Segmentation

Principles and pitfalls

Elie Gurarie

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MAX PLANCK INSTITUTE OF ANIMAL BEHAVIOR

Behaviors are always changing!

It can be important and interesting to know **where** / **when** / **why**.

Lots of work has gone into finding where a movement track changes properties.
This is, broadly, called *segmentation*.

Journal of Animal Ecology
British Ecological Society
Journal of Animal Ecology 2016, **85**, 69–84 doi: 10.1111/1365-2656.12379

SPECIAL FEATURE: STUCK IN MOTION? RECONNECTING QUESTIONS AND TOOLS IN MOVEMENT ECOLOGY

What is the animal doing? Tools for exploring behavioural structure in animal movements

Eliezer Gurarie[1,2]*, Chloe Bracis[3], Maria Delgado[4,5], Trevor D. Meckley[6], Ilpo Kojola[7] and C. Michael Wagner[6]

Edelhoff *et al. Movement Ecology* (2016) 4:21
DOI 10.1186/s40462-016-0086-5
Movement Ecology

REVIEW Open Access

CrossMark

Path segmentation for beginners: an overview of current methods for detecting changes in animal movement patterns

Hendrik Edelhoff*, Johannes Signer and Niko Balkenhol

First Passage Time

Spatial and simple

Asks, how long does it take an animal to leave a particular radius - **at every point**?

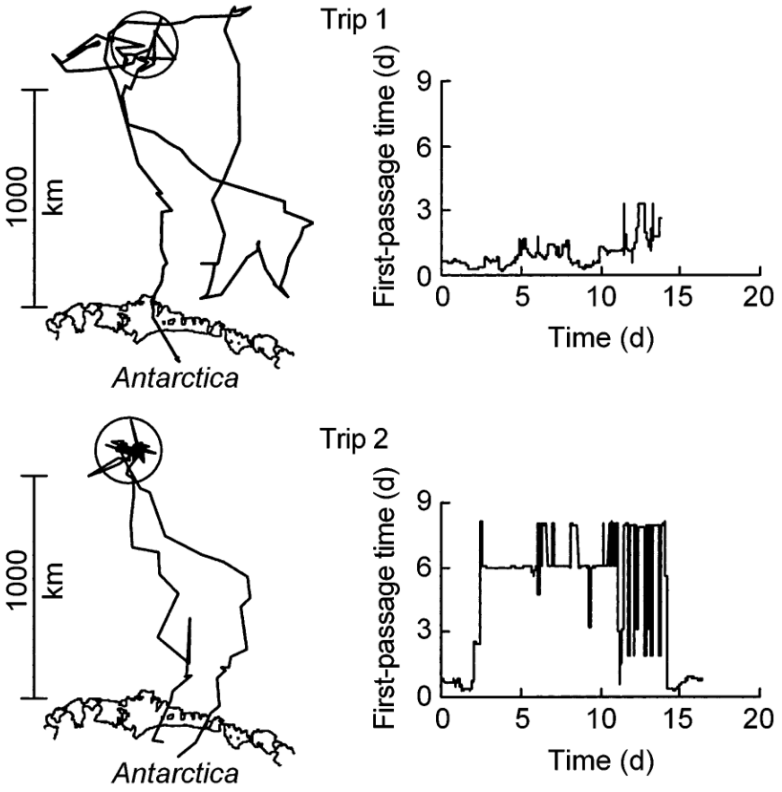
Ecology, 84(2), 2003, pp. 282–288

USING FIRST-PASSAGE TIME IN THE ANALYSIS OF AREA-RESTRICTED SEARCH AND HABITAT SELECTION

PER FAUCHALD[1] AND TORKILD TVERAA

Norwegian Institute for Nature Research, Division of Arctic Ecology, Polar Environmental Center, N-9296 Tromsø, Norway

In the `adehabitat` family of packages.



Lavielle Segmentation

Statisticially find the best division ofa **single time-series** (e.g. speed).

Assumes that the time series is independent Normal with possible change in **mean** and **variance**

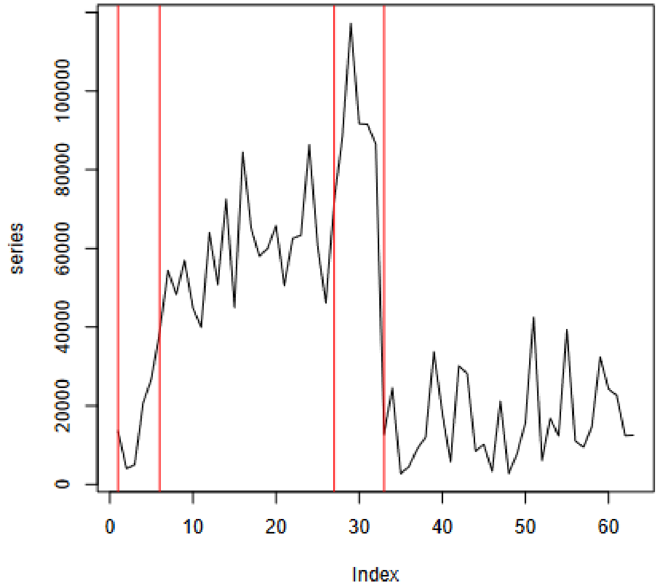
Very nicely implemented in `adehabitatLT` vignette:

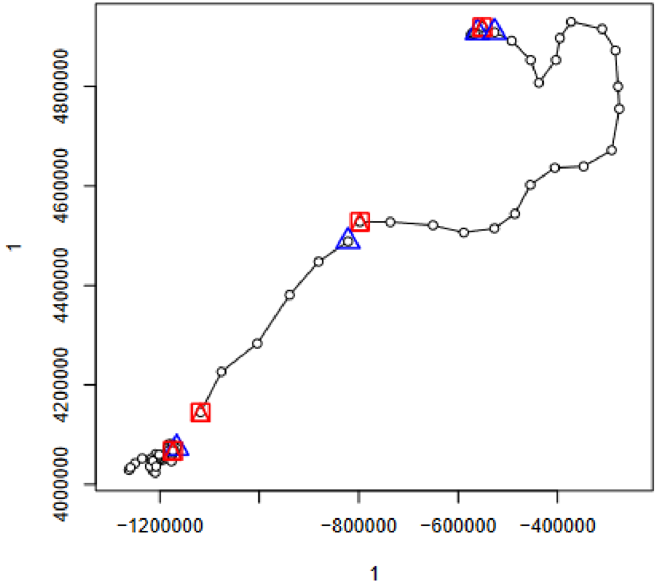
Analysis of Animal Movements in R: the `adehabitatLT` Package

Clement Calenge,
Office national de la chasse et de la faune sauvage
Saint Benoist – 78610 Auffargis – France.

March 2019

This is a dolphin track.





