Analysis of Greenland narwhals's behavioural responses to ship noise and airguns exposure using varying coefficients correlated velocity models

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ordre alphabétique.

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1 Introduction

Assessment of human disturbance on animal behaviour has become a major concern in the ecology community. Both instantaneous and long-term changes in animal behaviour have been studied by taking advantage of the large amount of wildlife data now available. One of the commonly accepted method to analyse such behavioural changes due to human activities is to perform "controlled exposure experiments". Animals are exposed to disturbances in a precise and monitored set up where different statistics can be measured: GPS positions, sound exposure level, temperature, pressure, heart beat, stroke rate... Several studies involving beaked whales [Tya+11], common sole larvaes [Bol+12], narwhals [Hei+21] and many other species have already been done. Marine mammals are particularly challenging to track since GPS data can only be retrieved when they emerge at the surface of the sea and a satellite is near enough. Moreover, some species can dive at great depth, so that the equipment must keep working in such extreme environment [Cio+22]. In this paper, a data-set of east Greenland narwhals's movement under controlled exposure experiments will be analysed.

As a consequence of climate change and decrease in sea ice coverage, the Greenland ecosystem is likely to be more and more exposed to anthropogenic activity in the next decades [Hei+21]. Shipping activities as well as sonar and seismic surveys are a few instances of new disturbances that could alter animals's habits. Hence, there is an urge for more knowledge about the impact this could have on endemic species such as the narwhals. This marine mammal is one of the most sensitive to sound exposure as it uses echolocation to orient itself beneath the water [Ter+21]. Moreover, recent studies showed that the population of narwhals in Southeast Greenland is already in decline [Gar+22]. The effects of sound and ship exposure on its diving and foraging behaviour have already been the subject of several studies [Hei+21; NHD19]. However, their horizontal movement has for now been analyzed with discrete time methods such as Markov chains [Hei+21]. A covariate representing the level of sound received by the narwhals was used to model the transition probabilities of the Markov Chain, and it was concluded that narwhals effectively tried to avoid the ship by moving fast toward the shore. ADD MORE DETAILED EXPLANATIONS. Here, we use a continuous time model to analyse the GPS positions and try to corroborate this analysis. The objective is to be able to quantify the effect of sound exposure on different characteristics of the movement.

We propose to use ~~A~~ stochastic differential equation with varying coefficient ~~will be used~~ to model the GPS tracks of the individuals. The continuous time correlated random walk (also known as integrated Ornstein-Uhlenbeck, or correlated velocity model) that has been introduced in [Joh+08] was judged appropriate for this data. It has been widely used in ecology to model 2D animal movement [Gur+17], and even 3D movement in some cases [GGN11].

à revoir

In the context of animal movement, this model can be written [Gur+17]

$$\begin{cases} dv(t) = -\frac{1}{\tau}(v(t) - \mu)dt + \frac{2\nu}{\sqrt{\pi\tau}}dW(t) \\ dx(t) = v(t)dt \end{cases} \tag{1}$$

$v(t)$ is the horizontal 2D velocity at time t and $x(t)$ is the position, typically in longitude and latitude or in UTM coordinates. $W(t)$ is a 2 dimensional brownian motion. The movement is supposed to be isotropic: velocity components $v_1(t)$ and $v_2(t)$ and locations components $x_1(t)$ and $x_2(t)$ are thus independent. The parameter τ drives how fast the velocity will increase or decrease with respect to the mean velocity μ on each time unit. When τ is high, velocity relaxes slowly to the mean velocity μ, meaning that the animal changes direction very slowly. Then, the parameter ν controls the norm of the velocity and drives how much random variability there is in the velocity vector.

This equation is a special case of velocity potential model, where the potential is a second degree polynomial [PAW13]. The inference method is based on the `smoothSDE` package [Mic+21]. Simpler SDE models as Brownian motion or Ornstein-Uhlenbeck with varying coefficient proved to be efficient at assessing deviation from a baseline model that represents the animal behaviour under normal conditions. For instance, it was used in [Mic+22] to estimate avoidance behaviours of beaked whales after exposure to military sonar systems. To our knowledge, the varying coefficient Integrated Ornstein-Uhlenbeck model has not been used yet to analyse such behavioural responses.

peut être à mettre avant ?

Eventually, most of the SDE used to model animal movement are unconstrained [Joh+08; Mic+21; Gur+17]. However, as mentioned in [HJH17], "inference without considering the spatial constraint could lead to biaised estimates for parameters governing animal movement". While a lot of results are known about the existence and properties of constrained diffusions, their application in the context of animal motion remains relatively underdeveloped [Bri03]. Recent papers include [HJH17] and [Rus+18], where, respectively, parameters (β, σ) of a reflected version of the CTCRW defined in [Joh+08] are estimated from sea lion telemetry data, and a repulsive potential function is used to constrain ants movement within a box. The way to model the motion of the animal near the boundary of the domain should be species-specific, accounting for the particular behaviors and spatial use of the studied animal : "One can speculate on how the animals behave when they get to the boundary. They may walk along it for a while. They may run at it and bounce back. They may stand there for a while." [Bri03]. While simulation methods for such models are well established, inference seems to be less advanced. Current approaches rely on computationally intensive MCMC algorithm such as Metroplis-Hastings, and require high frequency data. This requirement is typically met by linearly interpolating between the discrete time observations of the process [HJH17]. In the last section of this paper, we tried to consider constrained movement within the framework of the R package `smoothSDE`, therefore making the inference reasonably fast. We combined the work of Michelot [Mic+21] and the rotational advective correlated velocity model (RACVM) defined in [Gur+17] to incorporate a rotation of the velocity biaising the process to align with the boundary of the domain as it gets closer to it. The SDE for this model is

