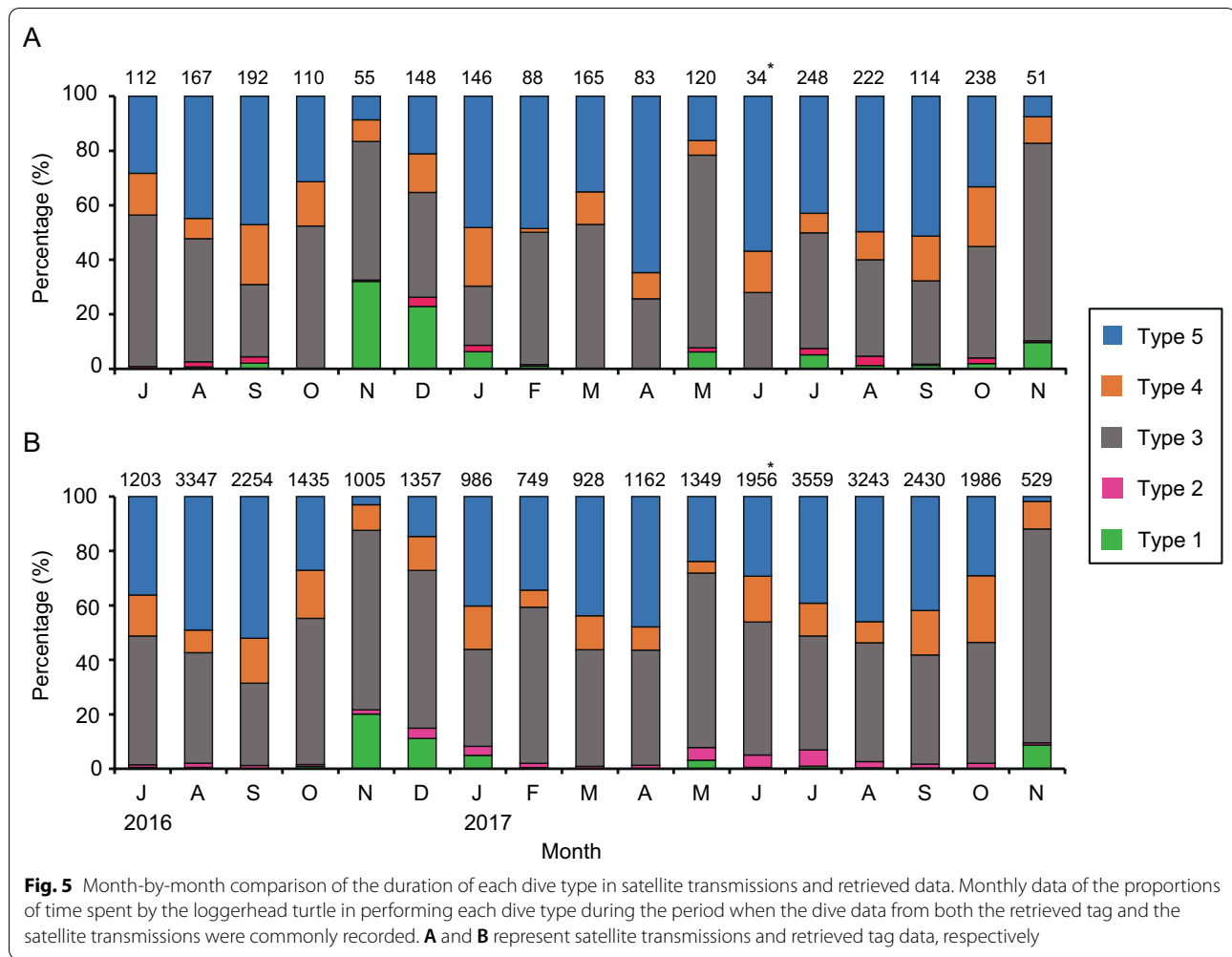


Table 1 A summary of the classification of dive types in retrieved data and satellite transmission data