IEEE TRANSACTIONS ON SIGNAL PROCESSING, VOL. 46, NO. 5, MAY 1998 1365

Optimal Segmentation of Random Processes

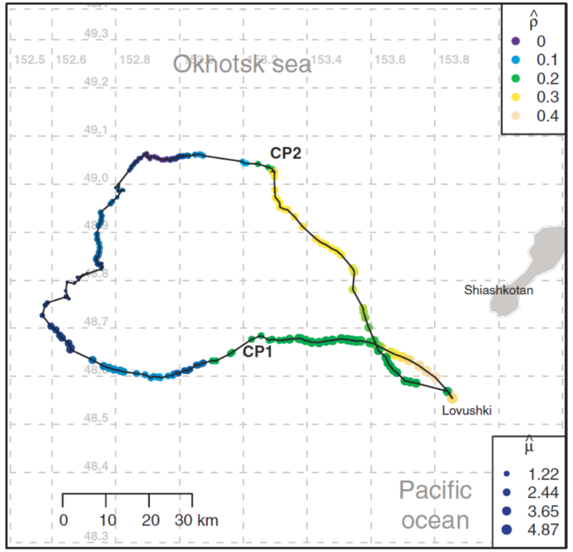
Marc Lavielle

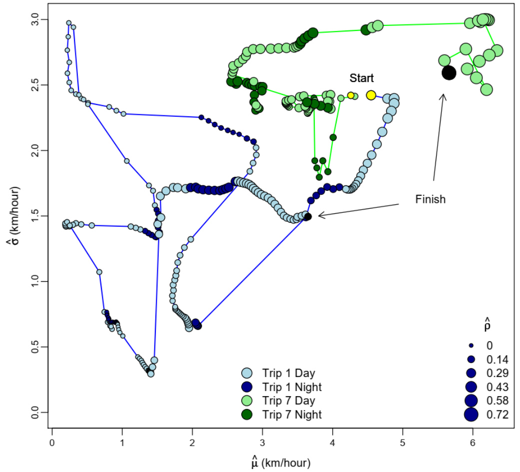
Behavioral Change Point Analysis

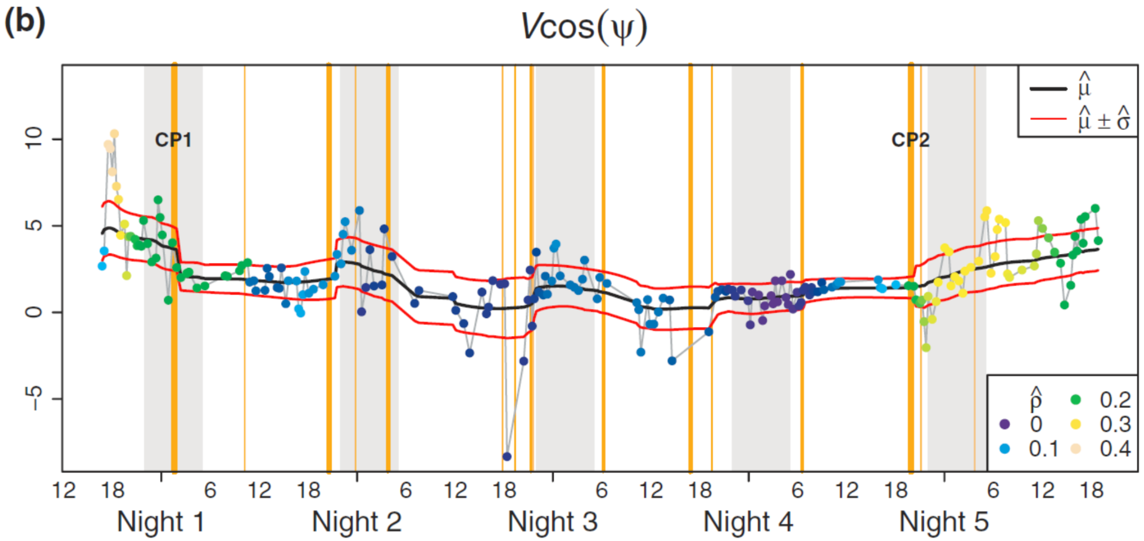
Gurarie et al. 2009

Expands on Lavielle by allowing for **irregular data** and **auto-correlation**.

