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Change detection in animal movement using discrete wavelet analysis

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ABSTRACT

Animals moving through a complex environment change their movement patterns frequently. Such transitions from one movement behavior to another are a result of multiple factors such as weather, habitat and interspecific interactions occurring either individually or in tandem. Understanding where and when these changes occur is the first step towards understanding the limiting or key factors acting at different scales.

We applied discrete wavelet analysis to find change points in the movement behavior of a Lesser Black-backed gull (*Larus fuscus*). We compared our results with results from the residence method proposed by Barraquand and Benhamou (2008) and the statistical method proposed by Lavielle (1999, 2005). Discrete wavelet analysis allows the identification and localization of change points by decomposing the frequency content of two time series consisting of step length and residence time data, while omitting the problem of redundancy of coefficients consistent with continuous wavelet transformation of movement data.

We show that the novel use of discrete wavelet analysis in animal movement studies is widely applicable on different focus variables, allowing changes in the movement behavior and precise change points to be detected.

1. Introduction

The study of animal movement patterns reveals fundamental information about their behavior, habitat and ecology (Turchin, 1998). Animals use an environment that is patchy and heterogeneous (Fritz et al., 2003). Every part of this complex environment may be perceived as a patch or inter-patch at different scales of observation and with movements in a changing landscape (Barraquand and Benhamou, 2008; Fauchald and Tveraa, 2003; Wiens, 1989; Wiens et al., 1995). For example, animals may spend more time in a nesting or resting place and show only limited movement. In contrast, other places are used intermittently for foraging, where animals may show more dynamic movements. Segregation criteria for such composite movements are difficult to draw up in such a continuum of space and time, though it is also a necessary step towards understanding the habitats used for the different biological needs of an organism and the modes to reach these habitats.

The multi-scale and non-stationary nature of animal movement requires rigorous statistical methods to detect change points in their movements. While the definition of change varies with different scenarios, we used Sharifzadeh et al.'s definition of change as points in time where the local trend of data values change (Sharifzadeh et al., 2005). Here we propose a method using discrete wavelet analysis to identify discontinuity in time series data representing different movement behaviors in animals. However, we did not deal with the notion of degree of change, but instead focused on localizing time stamps, at which the properties of movement changed abruptly, but before and after which the properties remained constant. With an increasing repository of telemetry data available, much attention has been paid to the paradigm relating to research on moving animals. The "first passage time" (Fauchald and Tveraa, 2003) is one of more straightforward methods, where first crossing duration is calculated at the perimeter of a circle of radius (R) centered at a relocation point. The methods, though effective, involve subjectivity in the choice of the dimension 'R'. More automated methods with less subjectivity are the Hidden Markov models (Morales et al., 2004) and State Space models (Fryxell et al., 2008). These identify hidden movement modes but require a prior choice of the movement model as some form of correlated random walk (Johnson et al., 2008; Morales et al., 2004). Change detection using the properties of the trajectories were demonstrated by Gutenkunst et al. (2007) using local path straightness, as well as by Tremblay et al. (2009) by fractal analysis using the self-similarity in trajectories.

Barraquand and Benhamou (2008) proposed a method of segmenting trajectories and change point detection based on 'residence time' or the time spent near each location. This method is more generic than other methods of segmentation and combines calculating an

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ecologically relevant parameter with a robust statistical method of change detection. It proposes the statistical processing of a new signal composed of the residence time at each point of the animal's relocation. The approach is similar to the first passage time, which computes how much time an animal takes to cross a circle of a given radius (R), with the center at the relocation point. The residence time is biologically more appropriate because it calculates the first passage time at each relocation, plus the passage times that occurred in this circle before or after the current relocation. The qualification to this is that the animal does not spend a time greater than maximum time (maxt) before re-entering the circle. The segmentation of the trajectory and change points are calculated using the statistical method proposed by Lavielle (Lavielle, 1999, 2005).

Lavielle's method can also be used to detect change points in the movement trajectories using a movement focus variable other than the residence time, for example step length, speed, acceleration, or change in direction. Lavielle's method allows non-parametric segmentation of a time series using the penalized contrast method. This method finds the best segmentation of a time series of focus variables (e.g. residence time or step length) into K segments. It searches the segmentation for which a contrast function (measuring the contrast between the actual series and the model underlying the segmented series) is minimized.

Since it is statistically robust, we adopted Lavielle's method for analyzing two variables: step length and residence time. In addition, we used a more widely tested approach to analyze time frequency changes, namely wavelet analysis (Addison, 2002; Bibian et al., 2001; Nason and Sachs, 1999), on step length and residence time.

