Animal Biotelemetry

METHODOLOGY

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Diving into the past: tools for recovering historic dive traces from film-based time depth recorders using data from Weddell seals

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Abstract

Background Over the past 4 decades, time depth recorders (TDRs) have become an essential tool for research into the previously unexplored diving behavior of marine organisms. Of the early TDRs invented in the 1970s, the Kooyman–Billups TDR was the first to be placed on a free-ranging animal. This device documented behavior for up to 2 weeks using a pressure-sensitive arm that moved an LED light across a rolling window of film, which would later be photocopied and annotated by hand. As TDR technology advanced from film-based instruments to small electronic tags and biotelemetry devices, comparisons of diving behavior measured by the changing devices have been hindered by the difficulty of comparing digital and analog datasets. However, historic analog data from early TDRs contain empirical information on the behaviors of animals that can inform modern studies. Here, we describe a novel computational method for recovering dive records from film-based Kooyman–Billups TDRs deployed on the Weddell seal (*Leptonychotes weddellii*).

Results Our recovery process involved record scanning, image processing, and bias correction. To assess the efficacy of our method, we compared dive statistics from the recovered dive traces with a previous analysis of the same records by hand in 1992, and found no large differences. Our recovery methods are published as open-source code in an R package.

Conclusions This tool will assist in recovering dive data from historic Kooyman–Billups TDRs and from similar devices of this time, which recorded data for at least 14 different species. Recovery of these datasets provides a unique opportunity to examine behavioral change over decadal time scales in ecosystems experiencing direct and indirect anthropogenic activity.

Keywords Biologging, Diving behavior, Marine mammals, Time depth recorders, Weddell seals

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Background

Time depth recorders (TDRs), mechanical devices that record both time and depth, have become an indispensable tool for researching the underwater behavior of diving marine organisms [1, 2]. When initially developed in 1963 by Dr. Jerry Kooyman, the first TDR relied on a modified kitchen timer to record the underwater behavior of an animal diving from an isolated hole for up to 60 min [1]. The Kooyman–Billups TDR was invented in the 1970s and used a roll of film housed within a watertight tube to track the dives of a free-ranging marine mammal for up to 2 weeks [3]. When the animal submerged, a pressure-sensitive transducer arm with a light-emitting diode (LED) at the tip transmitted across a moving window of film. Once recovered, the film was developed and photocopied onto paper. These continuous records were annotated by hand, a process that typically only allowed for the analysis of basic summary dive statistics such as dive depth and duration [4]. Although some of the first deployments occurred on Weddell seals in the Antarctic, this device was also used to study the diving patterns of at least 10 different species (Table 1).

The field of biologging further expanded in the 1980s by the introduction of a recorder developed by Yasuhiko Naito, which logged behavior using a pressure-sensitive diamond-tipped stylus on carbon-coated paper [5]. While mechanically similar to the Kooyman–Billups TDR, the compact design of the Naito recorder allowed for the observation of smaller diving species, such as seabirds [6]. Combined, these devices informed the free-ranging diving activities of at least 14 different species (Table 1) and enabled comparative studies on the behaviors and strategies of diving species around the world [7]. Of the 14 species observed using analog recording devices, 5 are listed as vulnerable or endangered by the International Union for Conservation of Nature (IUCN) [8]. Behavioral data from these early devices provide a unique opportunity to reanalyze the diving activities of at-risk species prior to modern conditions.

Since the invention of these early analog devices, the miniaturization of technology has given rise to the small digital TDRs and satellite-linked TDRs that are now commonly used to study the behavior of cetaceans, pinnipeds, diving seabirds, and marine reptiles over periods of months to years [22–24]. After many prototypes, the transition to continuous digital records started occurring in the late 1980s as computer chips became smaller and more capable [25]. Once long digital records could be captured by TDRs, computerized dive analysis programs and methods were also developed to allow the examination of a more encompassing suite of dive metrics than were previously possible [26–28]. However, this rapid development of technology created a large divide between historic and modern dive records, in part because historic data are not easily digitized, and therefore difficult to compare with newer records [2]. Nevertheless, these records hold valuable comparative datasets from over 40 years ago, and considering notable changes in habitats, recovery of these data would allow for more compelling interpretations of diving behaviors over time and across a wide range of species [29–32]. Here, we develop a novel method to extract the data contained in older Kooyman–Billups TDR records before they fade, deteriorate, or are lost to time. Although the methods we describe here are specific to the Kooyman–Billups TDR, our methods could be applied to digitize records from similar film-based devices of this time (Table 1).

Methods

Data acquisition

Dive records were obtained from Kooyman–Billups TDRs that were deployed on free-ranging adult Weddell seals during the austral summers of 1978, 1979, and 1981 from the McMurdo Sound, Antarctica seal population (77°30' S, 165° E). As initially reported in Castellini, Davis, and Kooyman, researchers attached Kooyman–Billups TDRs to hauled-out and non-pupping adult seals

Table 1 Summary of studies that used analog dive recorders

Device	Species	Year	IUCN listing and population trend
Kooyman–Billups TDR	Northern fur seals (*Callorhinus ursinus*) [9]	1976	Vulnerable; decreasing
	South African fur seals (*Arctocephalus pusillus*) [10]	1977	Least concern; increasing
	Weddell seals (*Leptonychotes weddellii*) [4]	1977	Least concern; unknown
	Antarctic fur seals (*Arctocephalus gazella*) [11]	1977	Least concern; decreasing
	Galapagos sea lions (*Zalophus wollebaeki*) [12]	1980	Endangered; decreasing
	Galapagos fur seals (*Arctocephalus galapagoensis*) [13]	1980	Endangered; decreasing
	California sea lions (*Zalophus californianus*) [14]	1982	Least concern; increasing
	Northern elephant seals (*Mirounga angustirostris*) [15]	1983	Least concern; increasing
	South American fur seals (*Arctocephalus australis*) [16]	1983	Least concern; increasing
	Leatherback sea turtles (*Dermochelys coriacea*) [17]	1984	Vulnerable; decreasing
Naito Recorder	Adelie penguins (*Pygoscelis adeliae*) [5]	1986	Least concern; increasing
	Northern elephant seals (*Mirounga angustirostris*) [18]	1988	Least concern; increasing
	Gentoo penguins (*Pygoscelis papua*) [19]	1988	Least concern; stable
	Macaroni penguins (*Eudyptes chrysolophus*) [20]	1989	Vulnerable; decreasing
	Blue-eyed cormorants (*Phalacrocorax atriceps*) [21]	1991	Least concern; unknown

using straps, epoxy glue, and hog rings [4]. Each seal was released and then recaptured approximately a week later. Following recovery of the device, the Kooyman–Billups TDR depth scale was calibrated by placing the device in a pressure chamber and steadily increasing pressure to 900 pounds per square inch (psi). This calibration process was documented on a roll of film separate from the dive record in 1978–1979, but on the actual dive records in 1981. The film from the device was then removed, developed, and photocopied on a scroll of paper at 7 × magnification, which created a scroll that could be up to 150 feet long. The resulting paper record was annotated by hand for summary dive statistics, which are reported in Castellini, Davis, and Kooyman [4].