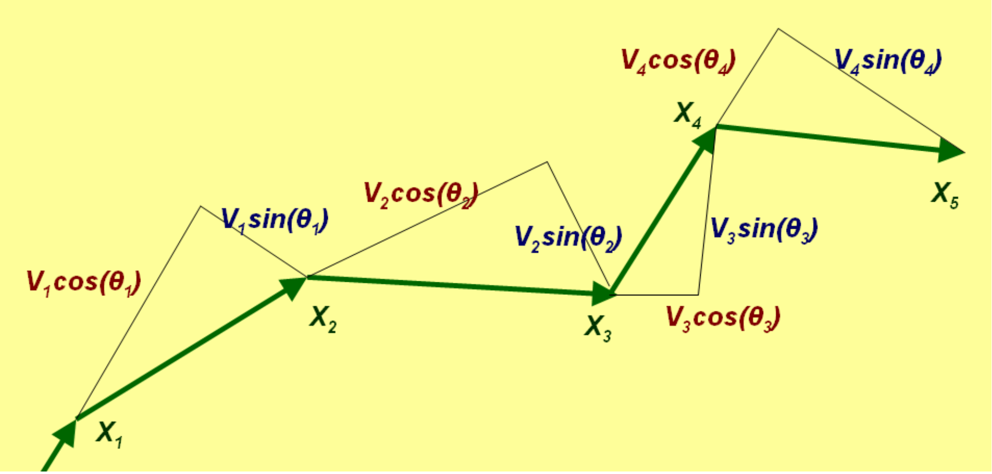
bcpapackage







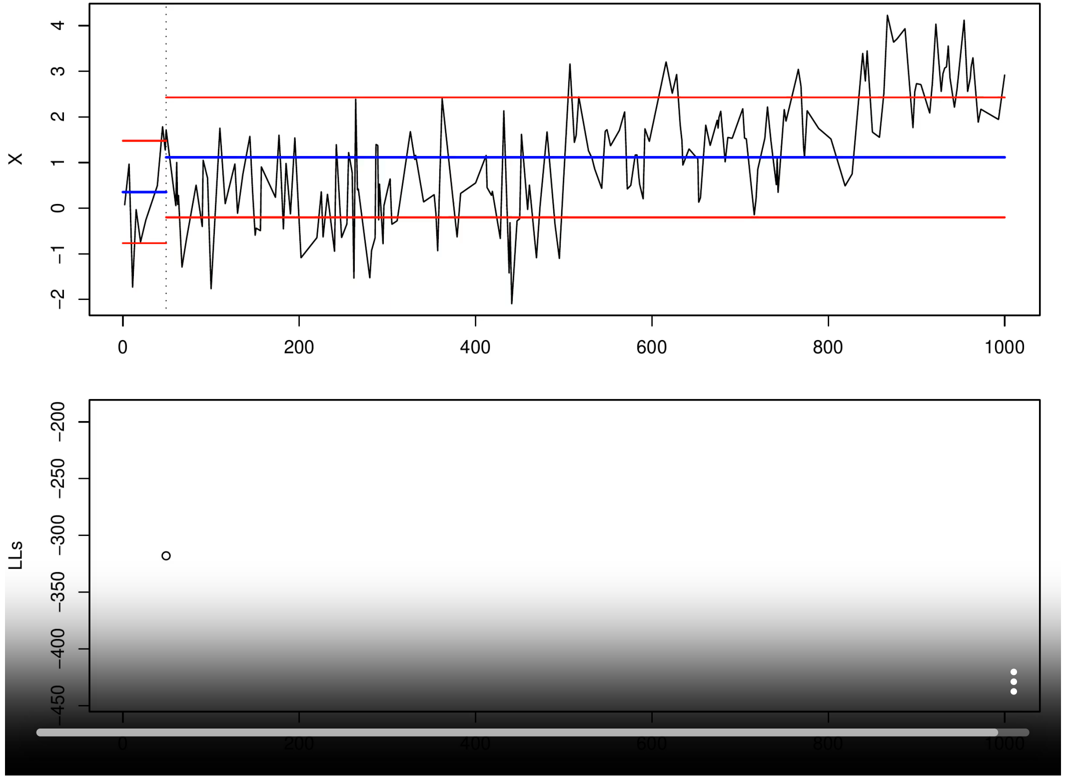
Likelihood-based - single changepoint



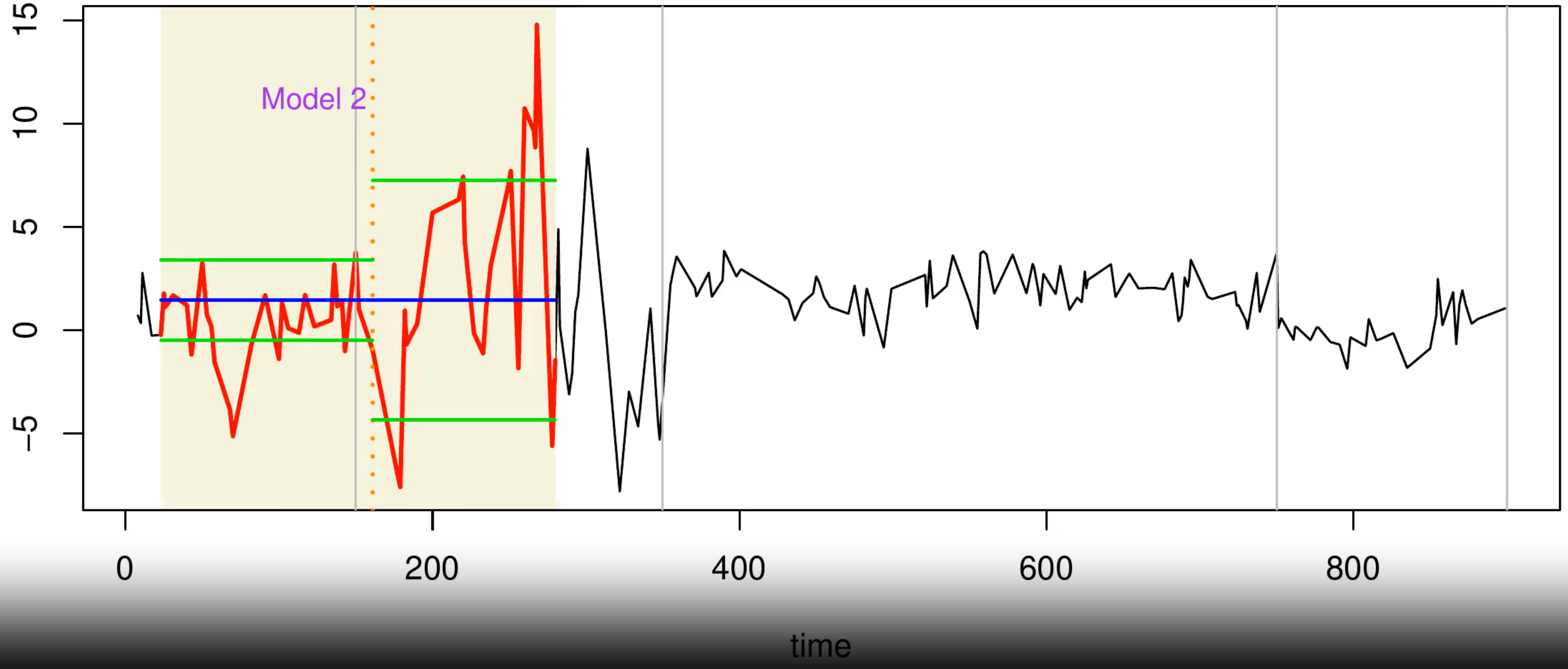
$$W(0) = W_0, \quad \mathrm{Var}[W(t)] = \sigma^2,$$

$$E[W(t)] = \mu, \quad \mathrm{Corr}[W(t), W(t-\tau)] = \rho^\tau,$$

$$L(\mathbf{\Theta}|\mathbf{X},\mathbf{T}) = \prod_{i=1}^{n} f(X_i|X_{i-1},\mathbf{\Theta}_1) \prod_{j=n+1}^{N} f(X_j|X_{j-1},\mathbf{\Theta}_2)$$



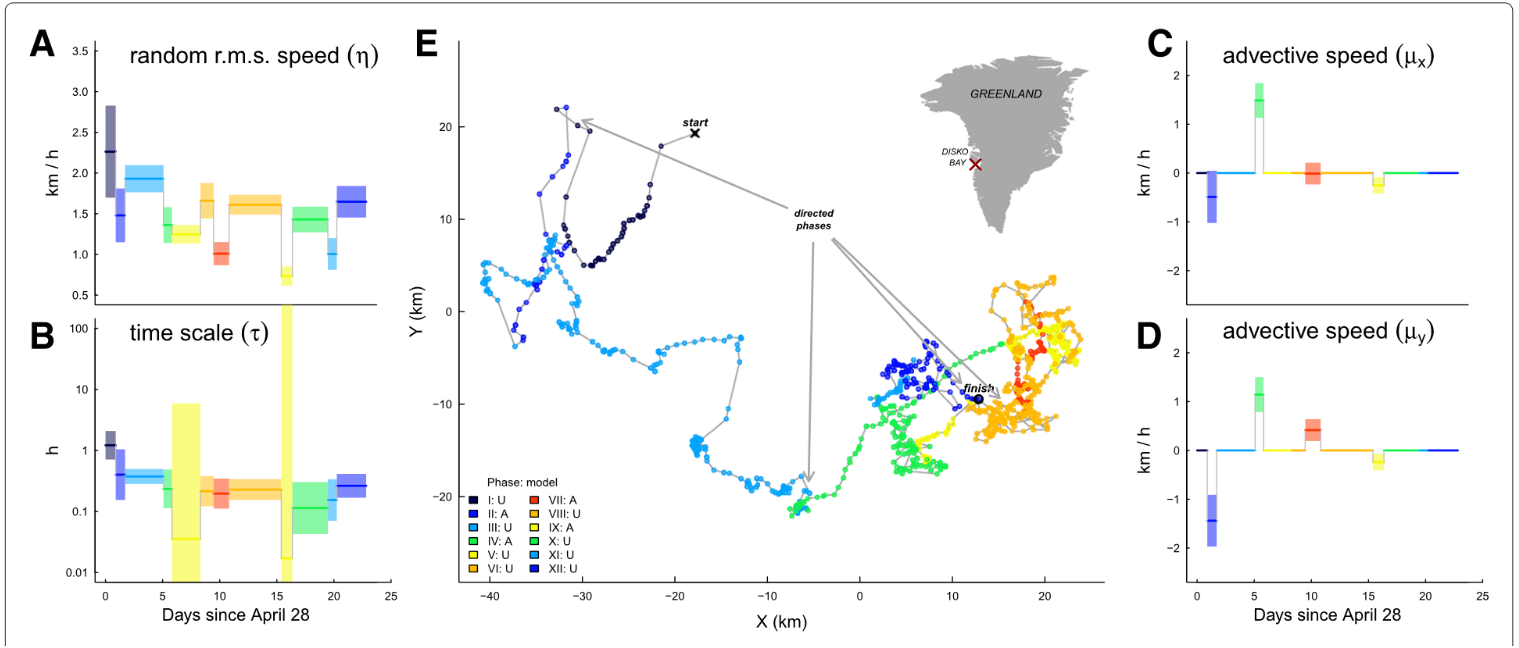
Window-sweeping



BCPA on Continuous Time Movement Models

Fits actual (continuous time) movement models and finds change points.

`smoove` R package (on GitHub)



