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A pioneer validation of a state-space model of vessel trajectories (VMS) with observers' data

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ABSTRACT

In the context of the expansion of animal tracking and bio-logging, state-space models have been developed with the objective to characterise animals' trajectories and to understand the factors controlling their behaviour. In the fisheries community, the electronic tagging of vessels commonly designated by Vessel Monitoring Systems (VMS) is developing and provides a new insight for the understanding, the analysis and the modelling of the trajectories of vessels and their prospecting behaviour. VMS data are thus a clue for the proper definition of fishing effort which remains a fundamental parameter of tuna stock assessments. In this context, we used the VMS (recording of hourly positions) of the French tropical tuna purse-seiners operating in the Indian Ocean to characterise three types of movement (states) on the VMS trajectories (stillness, tracking, and cruising). Based on empirical evidences, and on the regular frequency of VMS acquisition, this was achieved by the development of a Bayesian Hidden Markov model for the speeds and turning angles derived from the hourly steps of the trajectories. In a second phase, states were related to activities disentangling stillness into fishing or stop at sea. Finally the quality of the model performances was rigorously quantified thanks to observers' data. Confronting model prediction and true activities allowed estimating that 10% of the hourly steps were misclassified. The assumptions and model' choices are discussed, highlighting the fact that VMS data and observers' data having different time resolutions, the effective use of validating data was troublesome. However, without validation, these analyses remain speculative. The validation part of this work represents an important step for the operational use of state-space models in ecology in the broad sense (predators' tracking data, e.g. birds or mammals trajectories).

1. Introduction

State-space models are commonly used in ecology and associated fields to analyse tracking data (Royer et al., 2005; Gutenkunst et al., 2007), in mark-recapture framework (Ovaskainen, 2004; Gimenez et al., 2007) or in the stock assessment context.

Apart from their primary role in control and surveillance, Vessel Monitoring System (VMS) data have recently started to be used in the perspective of management plans like for instance for UK trawlers (Witt and Godley, 2007), or to estimate trawling effort allocation (Mills et al., 2007) or re-allocation after opening a marine protected area (Rijnsdorp et al., 2001). VMS data have also been simulated by Deng et al. (2005) to determine the VMS acquisition frequency required to describe trawl tracks in the prawn fishery of New Zealand. The ecological potential of such source of information is increasingly acknowledged especially in the case of open ocean (and for highly migratory species), where no exhaustive scientific stock assessment survey can be undertaken. Moreover, some recent demonstrations highlighted that for fishing boats, and more specifically, for Peruvian anchovy purse-seiners, trajectories are those of efficient predators when the prey they are fishing are heterogeneous in space (Bertrand et al., 2005). Such considerations opened the use of the characteristics of the trajectories of vessels as a proxy for the abundance of the species they are targeting as this has been done for other marine top predators (Grémillet et al., 2004; Sims et al., 2006; Witt and Godley, 2007; Robinson et al., 2007).

However, to do so, it is necessary to relate the fishing activities and more precisely, the local behaviour of the vessel, to various levels of the prey's presence. Previous works on animals or fishers that ought to characterise trajectories as a whole (e.g. Levy flights by Mandelbrot, 1977; Viswanathan et al., 1996; Bertrand et al., 2005; Bertrand et al., 2007) or those that focussed on the sole identification of fishing operations (e.g. neural networks, Bertrand et al., 2008) or areas of restricted search (ARS) (Knoppien and Reddingius, 1985; Fauchald and Tveraa, 2003; Tremblay et al., 2007), did not

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aim to qualify all the segments of a trajectory, segment by segment. The idea here was to build a model that associates one particular activity to any single element of a VMS trajectory. We identified four main activities: fishing, stopping, tracking and cruising. Other activities are described in the tuna fisheries literature (Gaertner et al., 1999). Indeed, the main objective when estimating the activity of the vessel for each segment of the trajectory was to identify fishing sets and prospecting phases off which it was relevant to distinguish between cruising and tracking.

The state-space methodology has proven to be efficient to describe population dynamics (Ovaskainen and Hanski, 2001; Buckland et al., 2004; Thomas et al., 2005; Patterson et al., 2008), or to re-estimate the real trajectory of a tagged animal according to the associated state in a given landscape (Royer et al., 2005; Jonsen et al., 2005). This framework has also been applied to infer foraging and encamped phases in Canadian elks' movements (Morales et al., 2004). The primary objective of this work was thus to develop a state-space model to estimate the behavioural states of fishing vessels from their trajectories regularly sampled by VMS. Speeds and turning angles were extracted in sequences from vessels' trajectories, and were used to estimate fishing activity. Thanks to empirical evidences, we choose to model shifts between states by an order one Markovian process. This model was built in a Bayesian framework so that the inference of the model parameters was outputs of Monte Carlo Markov Chains (MCMC). To our knowledge no publication has yet been produced on the use of such model on VMS data even though this is an active field of research (Vermard et al., 2010). More importantly, none is validated by field observations. The secondary objective of this paper was thus to validate the estimations of such a Bayesian Hidden Markov model by real observations. Without such ad hoc validation, these studies remain speculative and we believe that the present paper represents an important step for the operational use of VMS in fisheries ecology.