For this study, we obtained 19 of the original 34 photocopied paper records. There are 15 records that have already been lost to time, which highlights the urgent need for data recovery efforts. Details of each deployment are provided in the supplementary information (Table A1), and seal IDs align with those documented in Castellini, Davis, and Kooyman [4]. Although Kooyman–Billups TDRs could record behavior for up to 2 weeks, the cold Antarctic temperatures quickly depleted battery life, and records longer than 10 days were only possible by repeatedly deploying instruments on the same individual.

Data recovery steps

Data recovery methods were needed to correct artifacts resulting from how the inner mechanics of the Kooyman–Billups TDR transformed external pressure into an image on a moving strip of film. When the animal began diving and pressure surrounding the device increased, the modified pressure-sensitive Bourdon tube pivoted an LED carrying arm across the film (Fig. 1). The pivot point of this pressure-sensitive arm was located above the lower border of the rolling film, which produced a characteristic left-leaning "arc" across the record during a dive (Fig. 1). To account for variation in the film roll speed and accurately document time across the record,

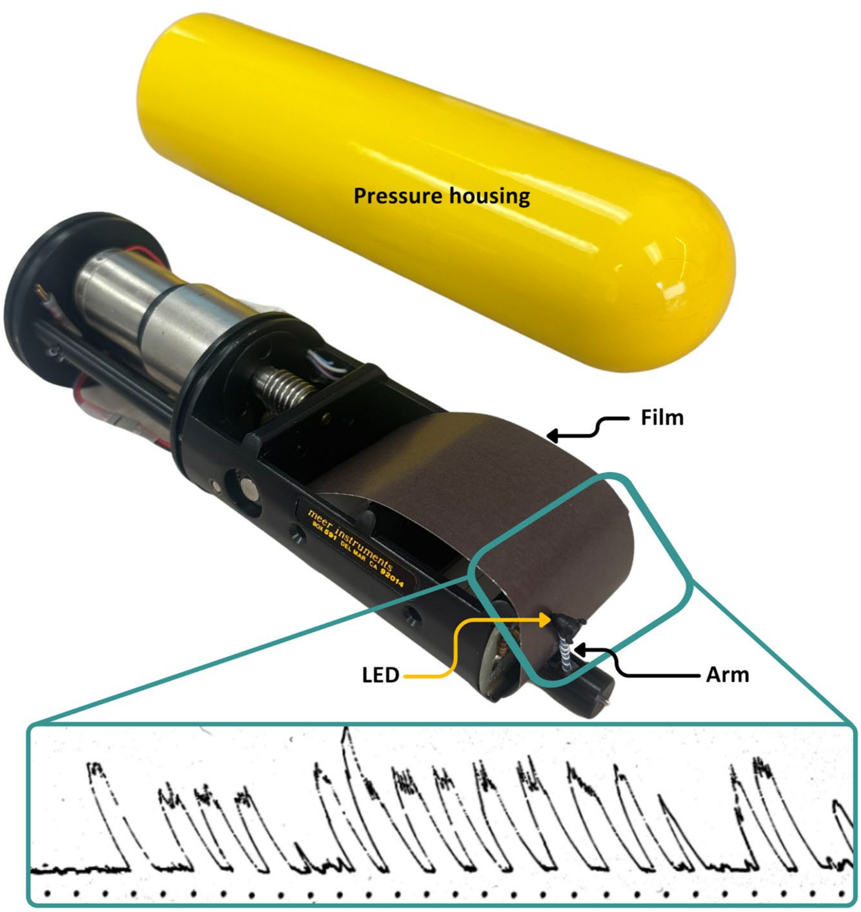

Fig. 1 Deconstructed Kooyman–Billups TDR. Note the position of the LED light (yellow arrow) relative to the film, which pivoted and exposed the film such that the diving behavior of the animal was recorded (bottom). The dive trace exhibits timing dots (at 12-min increments) and the left-leaning arc

a timing circuit was interfaced with a flashing LED light that created a series of timing dots below the dive (Fig. 1) [3]. Based on these characteristics, we developed a set of eight recovery steps. All steps beyond record digitization and image processing are fully automated in our R package:

(1) Manual record digitization to transform the paper record into a digital format.
(2) Image processing and automated centering of the digitized record.
(3) Removal of left-leaning arc.
(4) Zero-offset correction.
(5) X-axis transformation from position into time.
(6) Linear interpolation to create regular date and time series.
(7) Y-axis transformation from position into depth in meters.
(8) Smoothing of the data to remove device noise.

Step one: record digitization

Original paper traces were digitized using a high-speed scanner (NeuraScanner, Neuralog, Houston, TX) typically used for digitizing well log data. This device was capable of continuously scanning long paper records and provided a range of customizable values to capture particularly faint or faded traces. For each record, scanning threshold values were optimized in the NeuraScanner software (version 2017.07) and recalibrated to factory settings with blanks to produce the clearest scan for image processing purposes. Scans resulted in uncompressed black and white image files in tagged image file (tiff) format at 200 dots per inch resolution. Records that lasted longer than a week were scanned in two separate parts and stitched together using NeuraView (version 2021.08.25.1.).

Step two: image processing and record centering

All scanned record images were manually processed using identical workflows in ImageJ (version 1.53o) [33]. First, the scanned record was cleaned by removing stray lines and marks present on the original film and by filling faint or faded portions of the record that were not cleanly captured in scanning. All corrections were completed using the original paper record as reference. The origin coordinates of the record were then defined in ImageJ as the beginning of the dive trace when the TDR was first turned on. Finally, the scale of the scanned record was determined using the distance between two timing dots on the physical record and the "set scale" tool in ImageJ.

After the scale and origin had been set, the exact position of the centroid of each timing dot below the dive trace was recorded using the measuring feature in ImageJ. The resulting x (horizontal distance in cm from origin) and y (vertical distance in cm from origin) data for all timing dots were exported as a comma-separated values (csv) file.

Similar methodology was used to extract the dive trace itself from the scanned records. First, the whole record was cleaned of stay marks using the "despeckle" feature in ImageJ. Then, if the dive trace was extremely thick and/or fuzzy, the trace was skeletonized into a single line down the middle of the trace (see Supplementary Information) [34]. The entire trace was then selected using the wand tool in ImageJ, and the x and y positions of the selection were exported as a csv file.

The resulting two csv files (position of timing dots and position of dive trace) were read and the data within transformed into a uniform format using the "tidy_raw_trace" and "tidy_raw_timedots" functions in the package, recoverKBTDR (version 2.0; available on GitHub: https://doi.org/https://doi.org/10.5281/zenodo.14025657), that we developed in R (version 4.0.2) [35]. Using these functions, the orientation of the record was corrected (i.e., fixing the default values moving in the + y direction from decreasing to increasing) and any duplicate points introduced during image processing were removed. Then, drift in the y-offset from y = 0 in each record that originated due to shifts in alignment as the paper record was fed into the scanner was corrected using the "center_scan" function, which centered the y-values of the timing dots along a user-defined horizontal line. The dive trace was also centered by the same amount.