Bowhead whale
Balaena mysticetus

BCPA on Continuous Time Movement Models

Can do fun things like rotation

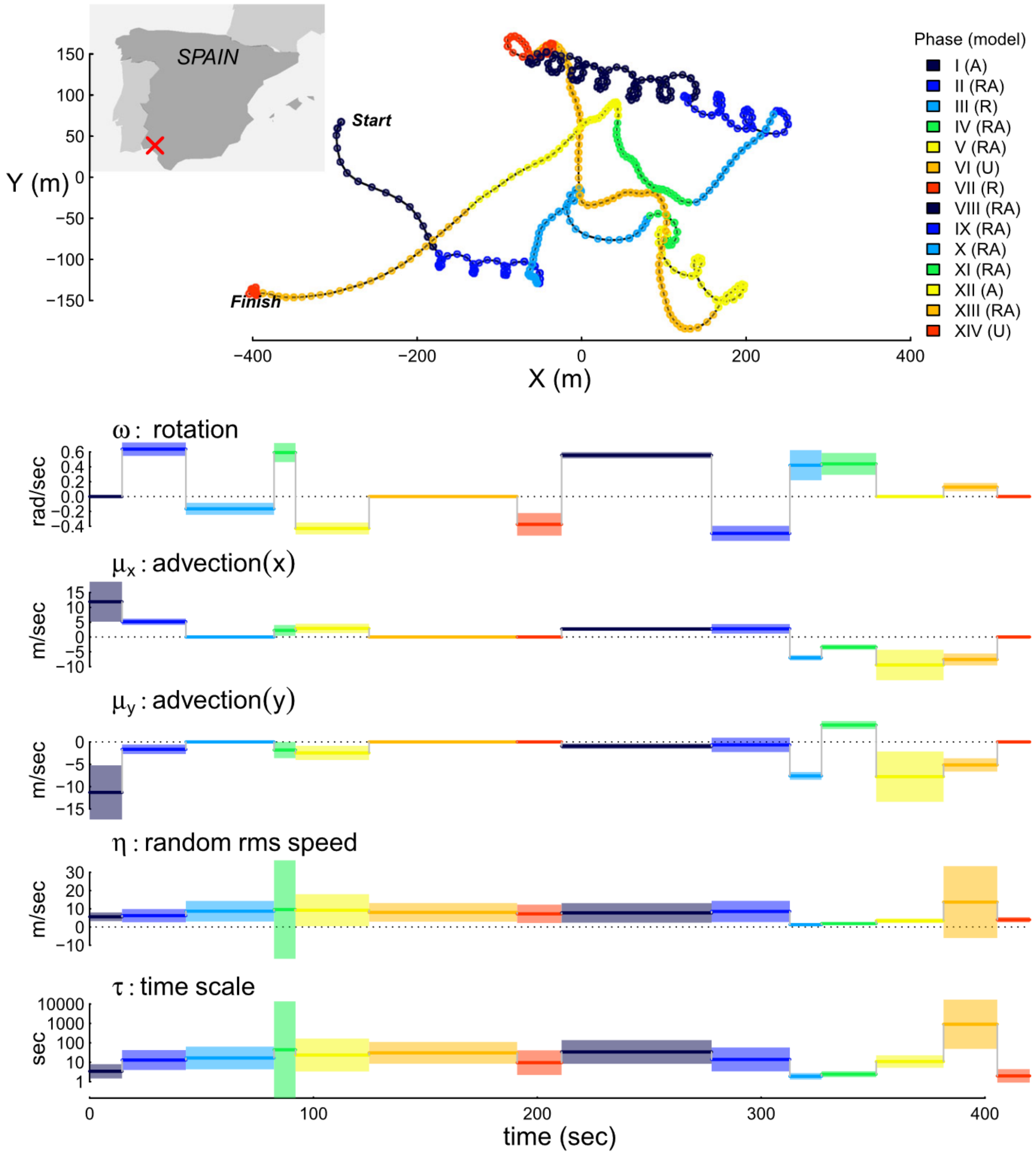
Gurarie *et al. Movement Ecology* (2017) 5:13
DOI 10.1186/s40462-017-0103-3

Movement Ecology

METHODOLOGY ARTICLE Open Access

Correlated velocity models as a fundamental unit of animal movement: synthesis and applications

Eliezer Gurarie[1*], Christen H. Fleming[1,2], William F. Fagan[1], Kristin L. Laidre[3], Jesús Hernández-Pliego[4] and Otso Ovaskainen[5,6]

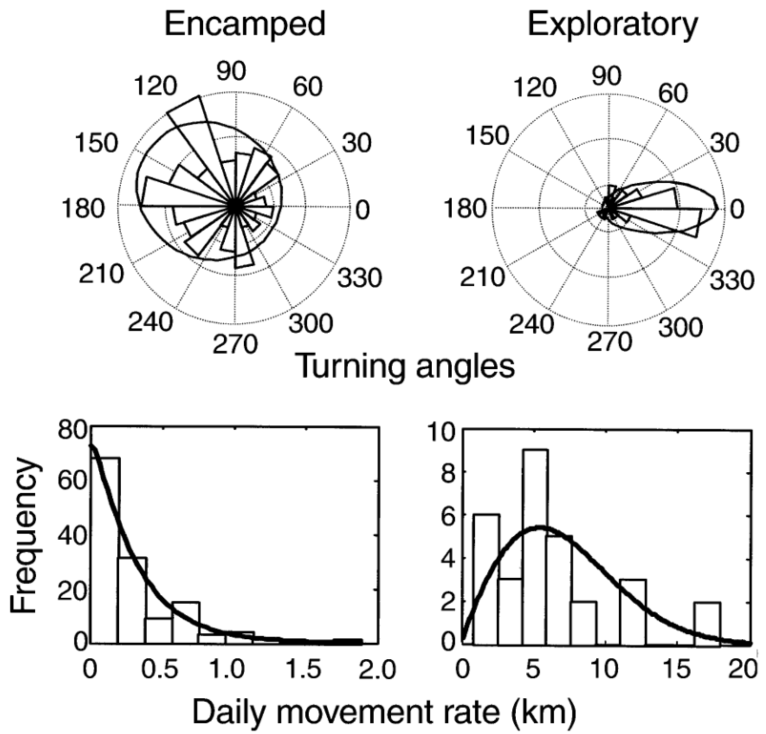


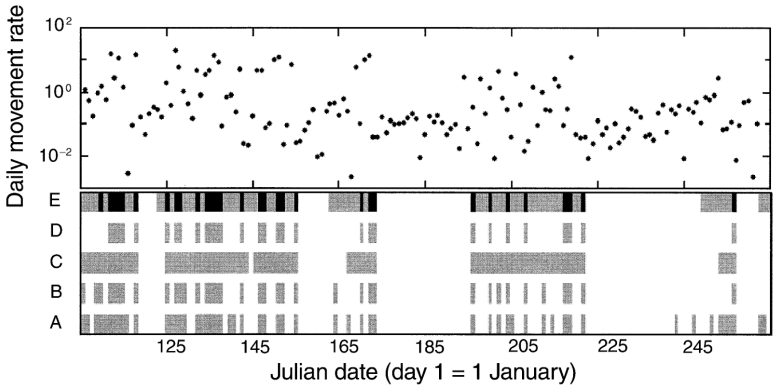
Multi-state random walks

aka. **State-Space" modeling** or **Hidden Markov Movement Model**

1. Define pre-fixed number of states, with particular movement parameters for example:
    - persistence coefficient ρ
    - and step-length distribution paramaters α and β
2. Estimate the **Markov transition probability matrix**
3. Make predictions from that probability matrix

Lots of examples! But they are all variations on **Morales et al. 2004**





Sea Turtles! movement and diving

States include:

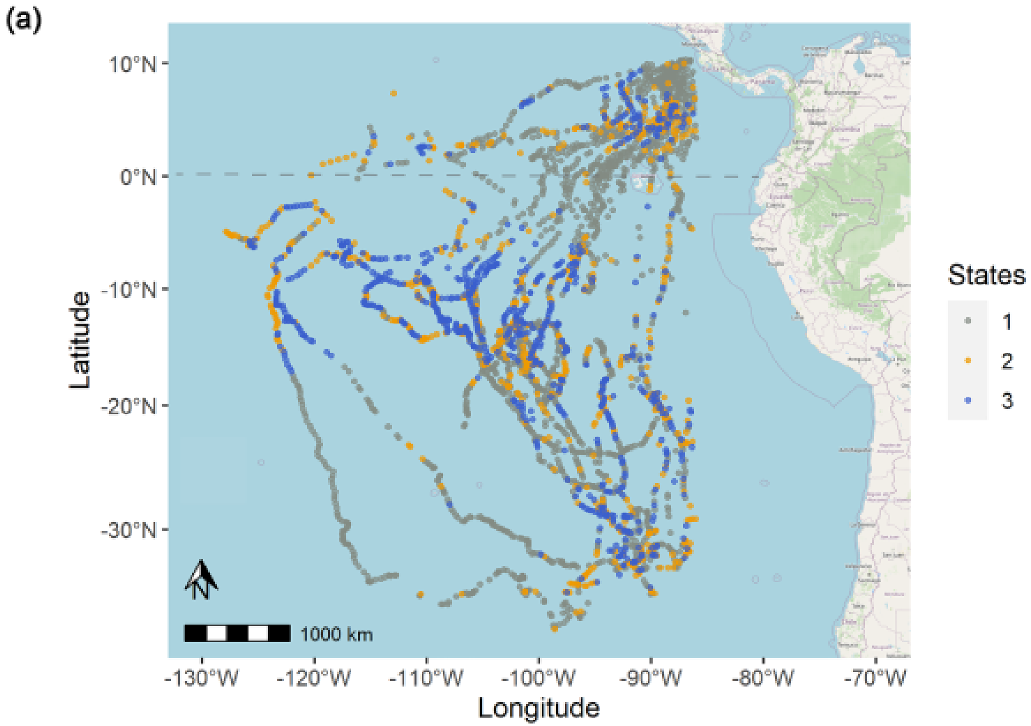
- **S1**, shallow dives, fast and directed horizontal movement;
- **S2**, mixture of dive depths, slower and less directed horizontal movement;
- **S3**, deep dives, intermediate speeds, and partially directed horizontal movement.

