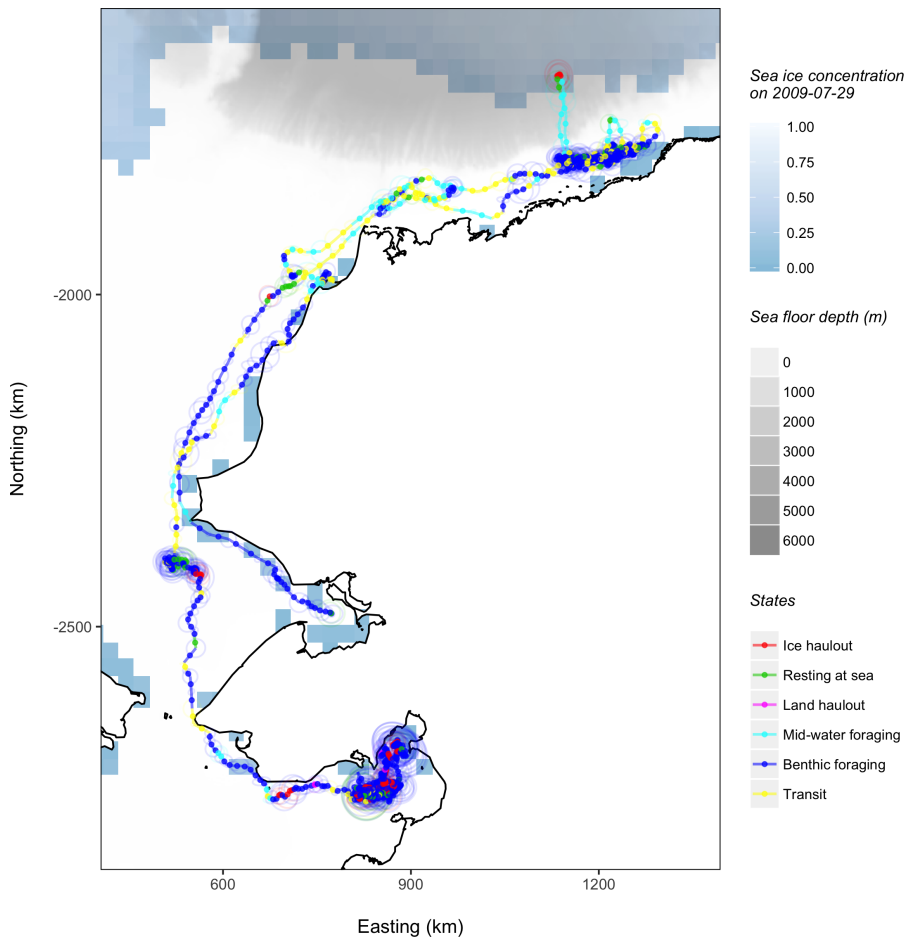
Multiple imputation HMMs

A bearded seal example using `momentuHMM`



Incorporating telemetry error into HMMs

- Common complications with telemetry data
  - Location measurement error
  - Missing data
  - Temporally-irregular observations
- Fitting HMMs that explicitly account for these uncertainties typically requires custom, computationally-demanding, and (often) time-consuming techniques
  - Markov chain Monte Carlo (MCMC)
  - Expectation-Maximization (EM) algorithms

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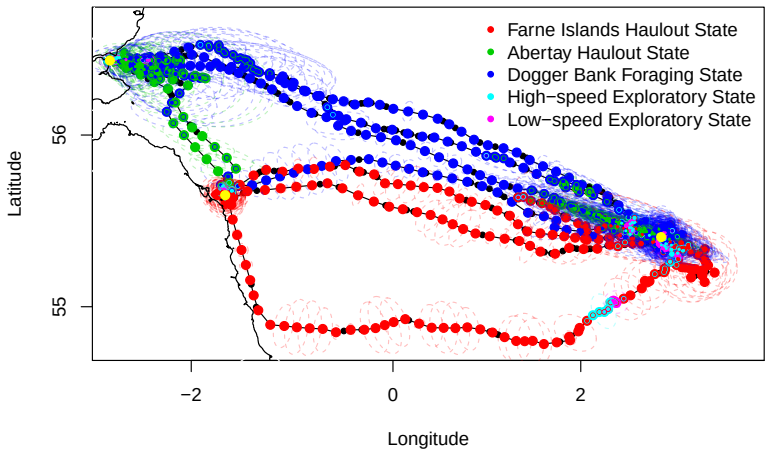
$\longrightarrow$ **Not practical for most practitioners** $\longleftarrow$