Step three: removal of left-leaning arc

The Kooyman–Billups TDR documented behavior using a pressure-sensitive arm that rotated around a central pivot point, which created a left-leaning arc across the record. As a result of the arc, there were often two depth (y) measurements that occurred at the same x position during a dive: one during the descent and one during the ascent phase of the dive (Fig. 2). To resolve this issue, the x-values of the trace were transformed using the geometry of the device and the equation of a circle. Since the height of the arm's pivot point (k) above the surface position varied slightly (< 1 mm) between instruments, the exact height was calculated mathematically using the maximum depth of a V-shaped dive as outlined in Fig. 2.

In this process, the length of the pressure-sensitive arm (r; 21.14 cm at the scale of the photocopied record) and the exact height of the arm's pivot point (k) values were then used to transform each point (x_t, y_t) along the dive using the equation of a circle (Fig. 2). Using the length of the arm and the position of the pivot point, the x-value at the surface (x_o) could be calculated. The transformed

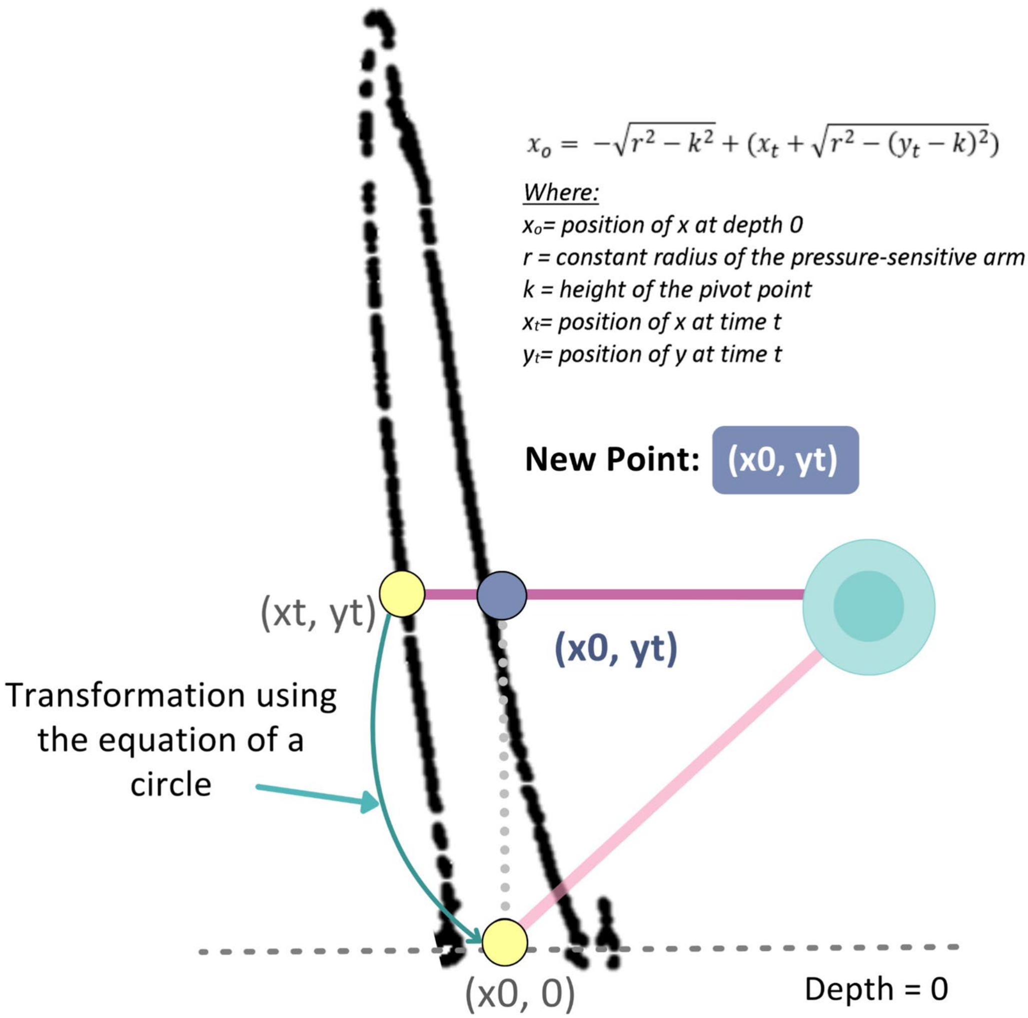

Fig. 2 Explanation of the equation, variables, and measurements used to correct the arc in the records. The left-leaning arc created dive points with overlapping x-values. The final transformation of the arc using the pivot point (teal dot) results in a shifted point (x_o, y_t; outlined in purple), such that the curvilinear nature of the record is removed

point became (x_o, y_t), which removed the curvilinear nature of the original dive trace. The accuracy of this correction was then visually confirmed by applying the arc correction across the entire record, verifying that the dives were not abnormally skewed in any direction. The "remove_arc" function within our R package automatically calculated all (x_o, y_t) values for the dive traces.

Step four: zero-offset correction

Next, records were examined to determine if the dive trace required zero-offset correction to adjust for drift in the pressure reading when the Kooyman–Billups TDR was at the surface. This correction was applied using the "zoc" function from the package, which was modeled after methods within the diveMove R package (version 1.6.0) [36]. This function applied a series of filters across a rolling window (i.e., distance along the x-axis; width of 500 data points) of the record to detect the position of the surface [37]. After the position of the surface was detected, the y-values of the dive trace were adjusted accordingly. The culmination of these efforts produced a file that contained a record that was unbiased along both x (time) and y (psi) axes.

Step five: x-axis transformation

After correcting the left-leaning arc in the records and performing any necessary zero-offset correction, the "transform_x_vals" function can be used to transform the x-axis of the dive record into time using the distance between timing dots. The distance between each set of timing dots was used to create a unique scale to account for slight reduction in film speed due to colder device temperatures. Using this scale, all points along the dive trace were assigned a numeric value that represented time in minutes from the origin using the dplyr R package (version 1.0.7) [38].

Step six: linear interpolation

Although the Kooyman–Billups TDR gathered dive data continuously, the seal often descended or ascended faster than the LED light could document the behavior on the film. This introduced gaps in the time series during the descent and ascent portions of dives, which needed to be corrected prior to dive analysis. RecoverKBTDR's "add_dates_times" function uses the "na.approx" function from the zoo R package (version 1.9) to generate linearly interpolated y-values into record gaps (Fig. 3) [39]. This function also transformed the data into standard time objects using the lubridate R package (version 1.7.20), and trimmed the record to only contain data from when the TDR was on the seal [40].

Step seven: depth transformation

For the 1981 records where the pressure calibration curve was present with the dive trace, the y-values of the dive trace were transformed into depth (m) below the surface. If the trace lacked a psi calibration curve (all 1978–1979 records), then depth was calculated using the maximum depth value that was previously reported for that record as the linear scale for depth [4]. All depth transformations can be automatically applied using the "transform_y_vals" function within the R package.