Parameter[b]	State 1 (SD)	State 2 (SD)	State 3 (SD)
μ	30 (9.9)	2.0 (1.3)	21 (8.4)
σ	8.9 (3.0)	5.9 (4.6)	4.8 (3.2)
P	0.16 (0.048)	0.68 (0.096)	0.84 (0.048)
λ	8.1 (4.8)	8.1 (4.8)	8.1 (4.8)

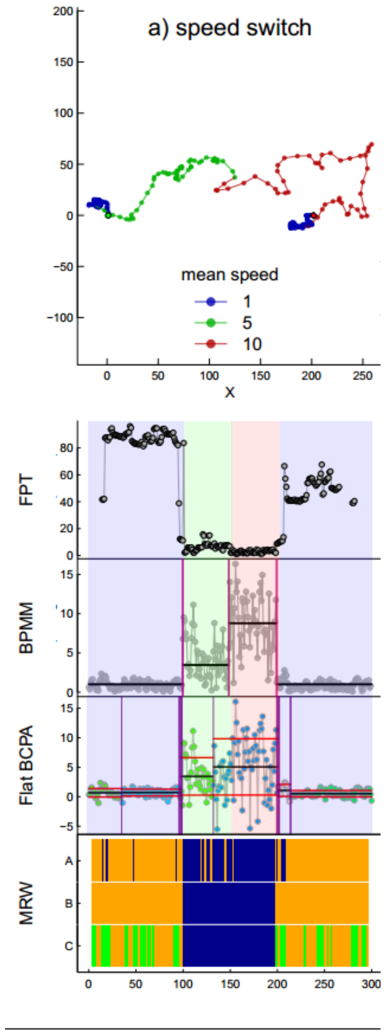
Received: 14 October 2022 | Revised: 12 May 2023 | Accepted: 16 May 2023
DOI: 10.1111/cobi.14114
Conservation Biology
CONTRIBUTED PAPERS

Incorporating multidimensional behavior into a risk management tool for a critically endangered and migratory species

Nicole Barbour[1,2,3,6] | George L. Shillinger[3,4,5] | Eliezer Gurarie[2,6] | Aimee L. Hoover[3] | Philippe Gaspar[7] | Julien Temple-Boyer[7] | Tony Candela[3,7] | William F. Fagan[2] | Helen Bailey[1]



Comparing tools



Four phase CVM

Slow Fast Faster Slow

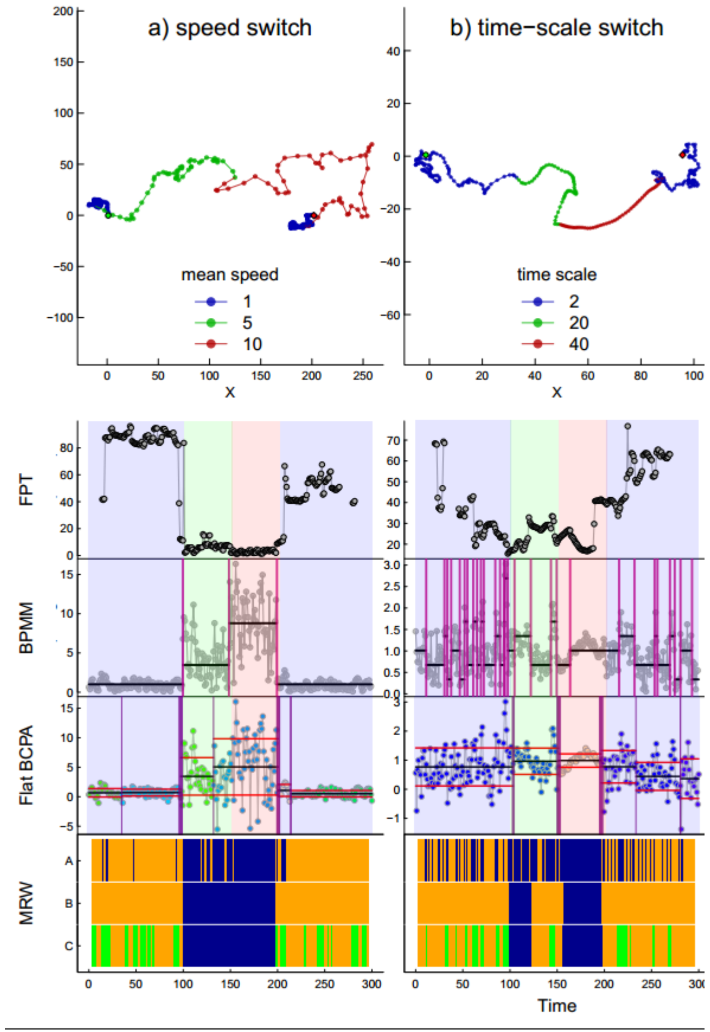
I. First Passage Time

II. Bayesian Partitioning

III. Behavioral Change Point Analysis

IV. Multi-state Random Walks

Comparing tools



Four phase CVM

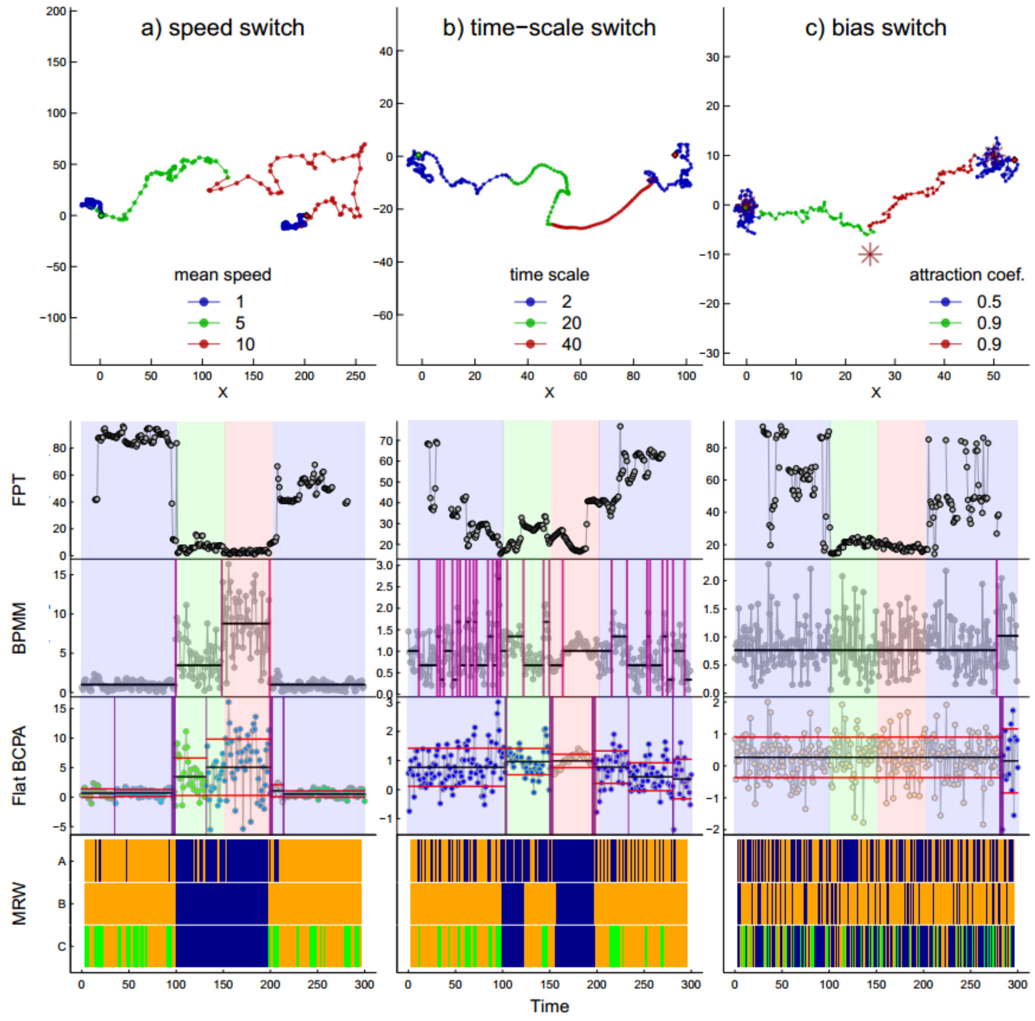
tortuous less tortuous

linear tortuous

Comparing tools

A tool **must** know what it is modeling!