éviter les citations reformuler.

insister sur le nouveau modèle

$$\begin{cases} dv(t) = -A(v(t) - \mu)dt + \frac{2\nu}{\sqrt{\pi\tau}}dW(t) \\ dx(t) = v(t)dt \end{cases} \tag{2}$$

where $A = \begin{pmatrix} \frac{1}{\tau} & -\omega \\ \omega & \frac{1}{\tau} \end{pmatrix}$. The new parameter ω is an angular velocity that controls how fast the velocity vector should rotate. The parameters τ and ω will be estimated as smooth functions of the distance to the boundary and the angle between the animal's direction and the boundary normal vector.
To summarize, the main contributions of the paper are

- Use of a varying coefficient Integrated OU model to analyze behavioural reponse with exposure covariate defined as the inverse of the Distance to the ship. This is a proxy for received sound exposure.
- Computation of the closed formulas for the RACVM defined in [Gur+17] of which Integrated OU is a special case with $\omega = 0$, and addition of this model in the framework of `smoothSDE`, therefore enabling the use of covariates for the parameters, and estimation from data irregularly spaced in time.
- Definition of a toy Constrained Rotational Correlated Velocity Model (CRCVM) for simulation study. Deviations angles from shoreline and distance to shore are used as covariates to constrain the movement within a polygon, and align the velocity with the boundary of the domain.
- Estimation of the CRCVM on the narwhal data using tensor splines.

+Annonce plan.

mettre en valeur angles, distance to shore comme covariates dans l'EDS. C'est un moyen que le drift de v(t) dépende de x(t).

2 Movement data of Greenland endemic narwhals

The dataset analysed in this paper has already been the subject of several studies, focusing mainly on the diving behaviour of the narwhals [Hei+21; Ter+21; NHD19]. Six male narwhals were equipped with FastLoc GPS receivers in August 2018 in Scoresby Sound fjord system in East Greenland by biologists from the Greenland Institute of natural ressources, with the help of local Inuit hunters. The Scoresby Sound fjord system is known to be the summer residence for an isolated population of narwhals. Here we recall briefly how the data has been retrieved. For more details about the study area and the tagging of the animals, the reader may refer to [Hei+21]. An offshore patrol vessel military ship was sailed to shoot airguns underwater between August 25 and September 1. It was equipped with two Sercel G-guns at 6m depth and moved at a speed of 4.5 knots. The guns were fired synchronously every 80 s, and the GPS navigation system recorded the location of every shot. ~~Eventually, the~~ data includes narwhals's latitude and longitude, ship's position, ~~narwhals's depth in metres~~, distance to the ship in metres, GPS time, distance to the shore in metres.

donner le pas de temps des observations

Experiments were divided in unexposed periods - for which the narwhals are not in line of sight with the ship - trial periods - when the narwhals are exposed to the ship and airguns are shot - and intertrial periods - when the narwhals are exposed to the ship but airguns are not shot. These periods are indicated by a categorical variable T_{ship} in the dataset.

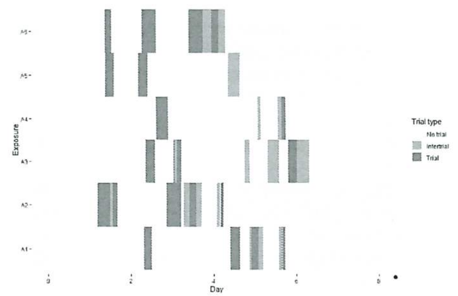


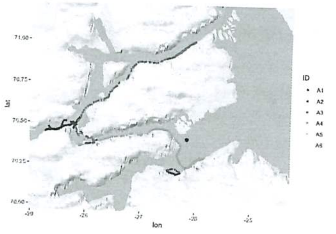
Figure 1: Trial and Intertrial periods for each narwhal

For each narwhal, the entire track was separated in a period before exposure defined as the period before the narwhal gets in line of sight with the ship for the first time, and a period during exposure, after the narwhal has been in line of sight with the ship for the first time. We kept only GPS measures 24 hours after tagging, to avoid any tagging effects on the narwhals's movement, as recommended in [Hei+21]. Measures that resulted in a velocity higher than 20 km/h were also discarded (only 2 data points for the same narwhal track). Overall, 4192 GPS positions were kept for the analysis and projected to UTM coordinates zone 26. The splitting between data before and after exposure resulted in 935 measures before exposure and 3257 measures after exposure. Table 1 shows how the data is distributed among the different narwhals. ~~and~~ figure 2 shows all the tracks before and during exposure.