Step eight: smoothing to reduce device noise

When the seal was at or near the surface and/or hauled out on ice, the tension on the transducer arm was less than when the device was under pressure. In the absence of pressure-induced tension, the transducer arm wobbled slightly which resulted in extra noise at shallow depths [3]. To accurately discern shallow dive behavior from transducer noise, each record was simplified using spline smoothing using the package's "smooth_trace_dive" function. This function smoothed the data such that there was low resolution when the seal was at the surface and higher resolution when the seal was diving. To smooth shallow noise, the caTools R package (version 1.18.2) was

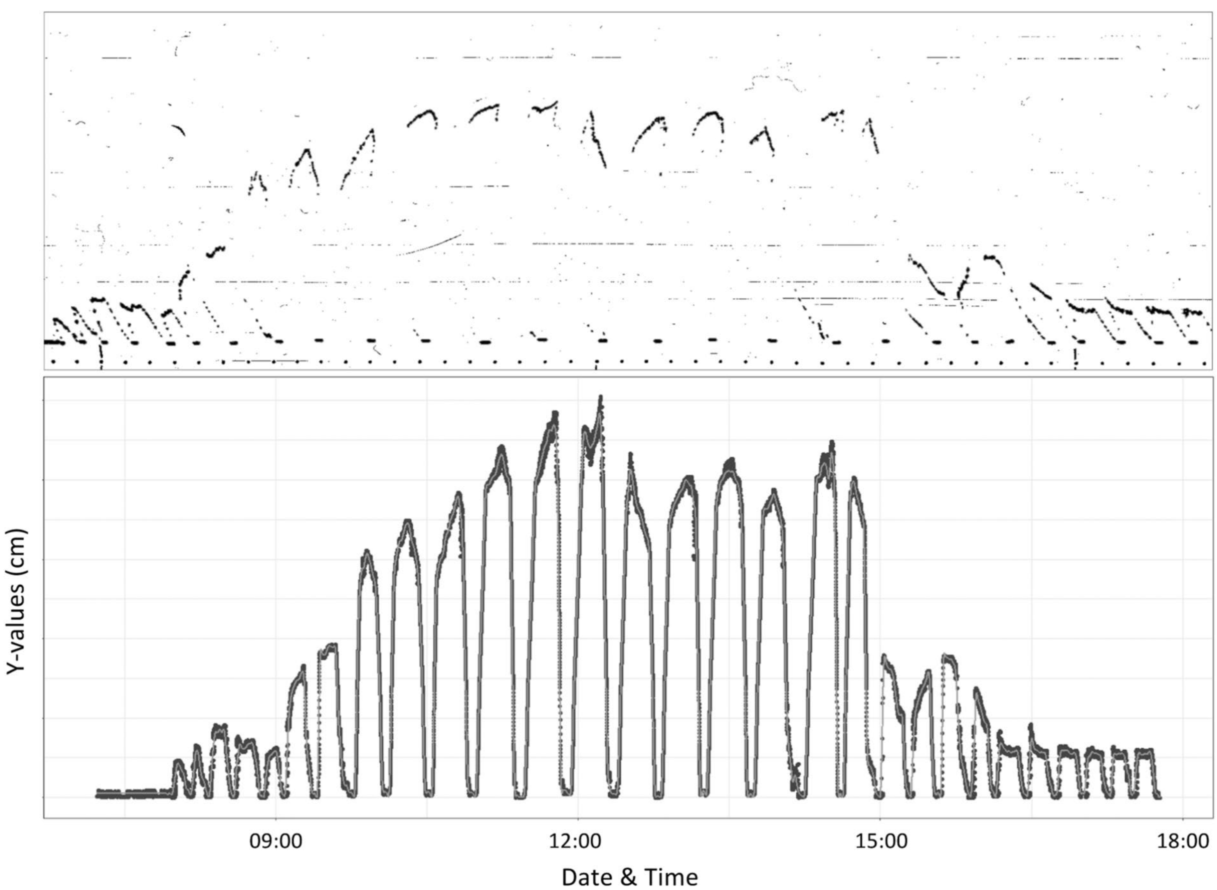

Fig. 3 Linear interpolation. Side-by-side comparison of a record before (top; raw record scan) and after (bottom; digital record after arc removal) linear interpolation, which filled gaps in the record and created a regular time series across the record

used to calculate mean depth along a rolling window of the record (window width was 0.1% of the record length) [41]. When the running mean depth was below a user-defined threshold, then a dive was not detected and the resolution of smoothing would decrease (knots = 100, spar value = 0.8). If the running mean exceeded the user-defined depth threshold, then a dive was detected, and the resolution of smoothing would increase to capture diving behavior.

To mathematically determine the best smoothing value to employ, each dive trace was recovered 21 separate times using spar values that ranged from 0 to 1 with increments of 0.05 (Fig. 4). The record, when smoothed under each spar value, was then analyzed using the diveMove R package at a 5-s sampling interval [36]. Then, bottom distance (i.e., distance in meters covered during the bottom phase of a dive) was compared among all spar values because it is the most sensitive to changes in smoothing penalties.

As a compromise between underfitting and overfitting the data, the spar value midway between the minimum bottom distance (i.e., black dashed line; d) and 0 was used (Fig. 4c; red dashed line). The R package has automated this process in the "find_best_spar" function.

Dive analysis

The final digitized records were then analyzed using the diveMove package in R [36]. For dive statistics, the records were calibrated using the "calibrateDepth" function at a 5-s sampling interval and filtered to only capture dives greater than 10 m deep to control for transducer noise at the surface. The hand-processed dive statistics initially reported in Castellini, Davis, and Kooyman were not filtered by any depth or duration threshold [4]. Digital processed dives that lasted longer than 100 min, had speeds that exceeded 5 m/s, or in sections of the record with extreme drift or unclear behavior were excluded from analysis.

The final dive statistics from the computer-analyzed dives made by each individual were exported using the "diveStats" function from the diveMove package and compared with the values that were previously reported on the same records [4]. For simplicity, we denoted the average values from the 1992 analysis as "bulletin" records and compared them to the "computerized" records after data recovery. Matched pairs t-tests were run on the seven dive parameters available in both record sets: total number of dives in each record, depth mean, maximum, and standard deviation, and duration mean,

