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Effects of environmental variables on the movement and space use of coastal sea snakes over multiple temporal scales

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ABSTRACT

Natural and anthropogenic changes in the marine environment can strongly influence the biology and behaviour of coastal organisms. Understanding how animals that rely on these habitats respond to environmental change is crucial to inform when management actions should be implemented to mitigate or reduce impacts. Here passive acoustic telemetry was used to monitor the movements of spine-bellied sea snakes (*Hydrophis curtus*) within a coastal ecosystem to define activity patterns in relation to environmental conditions. Presence, movement and three-dimensional home range metrics calculated from monitoring data were tested against environmental (water temperature, atmospheric pressure, wind speed, accumulated rainfall and tidal range) and biological (snout-vent length) factors on daily and monthly temporal scales to identify key environmental drivers of movement and the use of space. A generalised linear mixed model (GLMM) framework using Akaike information criterion (AIC) indicated that tidal reach and atmospheric pressure strongly influenced the daily presence and movements of tagged individuals, respectively. Accumulated rainfall significantly influenced the volume of space used on a monthly timescale. This study presents first estimates of three-dimensional home ranges of sea snakes as well as novel information on how environmental variables influence daily and monthly presence, movements and use of space of coastal sea snakes. These data are important in further understanding the ecology of sea snakes and can inform future management actions for this poorly studied taxon in the light of increased environmental and anthropogenic disturbances.

1. Introduction

Coastal ecosystems are complex and highly variable. Changes to these environments can play a significant role in movement and habitat use of animals with varying temporal scales of influence (Heupel, 2007; Thistle, 1981). For example, daily activity of animals can be driven by an environmental factor that varies over a daily cycle (e.g., tidal currents, moon phase; Naylor, 1999) while seasonal movements may be governed by more gradual environmental changes (e.g., photoperiod, water temperature; Heupel, 2007). Gradual changes in environmental variables often act as cues for seasonal changes of behaviour in animals, especially in coastal ecosystems (Froeschke et al., 2010; Heupel, 2007; Schlaff et al., 2014), whereas acute changes in these same variables may trigger different behavioural responses (Jury et al., 1995; Liu et al., 2010; Udyawer et al., 2013). Understanding how changing environmental factors drive behaviour and patterns of activity provides insight into the effects natural and anthropogenic changes may have on coastal populations and ecosystems, and ultimately informs management actions.

True sea snakes (Hydrophiinae) are air breathing marine reptiles that typically inhabit shallow coastal habitats and whose biology, like that of other reptiles, is inherently linked to environmental variables (Heatwole, 1999). Physiological restrictions (i.e., thermal tolerance, maintenance of water balance) imposed by environmental factors have played an important role in the evolutionary history and shaping of the global distributions of sea snakes. Previous global-scale studies have shown that the distribution of sea snakes is strongly correlated with sea surface temperature (Heatwole et al., 2012) and salinity (Brischoux et al., 2012a). Little is known about the influence of environmental factors on the biology and behaviour of sea snakes at the regional or local level, despite moonlight and tidal currents having been shown to play an important role in governing activity patterns in closely related semi-aquatic snakes inhabiting freshwater and coastal habitats (Heatwole, 1999; Lillywhite and Brischoux, 2012).

There are currently few data on the use of space by coastal sea snake species such as spine-bellied sea snake, *Hydrophis curtus*. This species is commonly found in tropical and sub-tropical waters of northern Australia (Dunson, 1975; Udyawer et al., 2014) and in habitats that are important nursery areas for other marine snakes (Stuebing and Voris, 1990). Studying activity patterns of coastal sea snakes using traditional mark-recapture or radio-tracking techniques is logistically

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difficult and rarely provides enough temporal resolution to explore links with long- or short-term environmental changes. The present study used passive acoustic telemetry that provided longer-term data on movements to: (a) explore potential environmental drivers of presence, movement and space used by spine-bellied sea snakes in a coastal habitat, and (b) investigate if drivers of movement were consistent across multiple temporal scales.

2. Material and methods

2.1. Study site

This study was conducted in Cleveland Bay (19.20°S, 146.92°E), on the northeast coast of Queensland, Australia (Fig. 1). Cleveland Bay is a shallow coastal bay (<10 m deep) with a maximum tidal range of approximately 4 m. The bay covers an area of approximately 225 km^2 with the western and southern margins bounded by the mainland and Cape Cleveland, respectively, and a large continental island, Magnetic Island, to the north of the bay (Fig. 1). The habitat of the bay consists mainly of soft sediment substrates with extensive seagrass meadows and small patches of coral reef (Unsworth et al., 2009). The southern shore is lined with mudflats and mangroves. Several waterways flow into the southern portion of the bay and provide the major input of freshwater. Water temperature within the bay averages 28.6 °C (range: 26.9–30.6 °C) during the warmer wet season (November–April) and 24.1 °C (21.4–27.5 °C) in the cooler dry season (May–October) (Fig. 2).