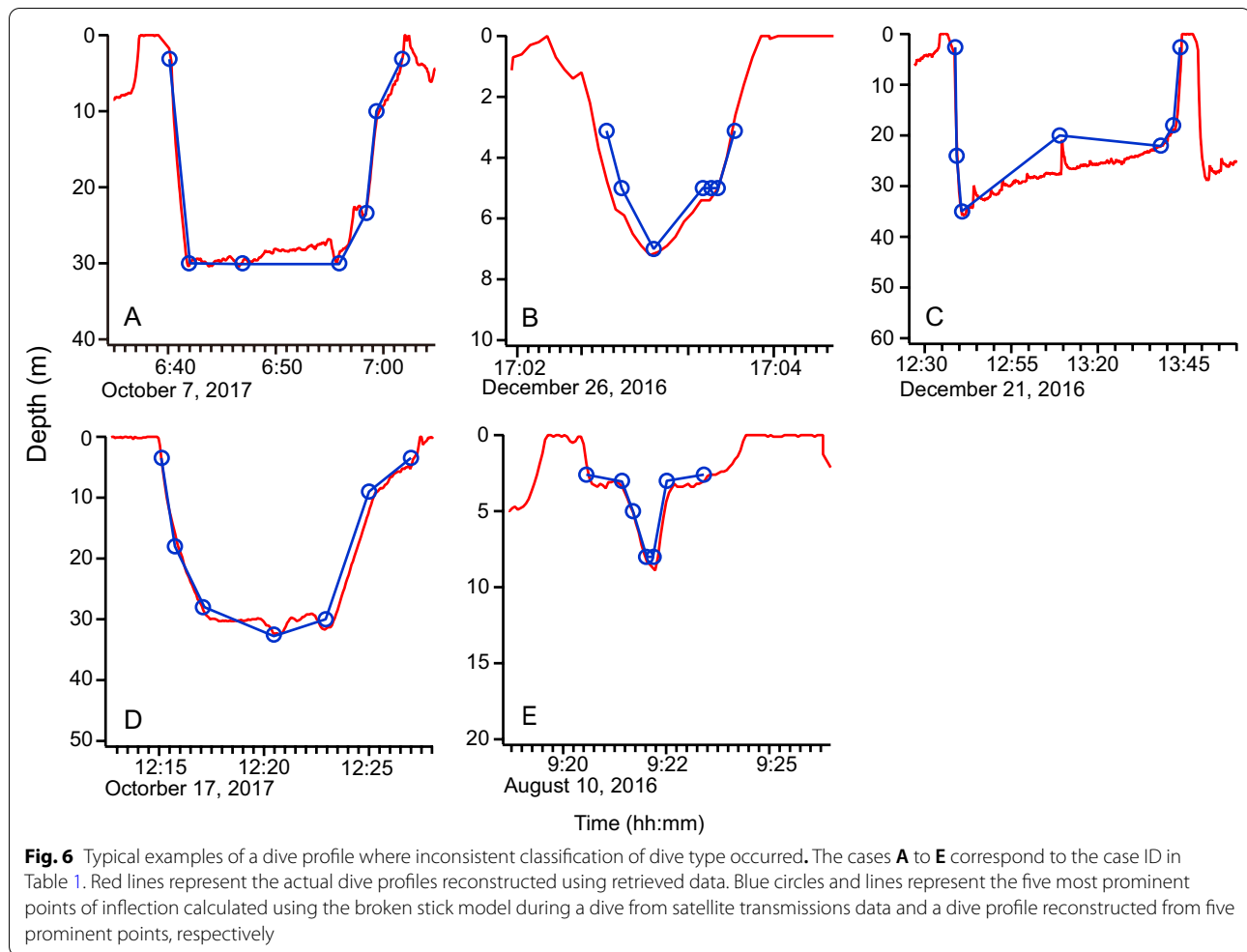
Case ID	Retrieved data	Satellite transmission data	N
A	Type5	Type 3	22
B	Type 2	Type 3	8
C	Type 3	Type 5	5
D	Type 5	Type 2	3
E	Type 3	Type2	1