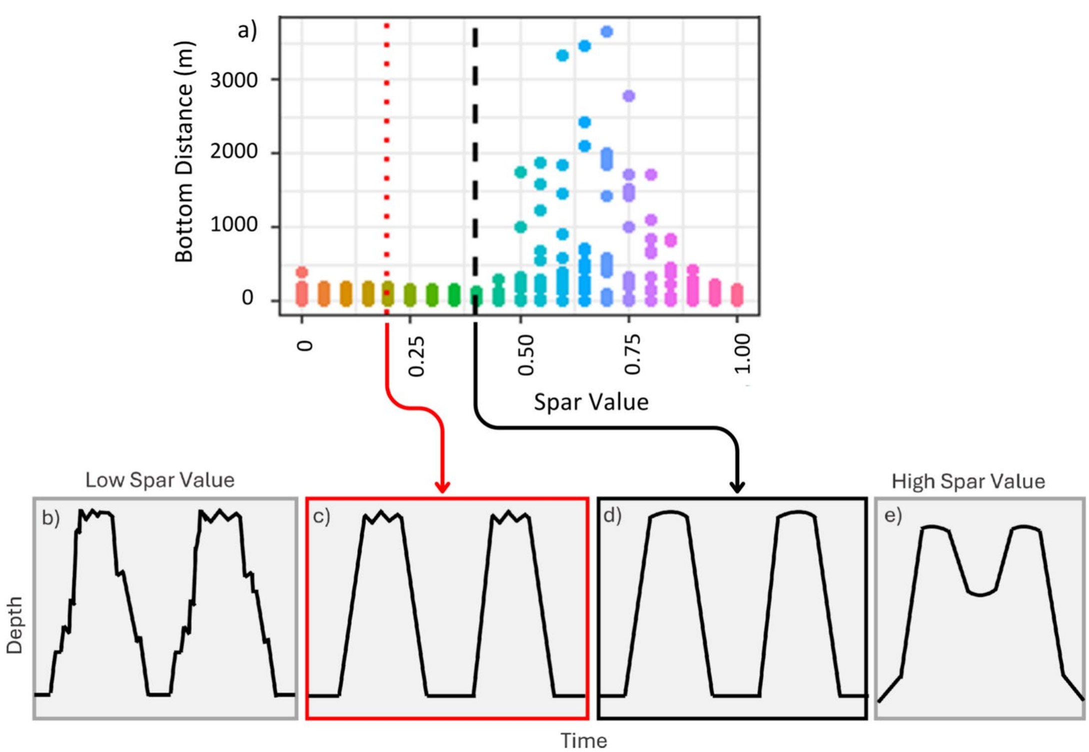

Fig. 4 Methods for determining smoothing value. The typical distribution of the change in bottom distance with increasing spar value (**a**; one dot represents a single dive), with schematics illustrating the influence of spar values on two sample dives (bottom row). The spar value that minimizes bottom distance also rounded the dives at depth (**d**; black dashed line). Higher spar values began merging neighboring dives (**e**), and lower spar values produced "ghost wiggles" in the record (**b**). The median between (**b**) and (**d**) was used for spline smoothing (**c**)

maximum, and standard deviation. Data were transformed for normality prior to testing.

Results

This recovery process involved record scanning, digitization, and bias correction, most of which has been automated and well documented within the recoverKBTDR R package (Fig. 5). This method resulted in the recovery of 4117 dives from 19 records. Record digitization took less than 2 h and could be replicated easily, with approximately 95% of the recovery time being image processing. Once the digitized dive record was produced, it was possible to rerun dive analyses with different threshold settings without the need to rescan the original dive trace.

Comparison of the computerized and bulletin values revealed broad similarities and a few expected differences

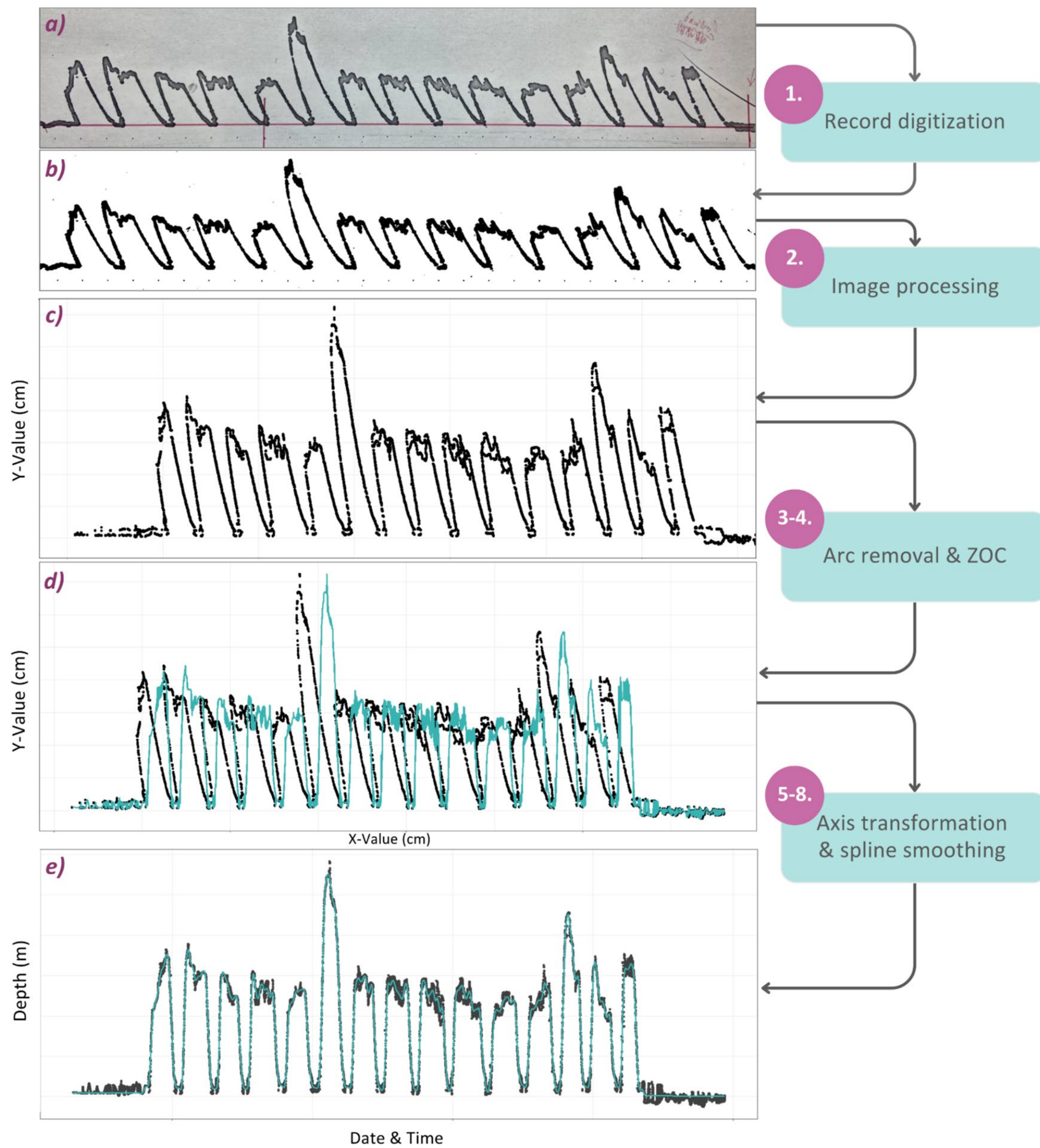

Fig. 5 Summary of recovery workflow. The paper record (**a**) was manually scanned to create a digital image (**b**). The digital record was then processed and centered in R (**c**), creating digital files of position along both the x and y axes in centimeters. The arc in the record was removed using the geometry of the device and ZOC was performed (original record in black and transformed x-values in teal; **d).** The record was then assigned accurate time and depth axes, and spline smoothing was performed to reduce transducer noise before analysis (teal line indicates smoothing curve; **e**)

(Fig. 6). Computerized records captured fewer dives than the bulletin records (Fig. 6a; mean difference = − 34 dives; t_{16} = − 2.7; *p*-value = 0.02), likely because shallow dives were difficult to separate from transducer noise such that our depth threshold was set to 10 m. The average maximum dive depths and average mean depths were similar in both records (Fig. 6b, c). The average standard deviation of dive depths was larger in the bulletin records due to the inclusion of very short and shallow dives (Fig. 6d; mean difference = − 13 m; t_{15} = − 3.2; *p*-value < 0.01).