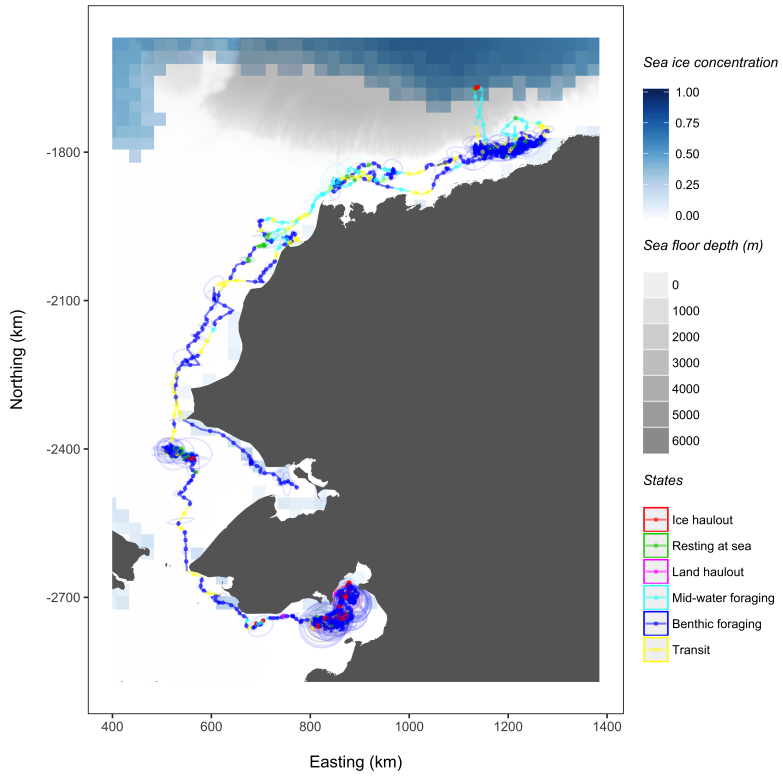
For example...

= 5 days!



McClintock et al. (2012) "A general discrete-time modeling framework for animal movement using multistate random walks", *Ecological Monographs.*

= 3 weeks!

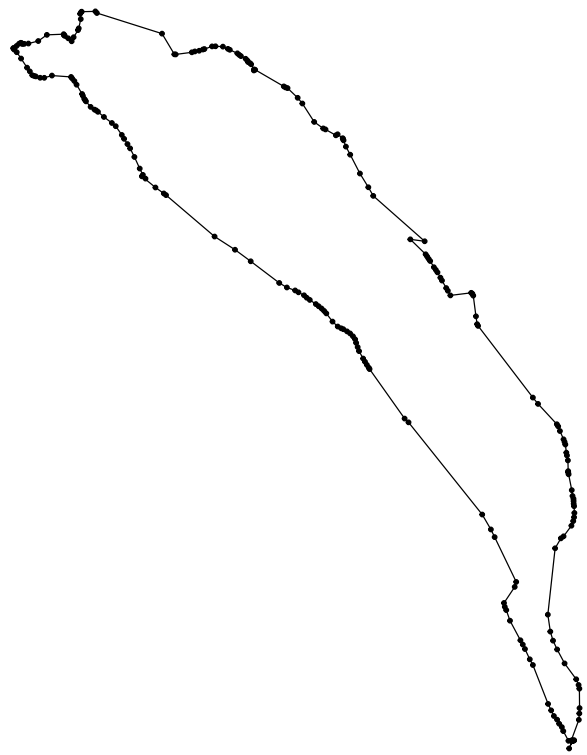


McClintock et al. (2017) "Bridging the gaps in animal movement: hidden behaviors and ecological relationships revealed by integrated data streams", *Ecosphere.*

Multiple imputation HMMs

Solution to irregular sampling and measurement error:

- Fit single-state continuous-time movement model
- Draw temporally-regular realisations from the fitted model
- Fit a HMM to each realisation