2.2. Field methods

Spine-bellied sea snakes (*H. curtus*; previously *Lapemis curtus*) were located at night and captured from the surface of the water using dip nets. Once captured, the life stage/maturity of each individual was recorded as either juvenile or adult, with the sex of adults determined using external morphological features (by investigating hemipenal bulges or exposing the hemipenes). Snout-vent length (SVL) and mass of each captured snake were recorded, and each individual was fitted with a passive integrated transponder (PIT) tag for future identification. Individuals in healthy condition and exceeding the minimum weight (>300 g) to have a body cavity large enough to house a transmitter were surgically implanted with depth sensitive acoustic transmitters (V9P-2H, Vemco Ltd.). Transmitters were small (diameter 9 mm, length 29 mm, weight 2.9 g) and less than 1% of the body weight of the individuals tagged (*mean* ± *se*; 0.87 ± 0.11%, $n = 19$) to avoid any deleterious effects of implantation. Methods of implanting tags were similar to those used by Pratt et al. (2010). In summary, a local anaesthetic (Xylocaine®; lignocaine) was administered at the site of implantation, a small ventro-lateral incision (c. 2 cm) made approximately 4–5 cm anterior to the cloaca and the transmitter inserted into the peritoneal cavity, after which the incision was closed using surgical sutures. Individuals were allowed 30–40 min to recover from the anaesthetic before being released at the location of capture. Transmitters were uniquely coded for each individual, transmitted measurements of depth at 69 kHz, and had a battery life of approximately 215 days.

An array of 63 VR2W underwater acoustic receivers (Vemco Ltd.) was used to passively monitor the movements of tagged sea snakes from January 2013 to March 2014 (Fig. 1). Sentinel tag range testing indicated that receivers had a maximum detection range of 525 m with no overlap between receiver ranges (unpublished data, M. Heupel). Acoustic receivers were positioned at fixed locations to cover the eastern and western sections of the bay that corresponded to Conservation Park zones (no trawling or net fishing allowed) within the Great Barrier Reef Marine Park (Fig. 1). The area between the two sections was part of the Townsville Port, and experienced heavy boat traffic as well as seasonal trawling; therefore placing receivers within that area for any period of time was not logistically feasible. Monitored animals from past studies utilising this array moved freely between the two sections and were often detected on either side of the Townsville port area. Receiver densities on both the eastern and western sections were similar (east: 0.38 receivers per km^2; west: 0.53 receivers per km^2) with similar average distances between receivers (east: 6.45 ± 0.11 km, $n = 35$;

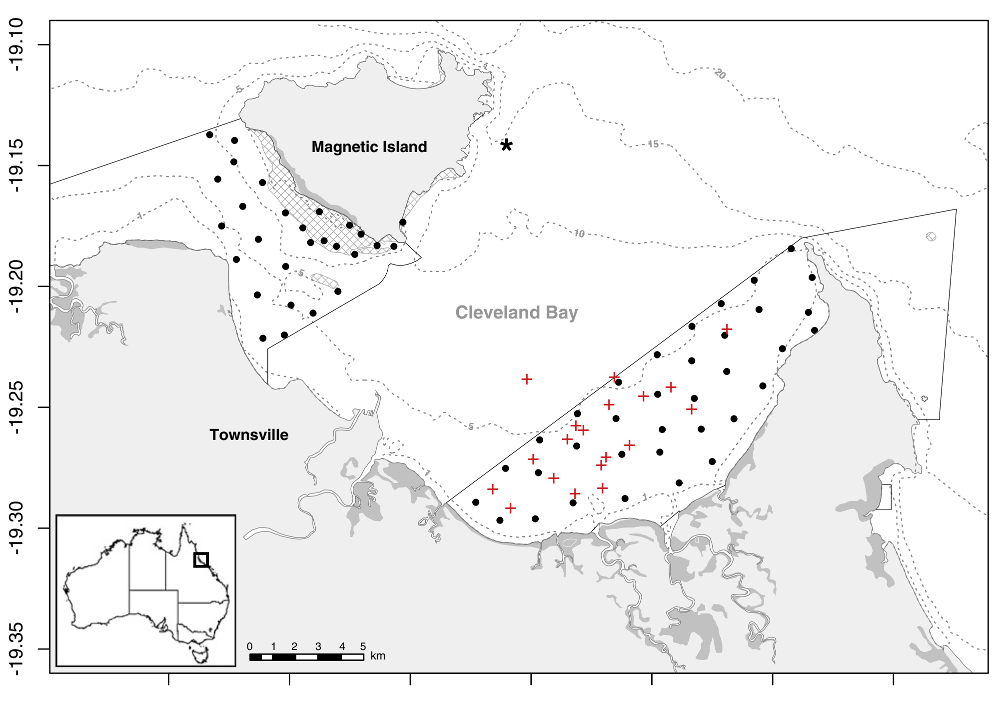

Fig. 1. Map of Cleveland Bay where solid points represent locations of acoustic receivers deployed on the east and western side of Cleveland Bay divided by a shipping channel. The location of the weather buoy within the study site is displayed as an asterisk (*). Capture locations of all tagged *Hydrophis curtus* are displayed as red crosses (+). Broken grey lines indicate bathymetry and solid lines are boundaries of conservation park zones. Cross-hatching indicates fringing reef habitats and dark grey areas along the coast indicate mangrove habitats.