Dive durations were also similar between the bulletin and computerized records. The average maximum dive duration (i.e., the average of the single longest dive made by each seal) and average standard deviation in dive duration determined for the computerized dive records were slightly shorter than that reported in the bulletin (Fig. 6e: mean difference = − 3.9 min; t_{17} = − 2.6; *p*-value = 0.02; Fig. 6g: mean difference = − 0.7 min; t_{15} = − 2.3; *p*-value = 0.04). In contrast, average dive durations were similar. These differences also reflect the absence of dives shallower than 10 m in the computerized records.

Discussion

Here, we described a novel method for recovering dive records from film-based Kooyman–Billups TDRs. This process involved record scanning, image processing, and multiple corrections performed in R to transform the paper record into a digital file complete with time and depth axes. The result of our recovery method is a continuous dive record that can be easily read into dive analysis software. Although a well log scanner was used to obtain images of the paper records, scanning could also be achieved using other available sheetfed scanners. Computerization of dive records reduced time for analysis from multiple people and days to a few hours [3, 4]. Approximately 95% of this time was the manual image processing steps (steps 1 and 2), with longer and discontinuous records taking additional time to process. Once the image was processed, the rest of the recovery process (steps 3–8) took less than 10 min on average. In addition, the mathematical functions developed for recovery are automatic, reproducible, and reduce user bias and error. These methods were also able to retain details in the dive trace (i.e., bottom phases and dive shapes) that were previously inaccessible. While the methods we describe here are specific to the Kooyman–Billups TDR, these methods would only require slight modification to the arc removal equation to recover behavioral data from studies that employed the Naito recorder.

The comparison of dive statistics between the bulletin and computerized records confirmed our methods produced results at least as accurate as the past, recognizing

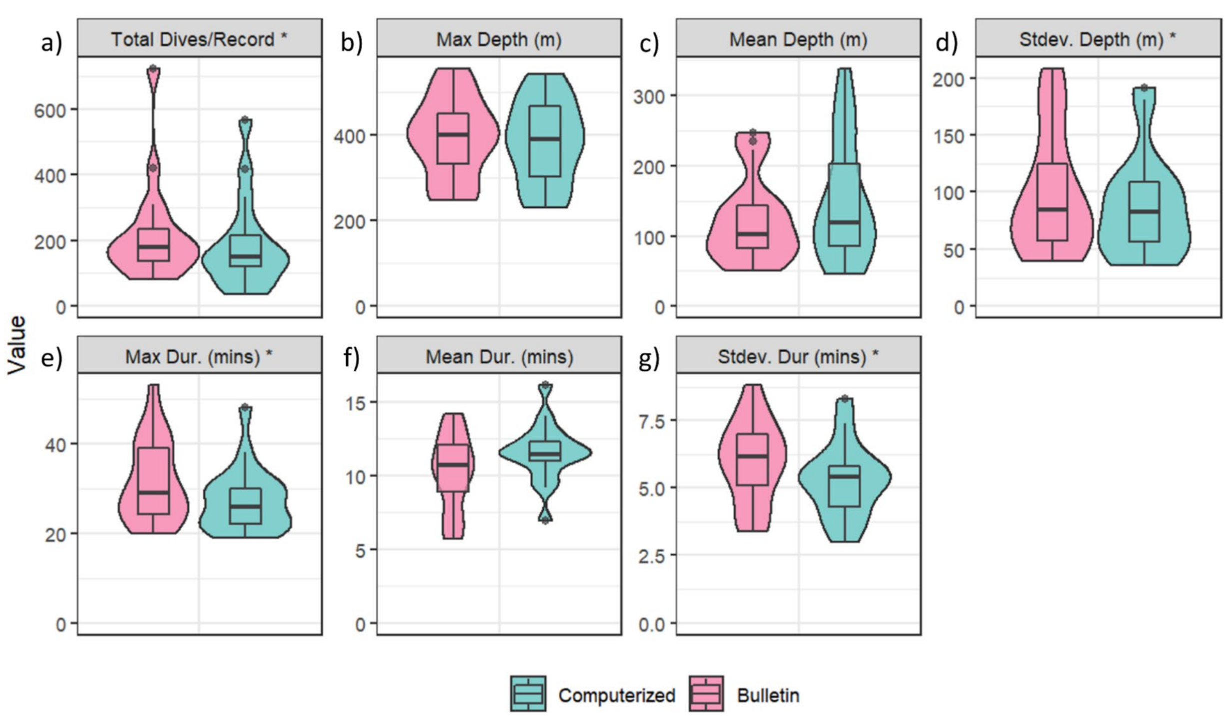

Fig. 6 Comparisons of computerized and bulletin dive metrics. Violin plots show the dive metrics (**a**–**g**) of the bulletin records (pink) and computerized records (teal), with inner box plots indicating the mean and quartiles. Asterisks (*) indicate a significant difference at a 95% confidence interval

that neither method produced "true" values. The small differences in the number of dives, dive depths, and durations can largely be attributed to the fact our method focused on recovering dives deeper than 10 m, and the original analysis did not filter dives by depth or duration [4]. While very short and shallow dives were likely quick exploratory dives or foraging for bald notothen fish (*Pagothenia borchgrevinki*), which reside in shallow ice crevices and are flushed out by air bubbles created by Weddell seals, they were difficult to accurately distinguish from device noise [42]. Our methods also struggled to document rapid and deep V-shaped dives that were preceded and followed by long periods of rest at the surface because spline smoothing caused the depth reading for these dives to be biased shallow. This behavior was rare overall, and visual inspection confirmed that deep dives within sequences were reliably documented. While smoothing parameters can be modified to document these behaviors, these limitations should be considered if these methods are applied to recover records from other diving species. Even with these shortcomings, our statistical and visual comparisons indicated that the recovery method captured behavior well.

Digitizing data from analog devices allows us to leverage modern analytical approaches to reanalyze these records for more powerful interpretations of comparative diving behaviors over time and species. As a result of the methods described here, we now have access to digital dive profiles and bottom phase activities, which have been used in a variety of studies to infer foraging behavior [43, 44]. Recent research has evaluated dive characteristics from the 1970s to 2010s to determine whether Weddell seals are feeding on a higher volume of smaller prey as a result of the declining abundance of a large prey item [45]. Future research could use historic dive records as a baseline to assess the efficacy of the 2017 Ross Sea Marine Protection Area in providing refuge for fished species, or whether shifting regional sea ice regimes have affected the timing and availability of foraging opportunities [29–32].

