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Diving into the analysis of time–depth recorder and behavioural data records: A workshop summary

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ABSTRACT

Directly observing the foraging behavior of animals in the marine environment can be extremely challenging, if not impossible, as such behavior often takes place beneath the surface of the ocean and in extremely remote areas. In lieu of directly observing foraging behavior, data from time–depth recorders and other types of behavioral data recording devices are commonly used to describe and quantify the behavior of fish, squid, seabirds, sea turtles, pinnipeds, and cetaceans. Often the definitions of actual behavioral units and analytical approaches may vary substantially which may influence results and limit our ability to compare behaviors of interest across taxonomic groups and geographic regions. A workshop was convened in association with the Fourth International Symposium on Bio-logging in Hobart, Tasmania on 8 March 2011, with the goal of providing a forum for the presentation, review, and discussion of various methods and approaches that are used to describe and analyze time–depth recorder and associated behavioral data records. The international meeting brought together 36 participants from 14 countries from a diversity of backgrounds including scientists from academia and government, graduate students, post-doctoral fellows, and developers of electronic tagging technology and analysis software. The specific objectives of the workshop were to host a series of invited presentations followed by discussion sessions focused on (1) identifying behavioral units and metrics that are suitable for empirical studies, (2) reviewing analytical approaches and techniques that can be used to objectively classify behavior, and (3) identifying cases when temporal autocorrelation structure is useful for identifying behaviors of interest. Outcomes of the workshop included highlighting the need to better define behavioral units and to devise more standardized processing and analytical techniques in order to ensure that results are comparable across studies and taxonomic groups.

1. Introduction

Directly observing the foraging behavior of animals in the marine environment can be extremely challenging if not impossible as such behavior often take place beneath the surface of the ocean and in extremely remote areas (Fedak et al., 2004; Hooker et al., 2007; Hindell, 2008). In lieu of directly observing foraging behavior, diving behavior and other associated behaviours including acceleration, jaw movements, head strikes, or changes in stomach temperature can be measured using electronic telemetry devices (Liebsch et al., 2007; Ropert-Coudert and Wilson, 2005; Skinner et al., 2009; Viviant et al., 2010). Diving behavior and associated behavioral metrics are of interest as these behaviors may be used as proxies for an individual's foraging effort and may serve as an indicator of changes in the physical and/or biological characteristics of the marine environment (Biuw et al., 2007; Croll et al., 1998; Hindell, 2008; Weimerskirch et al., 2005; Wilson et al., 2005).

Although there are numerous types of electronic recording devices that can be used to measure animal behavior, here we focus primarily on time–depth recorders as they are commonly used to measure the diving behavior of animals in the marine environment. Time–depth recorders were pioneered in the 1960s to measure and store depth at pre-determined intervals (Kooyman, 1965; Kooyman et al., 1976) and have since been used to describe the diving behavior of a wide range of species including fish, marine reptiles, seabirds, pinnipeds, and cetaceans (Croll et al., 1998; Boness et al., 1999; Hays et al., 2001; Lea et al., 2002; Wilson et al., 2005). In addition to recording time and depth, time–depth recorders may also record environmental data

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including water temperature, light levels, salinity, and/or other oceanographic properties in areas where animals may forage and transit (Boyd et al., 2001; Fedak, 2004; Hindell et al., 1991; Sokolov et al., 2006; Simmons et al., 2009).

In general, a dive can be defined as a unit of behavior in which an animal makes an excursion from a central point (e.g. the surface) to achieve a specific goal over a specific time period (Boyd, 1997). Although dives are a commonly used unit of behavior that represent a fundamental component of prey acquisition (Boyd, 1997; Bowen et al., 1999), the definition of a dive and derived secondary behavioral units can vary substantially depending upon how recording devices were programmed and how data were processed and analyzed. The lack of consistency in defining behavioral units, classifying the behavior, and the analytical approaches may ultimately limit the validity of comparisons between taxonomic groups and studies (Hooker and Baird, 2001; Halsey et al., 2007). Determining which dive metrics may be most appropriate for a given study may also vary and in some cases may be largely knowledge- and experienced-based and thus more subjective. In addition, our knowledge and perceptions regarding dive behavior may be limited to particular species during certain seasons, age classes, or sexes that are more accessible and can be easily captured and instrumented. Collectively, such issues associated with describing and quantifying the diving and foraging behavior of animals in the marine environment continue to present challenges for bio-logging practitioners.