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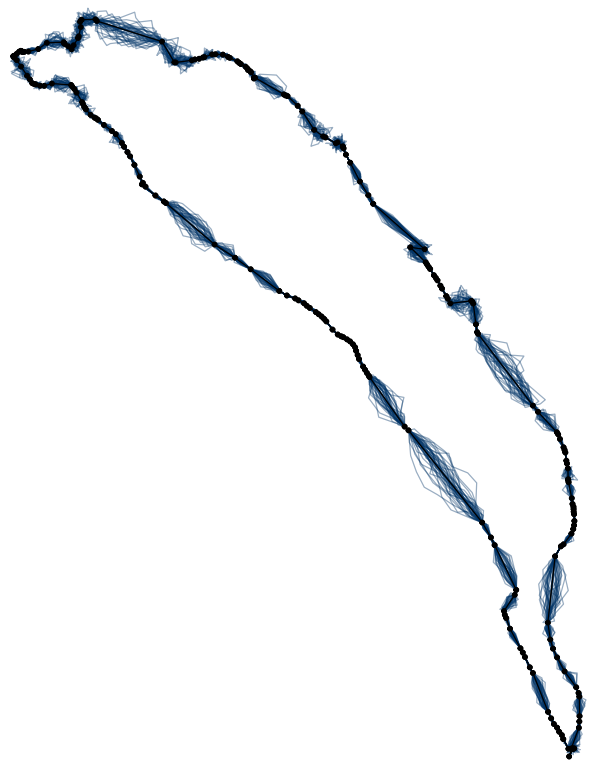


Multiple imputation HMMs

- Data streams that are dependent on location vary among the m realizations of the position process
- Inferences across the m HMM analyses reflect uncertainty attributable to measurement error and temporally-irregular or missing data
- Completely parallelizable
- Pool estimates using standard multiple imputation formulae:

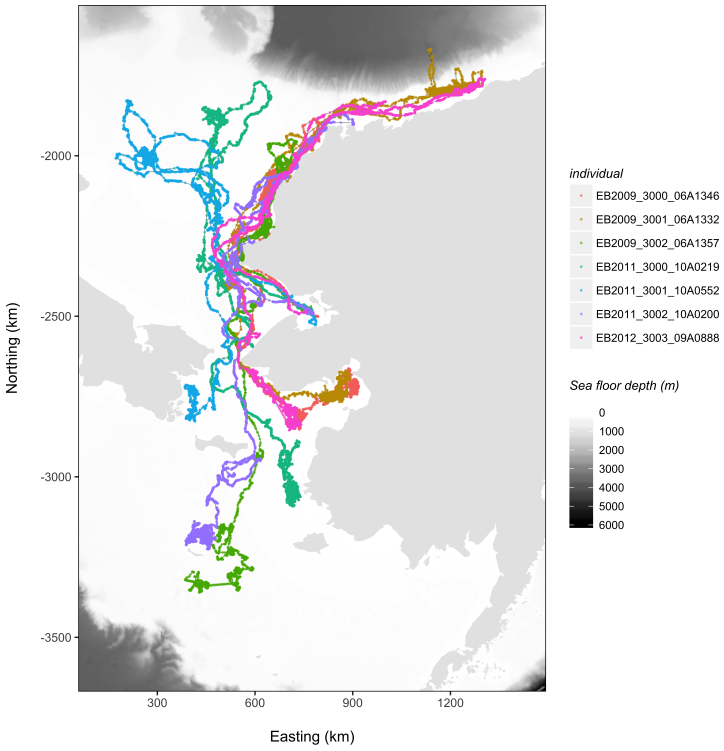
$$\bar{\theta} = \frac{1}{m} \sum_{i=1}^{m} \theta^{(i)}$$

$$\text{var}\left(\bar{\theta}\right) = \left[\frac{1}{m} \sum_{i=1}^{m} \text{var}\left(\theta^{(i)}\right)\right] + \left(1 + \frac{1}{m}\right) \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(\theta^{(i)} - \bar{\theta}\right)^2\right]$$

McClintock (2017) "Incorporating telemetry error into hidden Markov models of animal movement using multiple imputation", *JABES.*