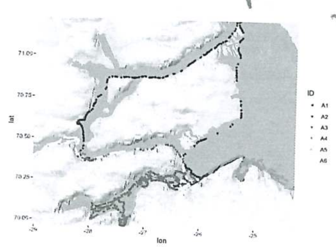
Narwhal ID	Number of measurement before exposure	Number of measurements during exposure
A1	258	576
A2	40	515
A3	222	680
A4	291	642
A5	48	419
A6	76	425
Total	**935**	**3257**

Table 1: Distribution of the data among the 6 individuals

description du pas de temps moyen? median, min, max?



(a) Tracks before exposure experiments



(b) Tracks during exposure experiments

Figure 2: Movement data of East Greenland narwhals

GPS positions are known only at specific times when the narwhals get close to the sea surface. The median time step between two GPS measurements in the data is about 5 minutes and only 0.3% of the time steps reach more than two hours, with a maximum at more than 4 hours.

à dire avant + dans le tableau

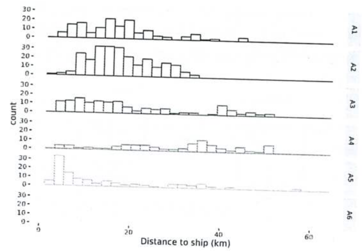
The distance from the ship was computed from the GPS ship and narwhals's positions. The values are comprised between 2.68 and 63.8 km. The land geometry for this specific region in South-East Greenland was gathered from OpenStreetMap database. For each GPS measurement time t_j, the nearest point $p(t_j)$ on the shoreline was computed and the distance to the shore was determined as the distance to this point. The resulting values range from 0 to 7.5 km. About 9% of the GPS measurements in the dataset turned out to be on land. This was primarily attributed to inaccuracies in the shoreline maps rather than errors in GPS measurements. The angle between the narwhal's heading was computed as the angle between each step vector $x(t_j + \Delta_j) - x(t_j)$ and the vector $x(t_j) - p(t_j)$. Histograms of the distance to the ship and the distance to the shore are shown in figure 3.

mettre un dessin avec les angles, qui aidera aussi à comprendre la modélisation des rotations?

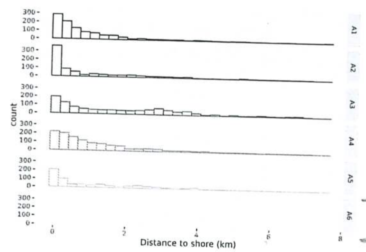
Donner definition exposure to shore

$$= \begin{cases} 1/\text{dist shore} & \text{if} \leq 200m \\ 0 & \text{if} > 200m \end{cases}$$

The closer the narwhal is to the shore, the greater the exposure



(a) Histograms of the distance to the ship for each narwhal



(b) Histograms of the distance to the shore for each narwhal

pas besoin de couleurs différents.

← peu lisible

Figure 3: Distance to ship and distance to shore covariates

~~An~~ The exposure covariate was defined as the inverse of the distance to the ship (in km). donner ref papier précédent D_{ship} is not known when the narwhal is not in line of sight with the boat, so that exposures are set to 0 in this case. The closer the narwhal is to the ship, the greater the exposure. This is a proxy for sound exposure levels received by the narwhals. It has been used as a covariate in the probability transition for the Markov chain that was defined in [Hei+21] to analyze horizontal avoidance behaviours of the narwhals.

en intro eventuellement mais pas ici

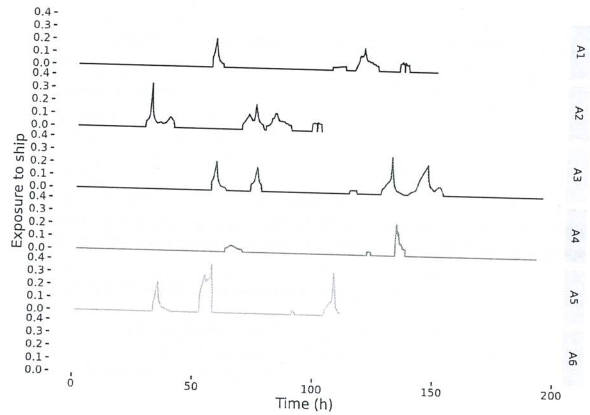


Figure 4

In equation 1, the characteristics of the movement are captured within the parameters τ, μ and ν of the correlated velocity model. Therefore, the effects of ship and airgun sounds exposure on the narwhals's movement need to be assessed by understanding how these parameters change depending on the ship exposure covariate. The package `smoothSDE` is a convenient tool to fit SDE with mixed effects (SDEME) in the parameters. It has already been used in the context of behavioural studies [Mic+22].

The covariates that will be used in the next sections are summarized in table 2