And the "best" tool depends on the **process** you are capturing



Biased CRW

three points of attraction

uniform speed and tortuosity

Targeted *segmentation*

Looking for a **specific** behavior.

- Migration or range-shift timing
- Calving / Parturition events
- Dispersal events

Model-based estimation of **behavioral changepoints**

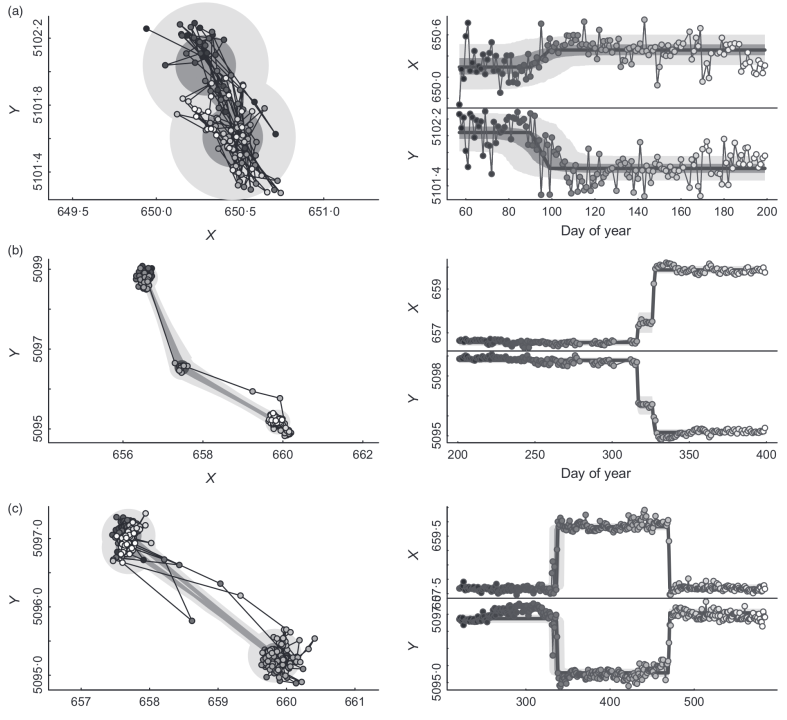
Migration and range-change estimation

WN or **OU** or **OUF** in each range … then

$$\mathbf{m}(t) = \begin{cases} \mathbf{m}_1 & \text{where } t < t_1 \\ \mathbf{m}_1 + (m_2 - m_1) \times (t - t_1)/\Delta t & \text{where } t_1 < t < t_1 + \Delta t \, . \\ \mathbf{m}_2 & \text{where } t > t_1 + \Delta t \end{cases}$$

- Identification of "subtle" shifts (hard for NSD)
- Estimation of parameters with confidence intervals
- Various hypothesis tests: **was the shift significant? did it return? was there a stopover?**

> WARNING: as always some **strong assumptions!**



Journal of Animal Ecology

BRITISH ECOLOGICAL SOCIETY

Journal of Animal Ecology 2017, **86**, 943–959 doi: 10.1111/1365-2656.12674

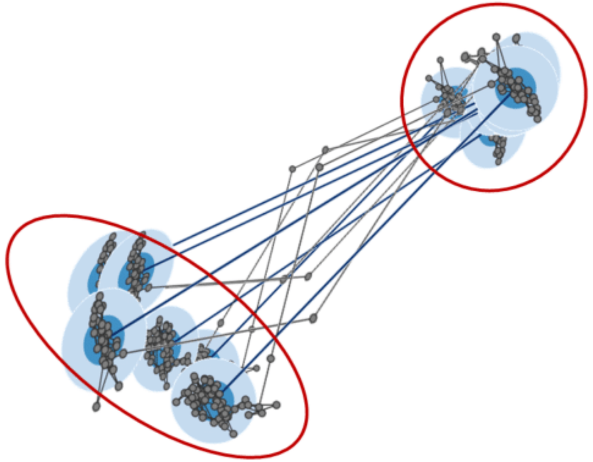
A framework for modelling range shifts and migrations: asking when, whither, whether and will it return

Eliezer Gurarie*[1], Francesca Cagnacci[2,3], Wibke Peters[2,4], Christen H. Fleming[1,5], Justin M. Calabrese[1,5], Thomas Mueller[6,7] and William F. Fagan[1]

`marcher` R package

Hierarchical Migration Modeling

What if you have too many individuals!?



Each individual:
Migration(A, m_1, m_2, t_1, dt)

Lots of individuals!

Herd Range:
winter: $M_1 \sim$ Range(location$_1$, shape$_1$)
calving $M_2 \sim$ Range(location$_2$, shape$_2$)

Migration Timing:
start: Mean and standard deviation of **departure times**
duration: Mean and standard deviation of **migration duration**