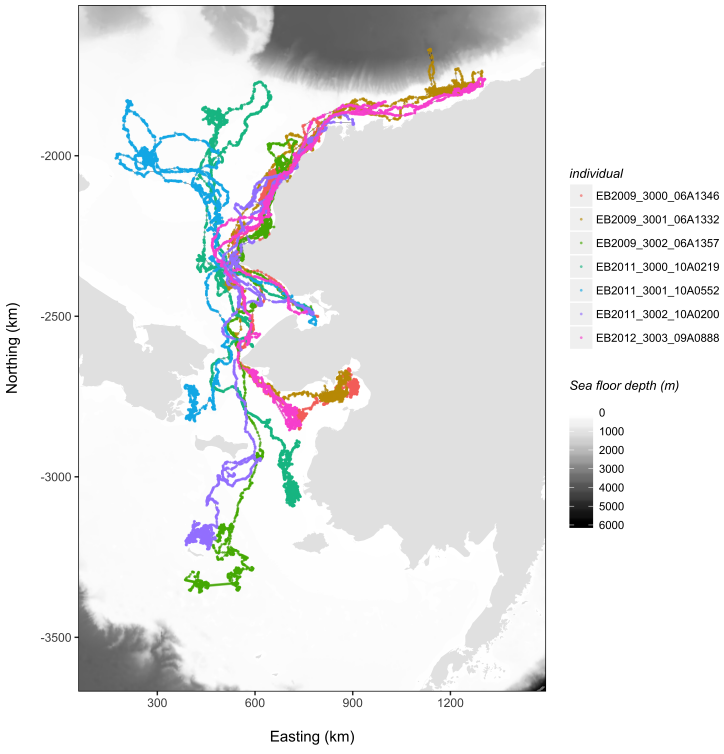
Bearded seal example

Bearded seal example



- 7 seals tagged near Kotzebue, AK
- 54542 temporally-irregular locations
- Dive and wet/dry data in 6hr bins
- 18% of 6hr time steps contain no locations
- Measurement error (Argos and Fastloc GPS)
- 7 data streams
- 6 behavior states:
  - "Hauled out on ice"
  - "Resting at sea"
  - "Hauled out on land"
  - "Mid-water foraging"
  - "Benthic foraging"
  - "Transit"

Bearded seal example



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Bearded seal example: data streams

Step length:
$L_t \mid S_t = s \sim \text{Gamma}\left(\mu_s, \sigma_s\right)$

Turn angle:
$\phi_t \mid S_t = s \sim \text{wCauchy}\left(0, \rho_s\right)$

Dive time:
$d_t \mid S_t = s \sim \text{Beta}\left(\alpha_s^d, \beta_s^d\right)$

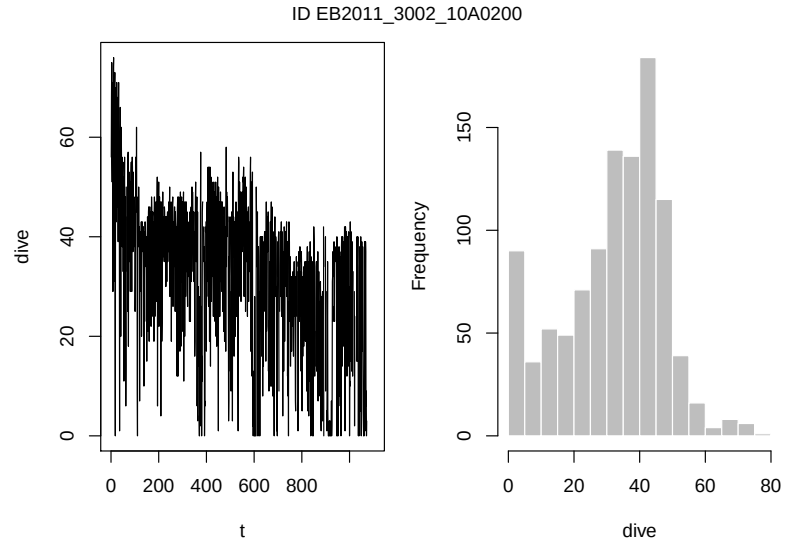
Dry time:
$w_t \mid S_t = s \sim \text{Beta}\left(\alpha_s^w, \beta_s^w\right)$