Outside of Weddell seals, our methods present rich opportunities to recover and reanalyze data from at least 14 other species, many of which are top predators (see Table 1). Movements and foraging activities from top predators have served as ecological indicators of the state of lower trophic levels and habitat quality [46, 47]. Comparisons of these activities over longer timescales would be particularly informative with many species experiencing accelerated rates of environmental change [48]. Trends in the percentage of the day spent foraging, trip durations, and the frequency of dives beyond the aerobic dive limit can reveal whether species are compensating for changes in their environment [49, 50]. With 43% of species listed in Table 1 experiencing population decline, having access to foraging behavior prior to modern conditions would benefit our understanding of factors that could be contributing to decline and guide management decisions.

From museum collections to poems, the utility of historic data has been demonstrated in a variety of studies to understand how species and their environments have changed over time [51–53]. Some more specific examples include using historical photographs to document the decline of large fish, whaling logs from the early 1900s to evaluate trends in whale abundance, or the use of Chinese poems to examine shifts in the range of a finless porpoise [51–53]. While recovery efforts have typically focused on tangible records such as journals or photos, recovering data collected from older technology is equally important. Prior to this recovery effort, 15 paper records had already been lost to time, and there are other analog devices of this era that would benefit from data rescue [54]. In addition, we have faced other challenges accessing older digital data due to corrupted hard drives and disc delamination. It is absolutely critical to not only digitize paper records as we describe here, but also migrate digital data stored on obsolete technology to more modern formats, such as the cloud. The loss of such rich historical data would be a scientific tragedy.

Conclusions

Our method for recovering data from the 1970s Kooyman–Billups TDR provides digital access to continuous historic dive records, which makes it possible to address more modern questions on long-term patterns of diving activity [26–28]. The 1970s Kooyman–Billups TDR also greatly advanced the field of biologging technology and was used by a plethora of studies to obtain a first look into the diving behavior of a free-ranging organism [4, 7, 9–17]. With the significance of this device and similar ones of this time, this method will allow for access to historic datasets for a variety of marine species for future long-term studies on diving behavior. Considering many organisms are experiencing alterations in their habitat, longitudinal studies of behavior can assist in the construction of effective conservation and ecosystem-based management decisions.

Abbreviations

TDR	Time depth recorder
csv	Comma-separated value file
tiff	Tag image file format
psi	Pounds per square inch

Variables

r	The length of the pressure-sensitive arm
k	The height of the arm's pivot point (k)
(x_t, y_t)	Coordinates of a point along a dive at time t
x_o	Position of x_t at the surface when depth is equal to 0

(x_o, y_t) Coordinates of transformed point along a dive after arc removal

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40317-025-00418-0.

Additional file 1

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Author contributions
EGT developed the primary code and methodology for data recovery and manages the GitHub repository. JMB assisted with the organization of ideas and the framework for the method and edited all drafts of this manuscript. DWS assisted with programming, workflow, algorithms, and modularization of code for the recovery method. MAC gathered the historic records during the 1978, 1979, and 1981 field seasons and assisted with finding critical information from previous field seasons. EGT led the writing of the manuscript, and all the authors edited and approved the final version of this manuscript.

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Availability of data and materials
The datasets generated using the methods described in this manuscript are available in the United States Antarctic Program database: https://doi.org/10.15784/601560. The R package recoverKBTDR (version 2.0) that was created from the recovery methods described within this manuscript is available in a GitHub repository: https://doi.org/10.5281/zenodo.14025657.

Declarations

Ethics approval and consent to participate
The historic data used within this manuscript (1978, 1979, 1981) were collected under a National Marine Fisheries Service Marine Mammal permit issued to Dr. Gerald Kooyman that can be found within the Federal Register (May 9th, 1975, page 20333). Historic data were also collected under the approval of two Antarctic Conservation Act permits issued to Dr. Gerald Kooyman (1978–1979: Federal Register, July 17th, 1981, page 37104; 1981: Federal Register, September 29th, 1981, page 47687).

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Kooyman GL. Techniques used in measuring diving capacities of Weddell seals. Polar Rec. 1964;12:391–4.
2. Kooyman GL. Genesis and evolution of bio-logging devices: 1963–2002. Mem Natl Inst Polar Res Spec Issue. 2004;58:15–22.
3. Kooyman GL, Billups JO, Farwell WD. Two recently developed recorders for monitoring diving activity of marine birds and mammals. In: MacDonald A, Priede I, editors. Exp Biol sea. London: Academic Press I.c; 1983. p. 197–214.
4. Castellini M, Davis R, Kooyman G. Annual cycles of diving behavior and ecology of the Weddell seal. Bull Scripps Inst Oceanogr. 1992;28.
5. Naito Y, Asaga T, Ohyama Y. Diving behavior of adelie penguins determined by time-depth recorder. Condor. 1990;92:582–6.
6. Wilson R, Vandenabeele S. Technological innovation in archival tags used in seabird research. Mar Ecol Prog Ser. 2012;451:245–62.
7. Gentry RL, Kooyman GL. Introduction. In: Gentry R, Kooyman G, editors. Fur seals: maternal strategies on land and at sea. Princeton University Press; 1986. p. 3–27.
8. The IUCN Red List of Threatened Species. https://www.iucnredlist.org/ (2025). Accessed 20 May 2025.
9. Kooyman GL, Goebel ME. Feeding and diving behavior of Northern Fur Seals. In: Gentry R, Kooyman G, editors. Fur seals: maternal strategies on land and at sea. Princeton University Press; 1986. p. 61–78.
10. Kooyman GL, Gentry RL. Diving behavior of South African Fur Seals. In: Gentry R, Kooyman G, editors. Fur seals: maternal strategies on land and at sea. Princeton University Press; 1986. p. 3–27.
11. Kooyman GL, Davis RW, Croxall JP. Diving behavior of Antarctic fur seals. In: Gentry R, Kooyman G, editors. Fur seals: maternal strategies on land and at sea. Princeton University Press; 1986. p. 115–25.
12. Kooyman GL, Trillmich F. Diving behavior of Galapagos sea lions. In: Gentry R, Kooyman G, editors. Fur seals: maternal strategies on land and at sea. Princeton University Press; 1986. p. 209–19.
13. Kooyman GL, Trillmich F. Diving behavior of Galapagos fur seals. In: Gentry R, Kooyman G, editors. Fur seals: maternal strategies on land and at sea. Princeton University Press; 1986. p. 186–95.
14. Feldkamp SD, Delong RL, Antonelis GA. Diving patterns of California sea lions, *Zalophus californianus*. Can J Zool. 1989;67:872–83.
15. Le Boeuf BJ, Costa DP, Huntley AC, Kooyman GL, Davis RW. Pattern and depth of dives in Northern elephant seals, *Mirounga angustirostris*. J Zool. 1986;208:1–7.
16. Trillmich F, Kooyman GL, Majluf P, Sanchez-Grinan M. Attendance and Diving Behavior of South American Fur Seals during El Niño in 1983. In: Gentry R, Kooyman G, editors. Fur Seals: Maternal Strategies on Land and at Sea. Princeton University Press; 1986. p. 153–67.
17. Eckert S, Nellis D, Eckert K, Kooyman G. Diving patterns of two leatherback sea turtles (*Dermochelys coriacea*) during internesting intervals at Sandy Point, St. Croix, U.S. Virgin Islands. Herpetologica. 1986;42:381–8.
18. Le Boeuf BJ, Naito Y, Huntley AC, Asaga T. Prolonged, continuous, deep diving by northern elephant seals. Can J Zool. 1989;67:2514–9.
19. Williams T, Briggs D, Croxall J, Naito Y, Kato A. Diving pattern and performance in relation to foraging ecology in the gentoo penguin, *Pygoscelis papua*. J Zool (Lond). 1992;227:211–30.
20. Croxall J, Briggs D, Kato A, Watanuki Y, Williams T. Diving pattern and performance in the macaroni penguin *Eudptes chrysolophus*. J Zool (Lond). 1993;230:31–47.
21. Kato A, Croxall KP, Watanuki Y, Naito Y. Diving patterns and performance in male and female blue-eyed cormorants *Phalacrocorox Atriceps* at South Georgia. Mar Ornithol. 1991;19:117–29.
22. Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG, et al. Biotelemetry: a mechanistic approach to ecology. Ecol Evol. 2004;19:334–43.
23. Whitford M, Klimley AP. An overview of behavioral, physiological, and environmental sensors used in animal biotelemetry and biologging studies. Anim Biotelemetry. 2019;7:1–24.
24. Horning M, Andrews RD, Bishop AM, Boveng PL, Costa DP, Crocker DE, et al. Best practice recommendations for the use of external telemetry devices on pinnipeds. Anim Biotelemetry. 2019;7:1–17.
25. Bengston JL, Hill RD, Suzanne E. Using satellite telemetry to study the ecology and behavior of antarctic seals. Korean J Polar Res. 1993;4:109–15.