Thanks to a long and fruitful collaboration with the French tropical tuna purse-seiners association and the French governmental department of Fisheries, we had access to their VMS data though under some confidentiality conditions. Meanwhile, due to the European Data Collection Regulation (DCR), 10% of the trips get observers on board providing us with data to validate the model.

2. Materials

2.1. Data

Since 2000, the European Commission legislated that all European fishing vessels longer than 24 m should be equipped with a Vessel Monitoring System (VMS) (and then all vessels longer than 15 m, in 2005) (EC, 1997 and 2003). The data used for this study were collected from the French-flagged purse-seiners based in the Seychelles islands, fishing several tropical tuna species (*Thunnus albacares*, *Katsuwonus pelamis*, *Thunnus obesus*) in the Western Indian Ocean (15 vessels in 2006, 17 vessels in 2007). The Global Positioning System (GPS) positions of the vessels were registered every hour and transmitted on shore by satellite (Argos or Inmarsat). Being GPS positions, the data were accurate (error smaller than few tens of meters) and regularly recorded every hour. Speeds (in knot) and turning angles (in rad) between consecutive positions were readily calculated from VMS data. They correspond to apparent hourly speeds and angles and not to the integration of the real speeds and angles along the vessel track. To honour the fact that vessels are most of time either full speed (around 12 knots) or immobile, we divided all speeds by the maximum possible speed for each vessel (~12 knots) so that they ranged between 0 and 1. Given the shoaling behaviour of the tropical tuna and given the fact that fishermen based their decision to fish on visual detection of tuna schools, fishing activity occurs at day. Only the daytime parts of the trajectories were then used. Starting and ending time of the day were deduced from the date and the latitude and longitude of each GPS position through an ad hoc routine to automatically select the daylight VMS data.

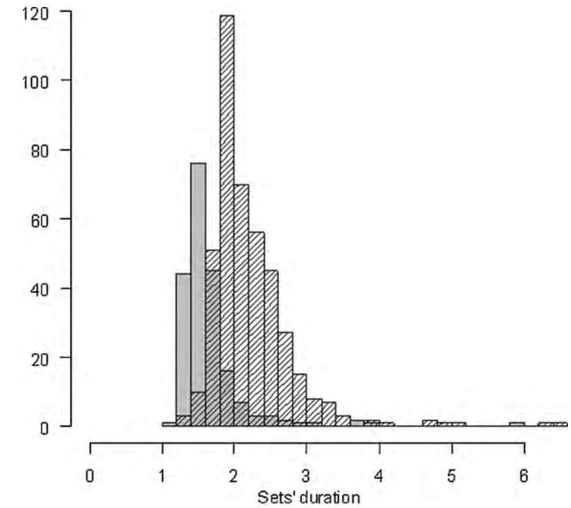

Fig. 1. Histograms of the duration (in hours) of fishing operations (fishing sets). Observers' data set (10% of the complete fleet). Hachured white: successful sets (m = 2.23 h, σ = 0.58 h). Grey: unsuccessful sets (m = 1.65 h, σ = 0.50 h).

The observers' program in the French purse-seiner fleet in the Indian Ocean is being undertaken in the framework of the European Data Collection Regulation (DCR – EC Reg. 1563/2000). This regulation specifies that 10% of the trips realised by each member country fleet have to get an observer on board. For the French fleet of tropical purse-seiners operating in the Indian Ocean, the program started in November 2005 and 16 trips over a total of 120 trips were available for the period 2006–2007. However, only 11 trips corresponded to vessels with a French flag reducing the number trips that were available for the analysis. Observers record the position of the vessel at least every hour, and at each change of speed or turning angle (course) of the vessel. They also record the beginning and ending time of each fishing operation. One of these trips considered as a standard one with regards to the number of days at sea, the number of fishing sets, and the ratio of sets on free-swimming schools and log schools, was used for calibrating the parameters of the model.

2.2. States and activities

We distinguished the states of a vessel (movement states which refer to its trajectory) from its activity. Schematically, the primer concerns the vessel, while the latter refers to the fishermen on board of this vessel. For the tropical tuna purse-seiner studied here, four major activities were considered. A fishing operation (activity 1 = fishing) lasted generally more than 1 h due to the time required to set the seine out and to get it back. Unsuccessful fishing sets (null sets) corresponded to stops of 1.65 h on average (σ = 0.5 h; Fig. 1). When the school was effectively trapped (positive sets), the extra time required to brail fish on board was 1 h per 100 tonnes on average. The average duration of a positive fishing operation was then 2.23 h (σ = 0.58 h; Fig. 1). The second type of activity (activity 2 = stop) corresponded to stops at sea. Stops were required either to maintain electronic equipments located on Fish Aggregating Devices (FADs) or to evaluate the effective presence of fishable schools. In this regards stops at sea contributed, even in a non-trivial manner, to the fishing effort. Long stops were hardly ever due to technical break-downs and damages. As a matter of fact, when such