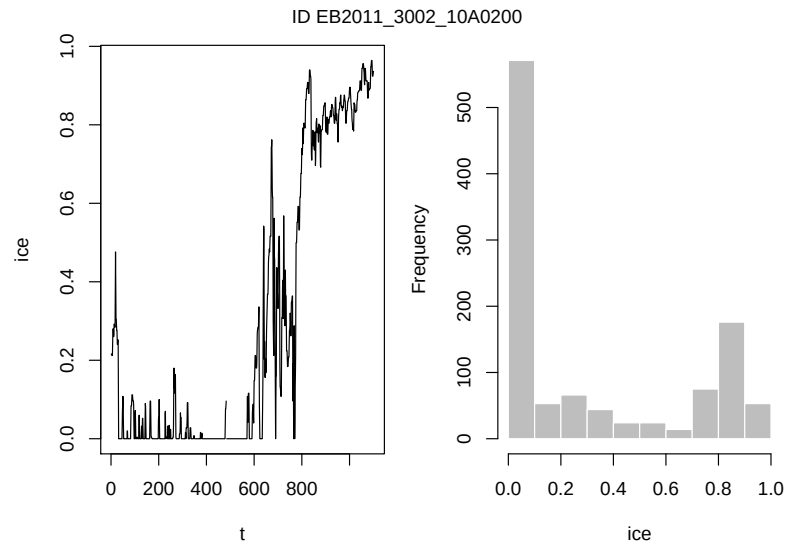
Sea ice cover:
$c_t \mid S_t = s \sim \text{Beta}\left(\alpha_s^c, \beta_s^c\right)$

Land cover:
$l_t \mid S_t = s \sim \text{Beta}\left(\alpha_s^l, \beta_s^l\right)$

Benthic dives:
$b_t \mid S_t = s \sim \text{Poisson}\left(\lambda_s\right)$

```
plot(data, animals="EB2011_3002_10A0200")
```





Bearded seal example: behavioral states

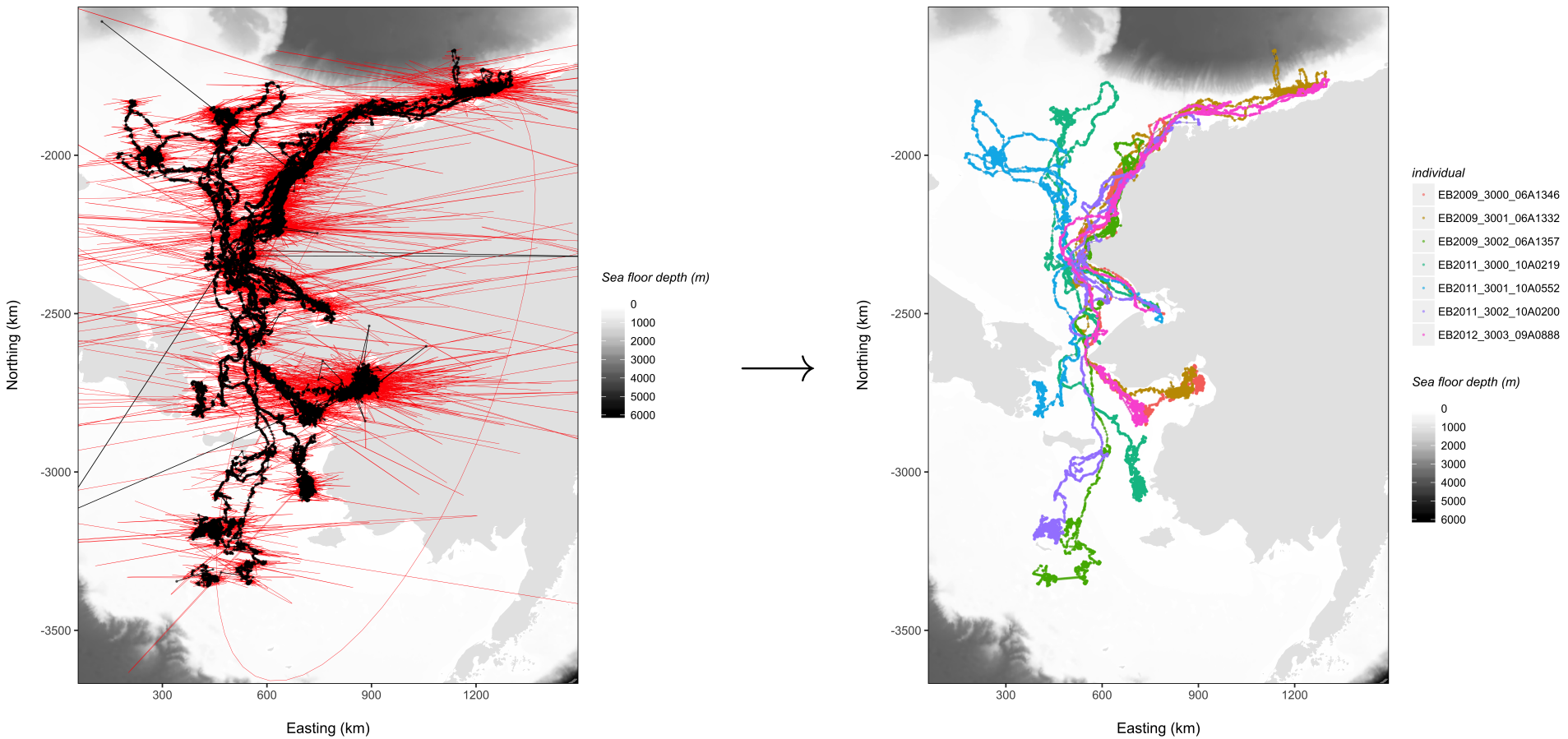
Behavioral state	Horizontal trajectory		Dive	Dry	Benthic	Ice	Land
	Step length	Directional persistence					
"Hauled out on ice"	shorter		lower	higher	lower	higher	lower
"Resting at sea"	shorter		lower	lower	lower	lower	lower
"Hauled out on land"	shorter		lower	higher	lower	lower	higher
"Mid-water foraging"			higher	lower	lower		
"Benthic foraging"			higher	lower	higher		
"Transit"	longer	higher	higher	lower	lower		