N represents the number of dive data

of abstracted dive profiles in a loggerhead sea turtle as a case study. Our results demonstrated that abstracted dive data from satellite transmissions almost exactly represented the characteristics of actual dive performance (dive depth and dive type) in a loggerhead turtle. Dive duration was slightly, but significantly, different between them, which was presumably caused by the fact that raw

data of dive duration were sorted into 64 bins in the satellite transmission data, owing to the limitations in the bandwidth of the communication system used to relay data. For instance, the duration of 296 s in an actual dive is sorted into a bin of 240 s in the satellite transmission data, generating a gap of 56 s in dive duration data between the two. The accumulation of such gaps may result in a significant difference in the dive duration. In addition, the gap in the depth and duration may slightly alter the shape of dive profiles and thus cause differences in the classification of dive types between actual and abstracted dive data. However, differences in dive-type classification occurred rarely (1.7% in this study); thus, the gaps would not be a big problem for understanding dive performance from the abstracted dive profile obtained via satellite transmission.

Each dive data enters a transmission buffer within the SRDL, and these data are randomly transmitted for the next 5 days. Therefore, the specific dive profiles obtained via the Argos system were not weighted by the surfacing



behavior immediately after each dive [12]. In fact, the proportion of time spent performing each dive type was not significantly different between the satellite transmissions and retrieved tag data for the entire period. However, in a short timescale (e.g., monthly), some significant differences in dive performance may be detected, presumably due to the small amount of data transmitted. Therefore, researchers should be careful about understanding the dive performance of animals when the data size via satellite transmission is small. The SRDL also transmits a summary data stream containing the mean and S.D. of maximum dive depth and duration of all dives calculated over each a given hour period (24-h period in our study). This summary data would help researchers to understand the dive performance when the dive data via satellite transmission is not enough.

The inconsistency in dive-type classification between the satellite transmissions and the retrieved tag data was mostly attributed to the abstraction of the dive profile by the BSM algorithm (cases A and D); the up-and-down

fluctuations at the bottom of the actual dive profiles were not reconstructed, and the bottom phases were represented as a flat profile in the abstracted profiles. In addition, instantaneous changes in the depth of the actual dive profiles were detected as a breakpoint, resulting in signature movement in the abstracted profile (cases B and C). For case E, the characteristic changes in depth that shape a dive profile occurred at depths shallower than 3 m, while depths over 3 m were defined as a dive in this study. Thus, we were unable to reconstruct the characteristics of the actual dive profile, resulting in inconsistent classification. Moreover, the dive profile in this case had an intermediate characteristic between two dive types, making it more difficult to classify dive patterns correctly.

Conclusions

The dive data abstracted using BSM with five breakpoints almost reconstructed the actual dive profiles, and thus the dive performance in a loggerhead turtle during a foraging period of over 1.4 years, although slight differences

in performance (dive duration, dive type) were observed upon analyzing the data over a short timescale. Our results confirm the certainty of abstracted dive profiles obtained from loggerhead turtles via satellite transmission. The satellite system allows remote collection of data from animals over many months or even years, regardless of their movements. Therefore, the ability to relay accurate behavioral data via a satellite system would have great utility.

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Author contributions

JO conceived and designed the study; NK, JO, MA, NK, KF, and HN. Conducted field research and data collection; NK analyzed the data; YM and ST supported the field research and data analysis; NK and JO drafted the manuscript; KF and HN revised the manuscript. All authors contributed critically to improving the manuscript and read and approved the final manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets analyzed in the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

Deployment of the satellite transmitters on loggerhead turtles nesting on Okinoerabu Island was conducted with the permission of the ordinance for the protection of sea turtles in Wadamari town, Kagoshima Prefecture (No. 28-54, 30-31). The research protocol for this study was approved by the Animal Experimentation Committee of the Fisheries Technology Institute, Japan (2016-003, 2018-003).

Consent for publication

Not applicable.

Competing interests

We declare we have no competing interests.

Author details

¹Graduate School of Agriculture, Kindai University, Nakamachi 3327-204, Nara 631-8505, Japan. ²Fisheries Technology Institute, Japan Fisheries Research and Education Agency, Fukai Ota 148, Ishigaki, Okinawa 907-0451, Japan. ³Graduate School of Informatics, Kyoto University, Yoshida Honmachi, Sakyo, Kyoto 606-8501, Japan.

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