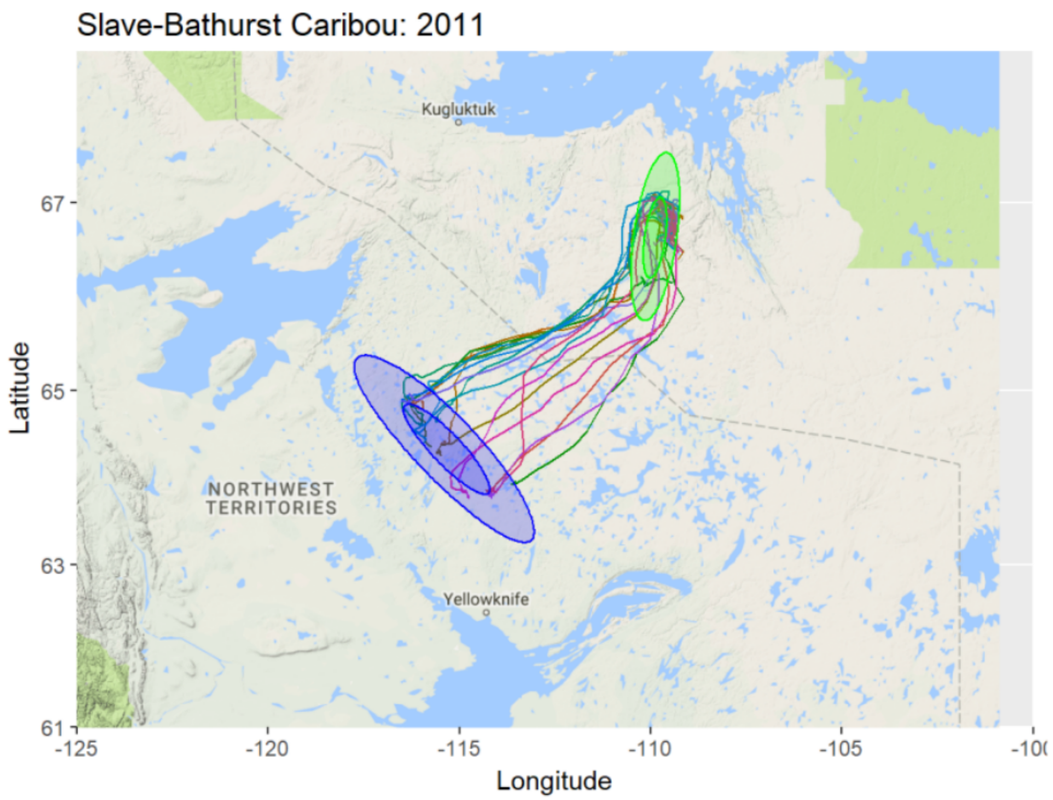
Hierarchical Migration Modeling

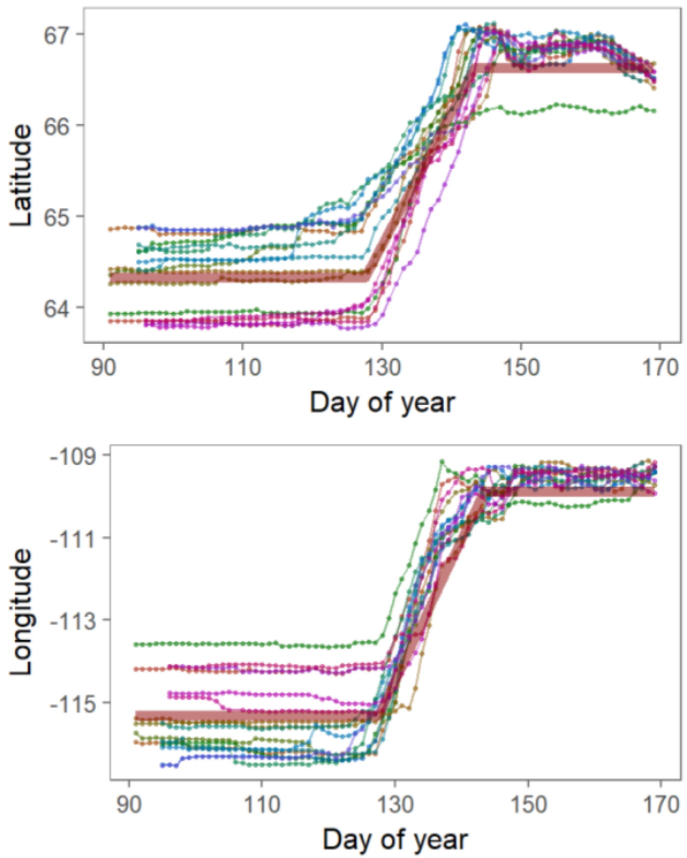
Herd Ranges:

$\mathbf{M}_1 \sim \text{BivarNormal}(\mu_1, \Sigma_1) \quad \mathbf{M}_2 \sim \text{BivarNormal}(\mu_2, \Sigma_2)$

Migration Timing:

$t^\star \sim \mathcal{N}(\mu_t, \sigma_t) \quad \Delta t^\star \sim \mathcal{N}(\mu_{\Delta t}, \sigma_\Delta)$





marcher in 3D?

mit Wibke Peters und Johannes Singer

Model

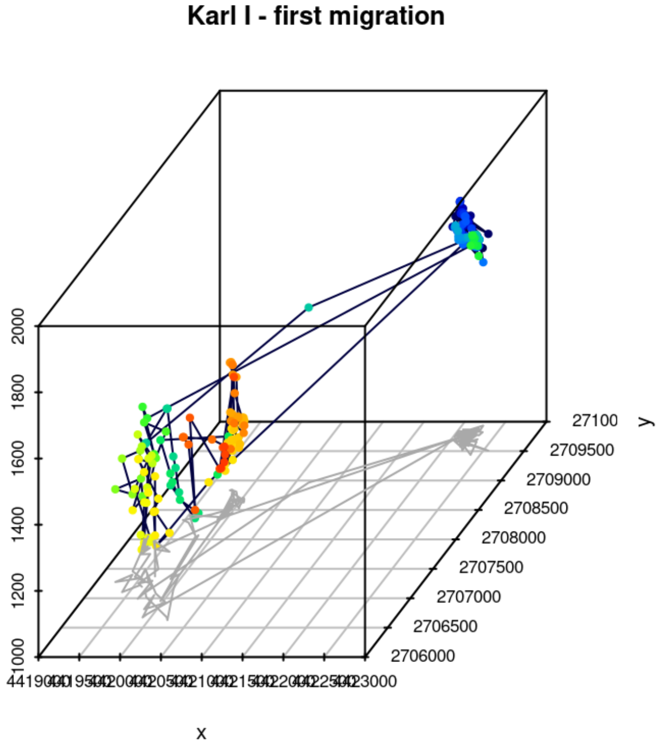
$$X_p \sim AR1(\mu_{x,p}, \sigma_{x,p}, \phi_{x,p})$$

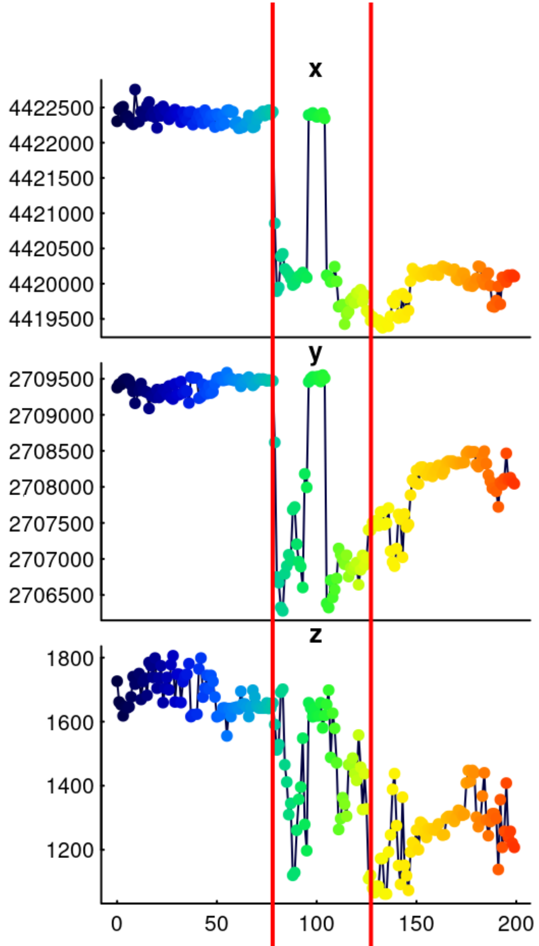
$$Y_p \sim AR1(\mu_{y,p}, \sigma_{y,p}, \phi_{y,p})$$

$$Z_p \sim AR1(\mu_{z,p}, \sigma_{z,p}, \phi_{z,p})$$

Likelihood

$$\mathcal{L}(\theta|V_d) = \prod_{d=1}^{D} \prod_{i=1}^{t_1} \mathcal{L}_{\mathcal{AR}}(\mu_{d,1}, \sigma_{d,1}, \phi_{d,1}|V_{d,i\leq t_1}) \times$$
$$\prod_{d=1}^{D} \prod_{i=t_1+1}^{t_2} \mathcal{L}_{\mathcal{AR}}(\mu_{d,2}, \sigma_{d,2}, \phi_{d,2}|V_{d,t_1<i\leq t_2}) \times$$
$$\prod_{d=1}^{D} \prod_{i=t_2}^{n} \mathcal{L}_{\mathcal{AR}}(\mu_{d,3}, \sigma_{d,3}, \phi_{d,3}|V_{d,i>t_2})$$





Detecting parturition times

When [**mammals** / **birds**] [**give birth** / **lay eggs**] they (generally) stops moving for a while to [**nurse** / **incubate**].

Several model-based methods to identify those locations / times.