Expected characteristics of 6 movement behavior states for a bearded seal movement model incorporating seven data streams. These data streams included horizontal trajectory ("Step length" and "Directional persistence"), the proportion of time spent diving below 4 m ("Dive"), the proportion of time spent dry ("Dry"), and the number of benthic dives ("Benthic") during each 6 h time step. The model incorporated environmental data on the proportion of sea ice and land cover in 25x25km grid cell(s) containing the start and end locations for each time step ("Ice" and "Land"), as well as bathymetry data to identify benthic dives. Blank entries indicate no a priori relationships were assumed in the model.

McClintock et al. (2017), "Bridging the gaps in animal movement: hidden behaviors and ecological relationships revealed by integrated data streams", *Ecosphere*.

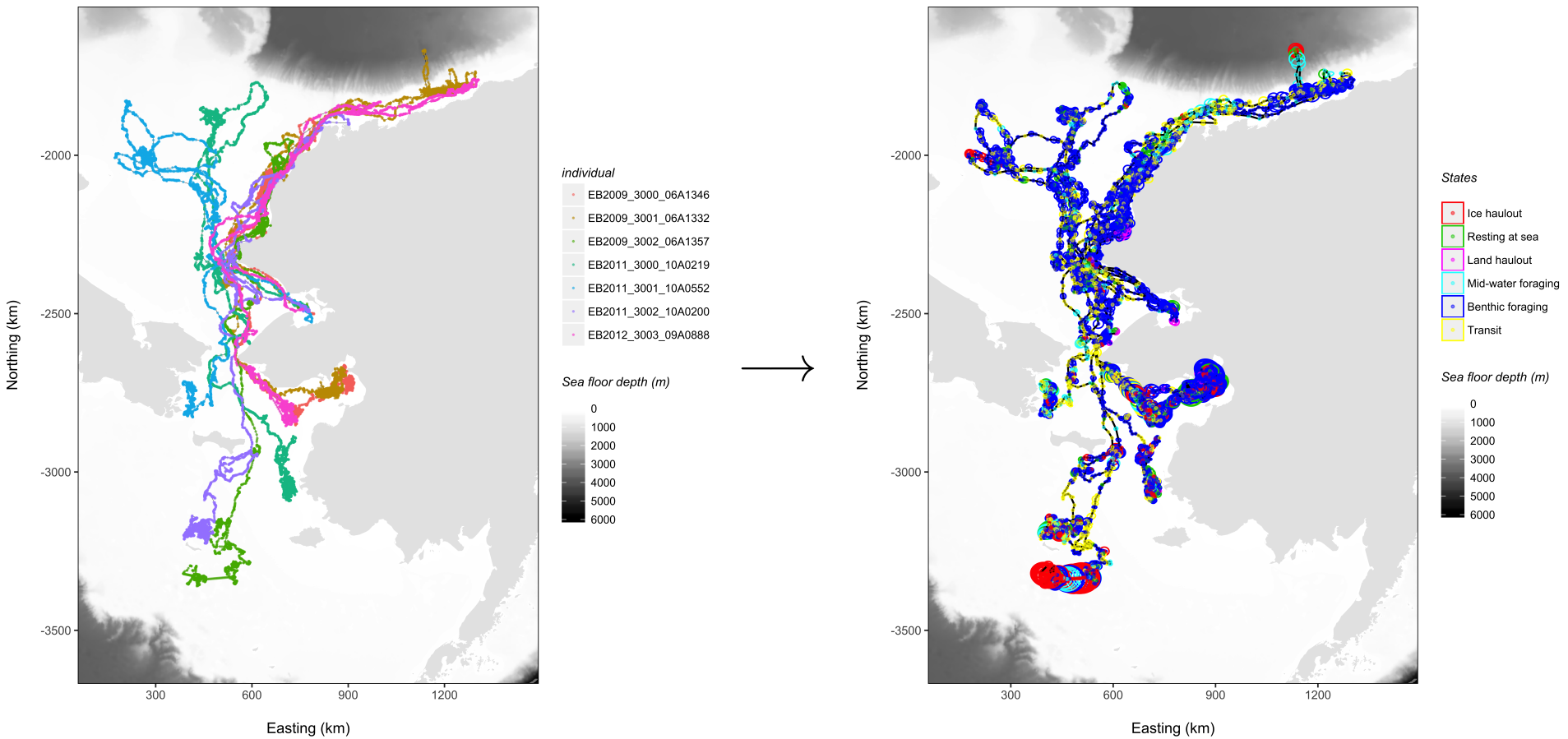
Bearded seal example: location uncertainty

```
crwOut <- crawlWrap(data, timeStep = "6 hours",
                    err.model = err.model)
```