Given the aforementioned challenges, a workshop was convened in association with the Fourth International Symposium on Bio-logging in Hobart, Tasmania, on 12 March 2011, with the goal of providing a forum for the presentation, review, and discussion of various methods and approaches that describe, process, and analyze time–depth recorder and associated time-series behavioral data. The international meeting brought together 36 participants from 14 countries from a diversity of backgrounds including scientists from academia and government, graduate students, post-doctoral fellows, and developers of electronic tagging technology and analysis software. The workshop was structured into two primary sessions. The first session included six spoken presentations focusing on historical, current, and recent developments in analytical approaches that are used to process, analyze, and interpret time-series depth and other behavioral data records from diving marine vertebrates. Each presentation was followed by a brief discussion. The second session was comprised of discussion focused on (1) identifying behavioral units that are suitable for empirical studies, (2) identifying analytical approaches and techniques that can be used to visualize and objectively classify diving behavior, and (3) identifying cases when temporal autocorrelation structure is useful for identifying behaviors of interest. Herein, we review the topics and issues that were presented and discussed during the workshop.

2. Overview of workshop presentations

Six spoken presentations were delivered at the workshop on a variety of topics and marine vertebrate species. The first presentation by Sebastián Luque described new methods and approaches for analyzing and characterizing diving behavior, particularly as it relates to zero-offset correction and the identification of bouts and dive phases using the diveMove R package (Luque and Fried, 2011). A presentation by Tomoko Narazaki focused on using acceleration and geomagnetic data to reconstruct fine-scale foraging behavior and paths of sea turtles. There were two presentations that were focused on multivariate approaches that can be used to describe and characterize diving behavior. Markus Horning's presentation focused on the use of constraint lines (e.g., Guo et al., 1998) to quantify the aerobic diving limit in Galápagos fur seals (*Arctocephalus galapogoensis*). A presentation by Jamie Womble reviewed various multivariate techniques that have been used to describe and classify diving behavior (Lea et al., 2002; Schreer and Testa, 1995, 1996; Villegas-Amtmann et al., 2008; Weise et al., 2010). In addition, she provided a more in-depth example using non-metric multidimensional scaling to identify the predominant gradients in the diving behavior of harbor seals (*Phoca vitulina richardii*) from two distinct habitats in Alaska. A presentation by Andrew Edwards discussed Lévy flight movement patterns in the context of marine predator search behavior and concluded that such movement patterns may not be as common as previously described (Edwards, 2011). The final presentation by Dan Costa included a brief history of the use of time–depth recorders and different approaches that have been used over the years for the processing and analysis of time–depth recorder data with contemporary examples from northern elephant seals (*Mirounga angustirostris*). Collectively, the presentations covered a diverse array of topics and highlighted advances in analytical methods while at the same time identifying future areas of research.

3. Workshop theme sessions

3.1. Identifying behavioral units

Primary data (i.e. depth, speed, orientation) produced by dive behavior telemetry studies are inherently descriptive in nature and frequently comprise physical measures of the environment linked to animal behavior by a shared real time basis. Empirical use of telemetry devices and other behavioral recording devices often requires the determination of secondarily derived behavioral units such as dives, bouts, trips, or other physiologically or biologically relevant events that are more appropriate in the context of given questions. Hence, there was a focus on reviewing recent methods for the determination of physiological and behavioral units with the primary goals of (a) identifying likely biologically relevant units or metrics, (b) reviewing suitable methods for the characterization of such units, and (c) reviewing the impact of intrinsic and environmental covariates on unit characterization.

During a discussion among bio-logging practitioners representing a wide variety of taxa, including fish, squid, seabirds, sea turtles, pinnipeds, and cetaceans, it became evident that clear terms of reference would be required to identify useful and relevant biologically relevant units. Discussions focused on the interaction of biologically significant units, environment and technology, and the utility of generalized core behavioral metrics across taxonomic groups.

Often the temporal and spatial scale of the biological and environmental phenomena are rarely aligned with the scales of behavior that are observed, whether using in-situ bio-logging and environmental recording devices, remote sensing technology, or direct physical observation and sampling. The scale of behavioral measurement units must be aligned as closely possible with the actual scales of biological and environmental phenomena that is measured, whether these are the distribution of prey fields in a foraging area, currents influencing organism movement or the physiological measurement of buoyancy within the organism. Proper alignment of temporal and spatial scales in this manner requires clear, defensible biologically significant units. The lynchpin to identifying significant units lies in their frame of reference.

The broad categories of taxa inhabiting the aquatic environment utilize and interact with this environment in fundamentally different ways. For example, air-breathing avian marine predators utilize the air and water columns under constraint of flight and breath-hold endurance, respectively; air-breathing predators utilize swimming as primary locomotion, utilize the water column under breath-hold