We propose a new and efficient approach towards detecting change points in animal movement time series data by exploiting the properties of discrete wavelet analysis. Wavelets have been well defined in change point detection (Yu et al., 2008) in fields such as the medical sciences, economics and geology, and its use has been well documented. In addition, wavelet analysis has been recently used to detect regime shifts and non-stationary properties of moving animals (Gaucherel, 2011; Polansky et al., 2010; Wittemyer et al., 2008). The novelty of the method we propose in this paper lies in adapting the use of discrete wavelet transform (DWT) on animal movement data, instead of the continuous wavelet transform (CWT) that is widely used in this field. Although CWT is useful in signal processing at all scales, it generates a large amount of data and further analysis of the wavelet coefficients becomes cumbersome. DWT is a more suitable alternative for analyzing scales and positions based on powers of 2 (dyadic scales). DWT avoids the redundancy in data characteristic of continuous wavelet analysis. This is important because the redundancy in CWT is indicative of the correlation of wavelet coefficients: these are intrinsic to the wavelet function rather than the time series, which makes the interpretation of the coefficients dependent on the chosen scale and the specific problem in question (Cazelles et al., 2008). Therefore, DWT makes further analysis of coefficients more efficient and is just as accurate (Mallat, 1989).

An important characteristic of wavelet analysis is that it does not assume stationarity of the data (Pittiglio et al., 2011) and animal movement is formed of temporal signals containing numerous non-stationary or transitory characteristics. Thus, these characteristics form movement signatures that can be identified and localized using wavelet analysis across a range of temporal scales. The discrete wavelet method consists of decomposing the signal into a hierarchical set of low frequency content (called the approximations) and high frequency content (called the detail). The Mallat algorithm is used for the fast wavelet transform of the signal. While the low frequency content of the signal gives the identity and global trends of the signal and coarse variations over time, the high frequency content is generally composed of the finer nuances and has the information needed to detect change points and frequency breakpoints. Since the 1990s, a large number of methods have been proposed for the use of wavelet transform to detect change points in different fields. However, the underlying idea is essentially based on the theory that change points are detected by finding large values of wavelet coefficients at different scales. The methods differ mainly on the quantification of how large the values need to be in order to be deemed a significant change point (Yu et al., 2008). The choice of threshold has varied from the maximum absolute value of coefficients (Wang, 1995) to extreme values over a certain threshold based on a pareto distribution (Raimondo and Tajvidi, 2004). Other statistical details such as standard deviation and variance from a normal distribution of the coefficients can also be considered for threshold selection (Bibian et al., 2001).

Here we use empirical data from the GPS tracking of Lesser Black-backed gulls (*Larus fuscus*). The change points with respect to their movement may show smooth transition while moving between proximal patches, for example, from the nesting site to the roosting site or while exploring for better resources. These would be represented as low coefficient values of the wavelet transform in the movement parameters. Sharp transitions in movement parameters such as step length or speed in the case of Lesser Black-backed gulls are apparent when the birds make long distant movements to the open sea for feeding, or sudden migratory movements (often more than 100 km) from the breeding, wintering or stop-over sites (Klaassen et al., 2012). These would be represented as high coefficient values in the wavelet transform of the movement parameter used for analysis.

Our aim was to test the effectiveness of a new, efficient, change detection method using discrete wavelet analysis for segmentation of the movement trajectories. Two focus variables, namely step length and residence time, were used to demonstrate the method, which we then compared with trajectory segmentation using Lavielle's method.

2. Methods

2.1. Gull data

Adult Lesser Black-backed gulls were mounted with Argos-GPS solar-powered Platform Terminal Transmitters (PTTs) from Microwave Telemetry Inc., Columbia, MD, USA (Ens et al., 2008)in Vlieland, one of the Wadden islands in the Netherlands. The tracking data of one bird (bird ID 41781) for the period May 2007 to May 2008 was used for the study. This period was chosen because it contained the maximum number of fixes. The gull was fitted with a 30 g PTT. The Argos-GPS PTTs had a locational accuracy of ± 22 m, a heading accuracy of $\pm 1°$ and a ground speed accuracy of ± 1 km/h (Klaassen et al., 2012). Fixes were recorded from 05:00 to 22:00 h, in 1-hour steps (18 fixes per day). A total of 3751 fixes were collected during the study period. Missing GPS fixes was estimated using expected values from a Kalman Smoother (Shumway and Stoffer, 2006) obtained from a state space model. This smoothing technique did not create artificial time dependency (Polansky et al., 2010).

The continuous position of the gull in time t, obtained as spatial coordinates $x(t)$ and $y(t)$, was used to construct a time series $X_n = (X_0,\ldots\ldots X_n)$. The step length was calculated as the distance between the current point and the next one in the data set (i.e. N, and $N + 1$, where N was the current record).

2.2. Calculation of the residence time

Computation of the residence time $\tau_R(i)$ was done by calculating the number of times the path crossed the perimeter of the circle centered on a location, both forward and backward. The duration of the path within each circle was then calculated as (Barraquand and Benhamou, 2008):

$$\tau_R(i) = \left[F_{1,R}(i) - B_{1,R}(i)\right] + \sum_{v=1}^{V(i)}\left[F_{2v+1,R}(i) - F_{2v,R}(i)\right] + \sum_{w=1}^{W(i)}\left[B_{2w,R}(i) - B_{2w+1,R}(i)\right]$$