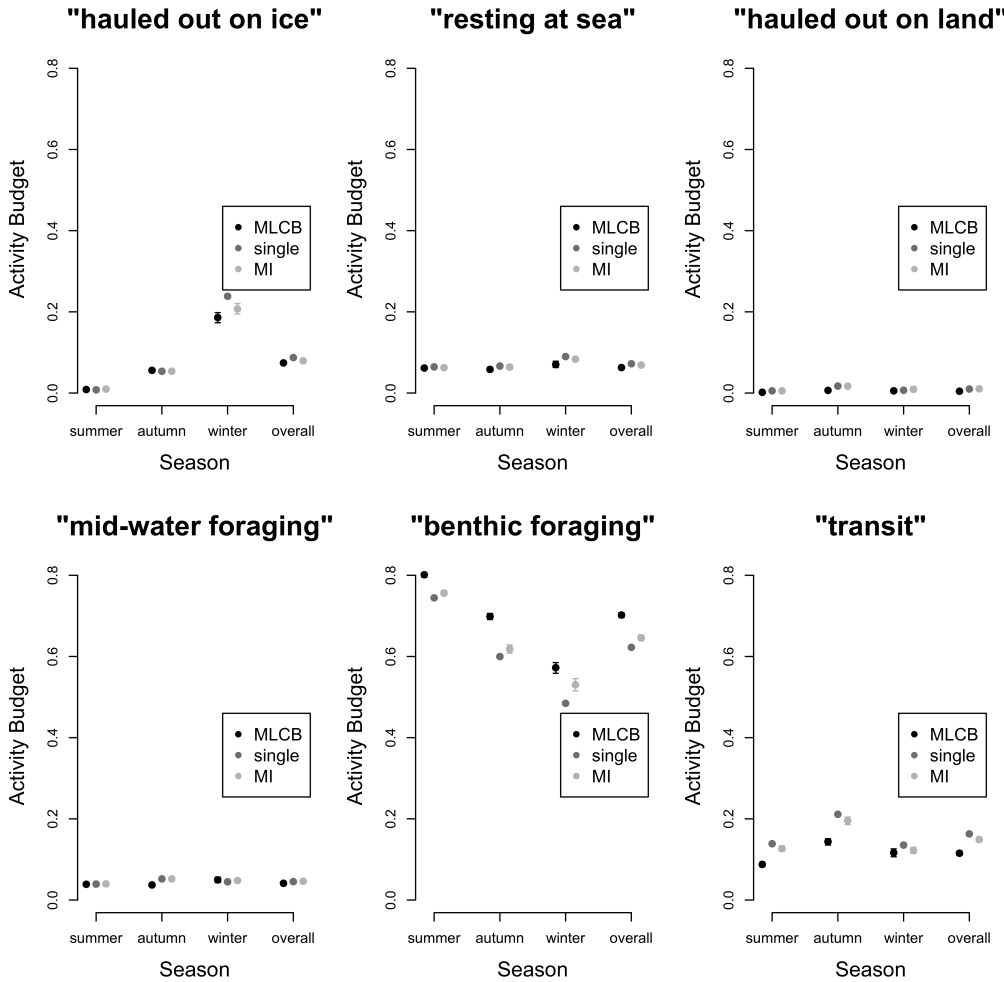


Bearded seal example: multiple imputation HMM

```
miFits <- MIfitHMM(crwOut, nSims,
                   nbStates=6, dist, Par0, DM)
```