Ecology and Evolution

Open Access

Inferring parturition and neonate survival from movement patterns of female ungulates: a case study using woodland caribou

Craig A. DeMars[1], Marie Auger-Méthé[1], Ulrike E. Schlägel[2] & Stan Boutin[1]

[1]Department of Biological Sciences, University of Alberta, Edmonton, AB T6G 2E9, Canada
[2]Department of Mathematical and Statistical Sciences, University of Alberta, Edmonton, AB T6G 2G1, Canada

ARTICLE

Macrosystems Ecology

ECOSPHERE
AN ESA OPEN ACCESS JOURNAL

Continental synchrony and local responses: Climatic effects on spatiotemporal patterns of calving in a social ungulate

Ophélie H. Couriot[1,2,3] | Matthew D. Cameron[4] | Kyle Joly[4] | Jan Adamczewski[5] | Mitch W. Campbell[6] | Tracy Davison[7] | Anne Gunn[2,8] | Allicia P. Kelly[9] | Mathieu Leblond[10] | Judy Williams[5] | William F. Fagan[1,2] | Anna Brose[2] | Eliezer Gurarie[1,2]

Parturition model for caribou

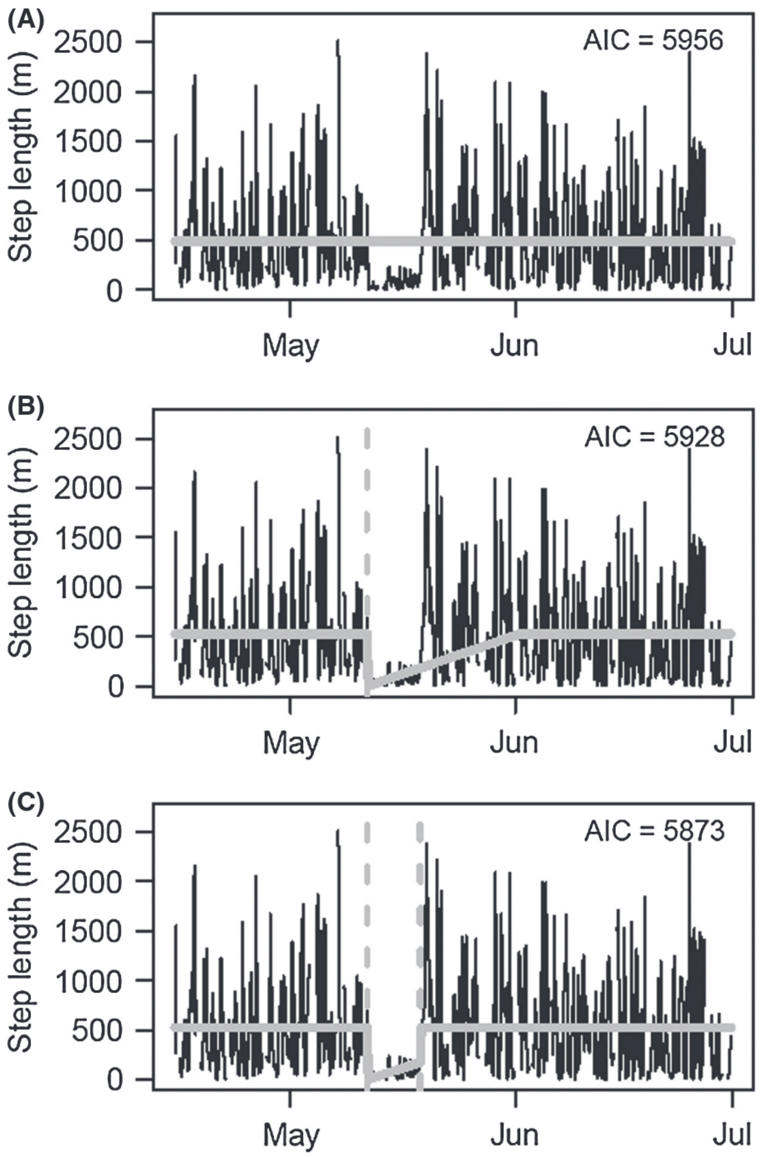
- Focus on "speed" (displacements / time intervals)
- Modeled as Gamma distribution (shape / scale parameters)
- The parameters shift:
  - no change - **no birth**
  - fall to (near) zero and recover slowly: **calf survival**
  - fall to (near) zero and recover suddenly: **calf died**

$$R(t) = \begin{cases} \alpha_m \times \beta_m & \text{when } t < \tau_c \\ \left(\alpha_c + \frac{\alpha_m - \alpha_c}{\kappa} t\right)\left(\beta_c + \frac{\beta_m - \beta_c}{\kappa} t\right) & \text{when } \tau_c \le t \le \tau_c + \kappa, \\ \alpha_m \times \beta_m & \text{when } t > \tau_c + \kappa \end{cases}$$

- can be identified & compared with maximum likelihood

TuktuTools R package

C.A. DeMars *et al.*



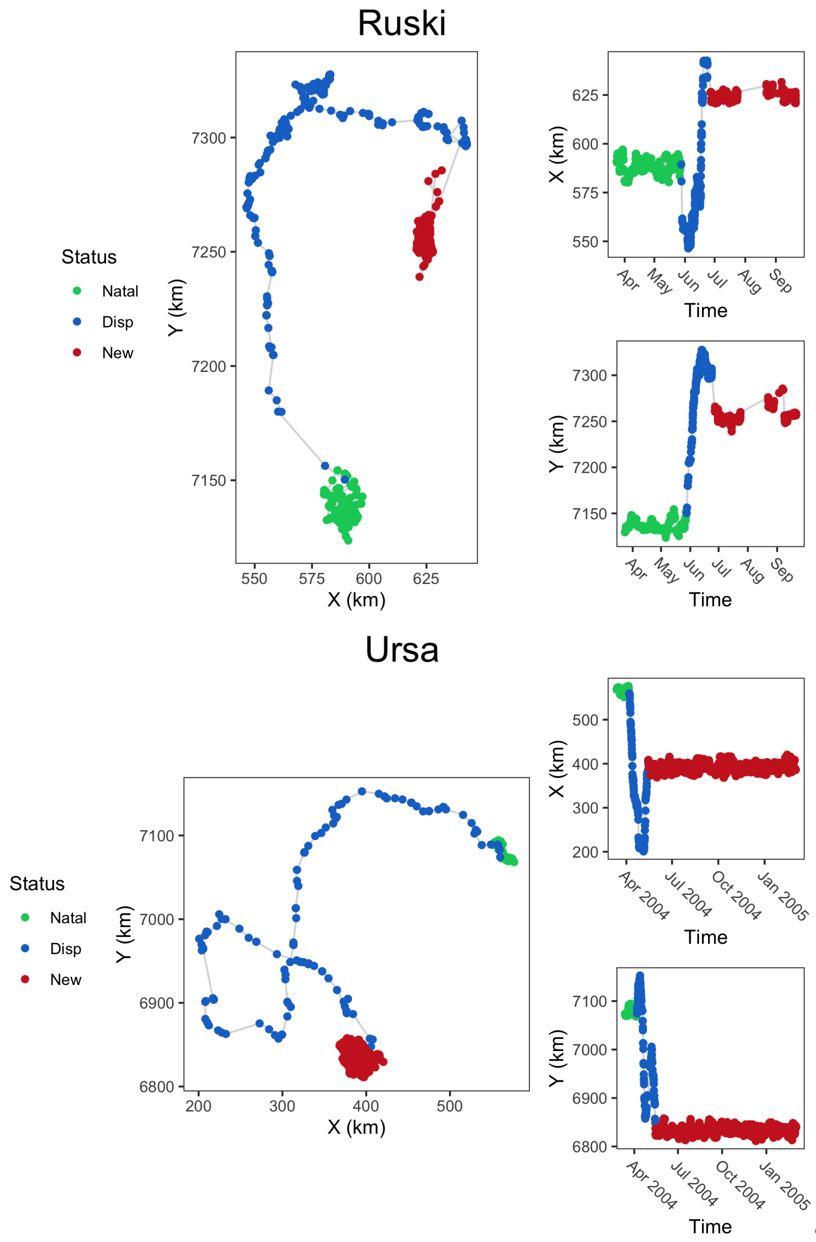
Dispersal events

Fundamental ecological process, important general question

Model:

$$\mathbf{Z}(t) = \begin{cases} \mathrm{OUF}(\tau_{v1}, \tau_{z1}, A) & t < t_d \\ \mathrm{CVM}(\tau_v, \nu) & t_d \leq t < t_s \\ \mathrm{OUF}(\tau_{v3}, \tau_{z2}, A) & t \geq t_s \end{cases}$$

R package `disperser` (not ready for prime time)



You Choose!

- Multi-state Random Walk with `momentuhmm`
- Behavioral Change-points of Continuous-time Movement Models with `smoove`
- Migration / range-shift estimation with `marcher`
- Hierarchical migration model with `TuktuMigration`