26. Heerah K, Hindell M, Guinet C, Charrassin JB. A new method to quantify within dive foraging behaviour in marine predators. PLoS ONE. 2014;9:1–15.
27. Schreer JF, Testa JW. Classification of Weddell Seal Diving Behavior. Mar Mammal Sci. 1996;7:194–7.
28. Sibly RM, Nott HMR, Fletcher DJ. Splitting behaviour into bouts. Anim Behav. 1990;39:63–9.
29. Ainley DG, Nur N, Eastman JT, Ballard G, Parkinson CL, et al. Decadal trends in abundance, size and condition of Antarctic toothfish in McMurdo Sound, Antarctica, 1972–2011. Fish Fisheries. 2012;14:343–63.
30. Parkinson CL. A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic. Proc Natl Acad Sci USA. 2019;116:14414–23.
31. Massom R, Stammerjohn S. Antarctic sea ice change and variability—physical and ecological implications. Pol Sci. 2010;4:149–86.
32. Salas L, Nur N, Ainley D, Burns J, Rotella J, et al. Coping with the loss of large, energy-dense prey: a potential bottleneck for Weddell Seals in the Ross Sea. Ecol Appl. 2017;27:10–25.
33. Schneider C, Ferreira T, Rasband W. NIH Image to ImageJ: 25 years of image analysis. Nat Methods. 2012;9:671–5.
34. Abu-Ain W, Abdullah SNHS, Bataineh B, Abu-Ain T, Omar K. Skeletonization Algorithm for Binary Images. Procedia Technol. Elsevier B.V.; 2013;11:704–9.
35. R Core Team. R: a language and environment for statistical computing. Vienna, Austria; 2021.
36. Luque SP. Diving behaviour analysis in R. R News. 2007;7:8–14.
37. Luque SP, Fried R. Recursive filtering for zero offset correction of diving depth time series with GNU R package diveMove. PLoS ONE. 2011;6:1–9.
38. Wickham H, Francois R, Henry L, Muller, K. dplyr: A Grammar of Data Manipulation. R package version 1.0.7. 2021.
39. Zeileis A, Grothendieck G. zoo: S3 infrastructure for regular and irregular time series. J Statist Softw. 2005;14:1–27.
40. Grolemund G, Wickham H. Dates and times made easy with lubridate. J Statist Softw. 2021;40:1–25.
41. Tuszynski J. caTools: Tools: Moving Window Statistics, GIF, Base65, ROC AUC, etc. R package version 1.18.2. 2021.
42. Fuiman LA, Davis RW, Williams TM. Behavior of midwater fishes under the Antarctic ice: observations by a predator. Mar Biol. 2002;140:815–22.
43. Burns JM, Schreer JF. Changes in the behavioral repertoire of Weddell seal pups diving in McMurdo Sound, Antarctica. In: Davidson W, editor. Antarctic ecosystems: models for wider ecological understanding. Caxton Press: Christchurch; 2000. p. 85–95.
44. Shero MR, Goetz KT, Costa DP, Burns JM. Temporal changes in Weddell seal dive behavior over winter: are females increasing foraging effort to support gestation? Eco Evol. 2018;80:11857–74.
45. Tsai E. Diving into the past: Recovering historic dive records for decade-to-decade comparison of diving behavior in Weddell seals [thesis]. TX (USA): Texas Tech University; 2022.
46. McMahon CR, Hindell MA, Charrassin JB, Corney S, Guinet C, et al. Finding mesopelagic prey in a changing Southern Ocean. Sci Rep. 2019;9:55152–4.
47. Hindell MA, Reisinger RR, Ropert-Coudert Y, Huckstadt LA, Trathan PN, et al. Tracking of marine predators to protect Southern Ocean ecosystems. Nature. 2020;580:87–92.
48. Stammerjohn SE, Scambos TA. Warming reaches the South Pole. Nat Clim Change. 2020;10:709–10.
49. Crocker DE, Costa DP, Le Boeuf BJ, Webb PM, Houser DS. Impact of El Niño on the foraging behavior of female northern elephant seals. Mar Ecol Prog Ser. 2006;309:1–10.
50. Weise MJ, Costa DP, Kudela RM. Movement and diving behavior of male California sea lion (*Zalophus californianus*) during anomalous oceanographic conditions of 2005 compared to those of 2004. Geophys Res Lett. 2006;33:L22S10.
51. McClenachan L, Ferretti F, Baum JK. From archives to conservation: why historical data are needed to set baselines for marine animals and ecosystems. Conserv Lett. 2012;5:349–59.
52. McClenachan L. Documenting loss of large trophy fish from the Florida keys with historical photographs. Conserv Bio. 2009;23:636–43.
53. Zhang Y, Liu J, Zheng S, Wang J, Wang K, et al. Range contraction of the Yangtze finless porpoise inferred from classic Chinese poems. Curr Bio. 2025;35:329–30.
54. Wilson RP, Burget AE, Wilson BH, Wilson PT, Nöldeke C. An inexpensive depth gauge for marine animals. Mar Biol. 1989;103:275–83.

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