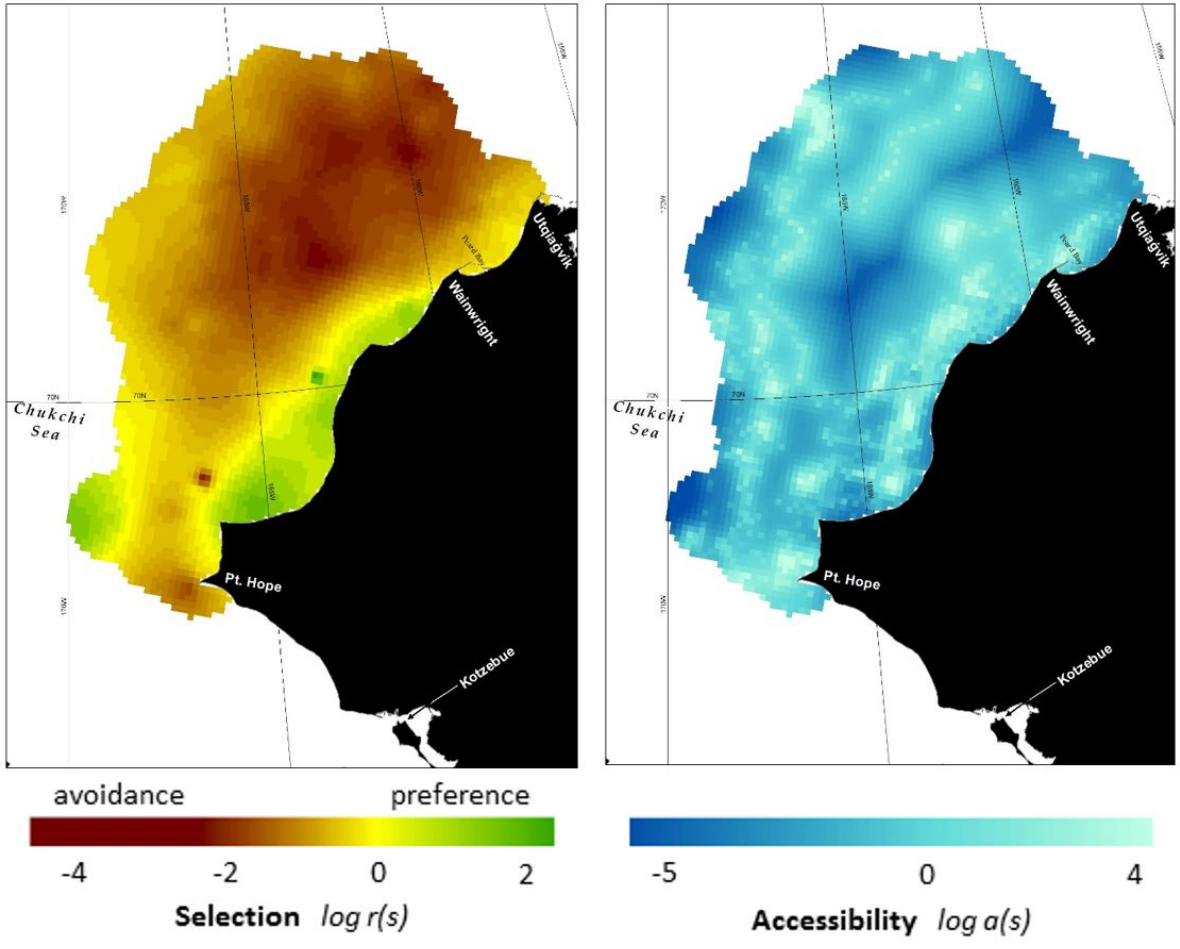
Bearded seal example: activity budgets



Estimated activity budgets among six behavioral states from 7 bearded seal tag deployments between 2009 and 2012 near Alaska, USA. Results from the single and multiple imputation analyses are presented alongside those reported by McClintock et al. (2017; MLCB).

Bearded seal example: state assignments

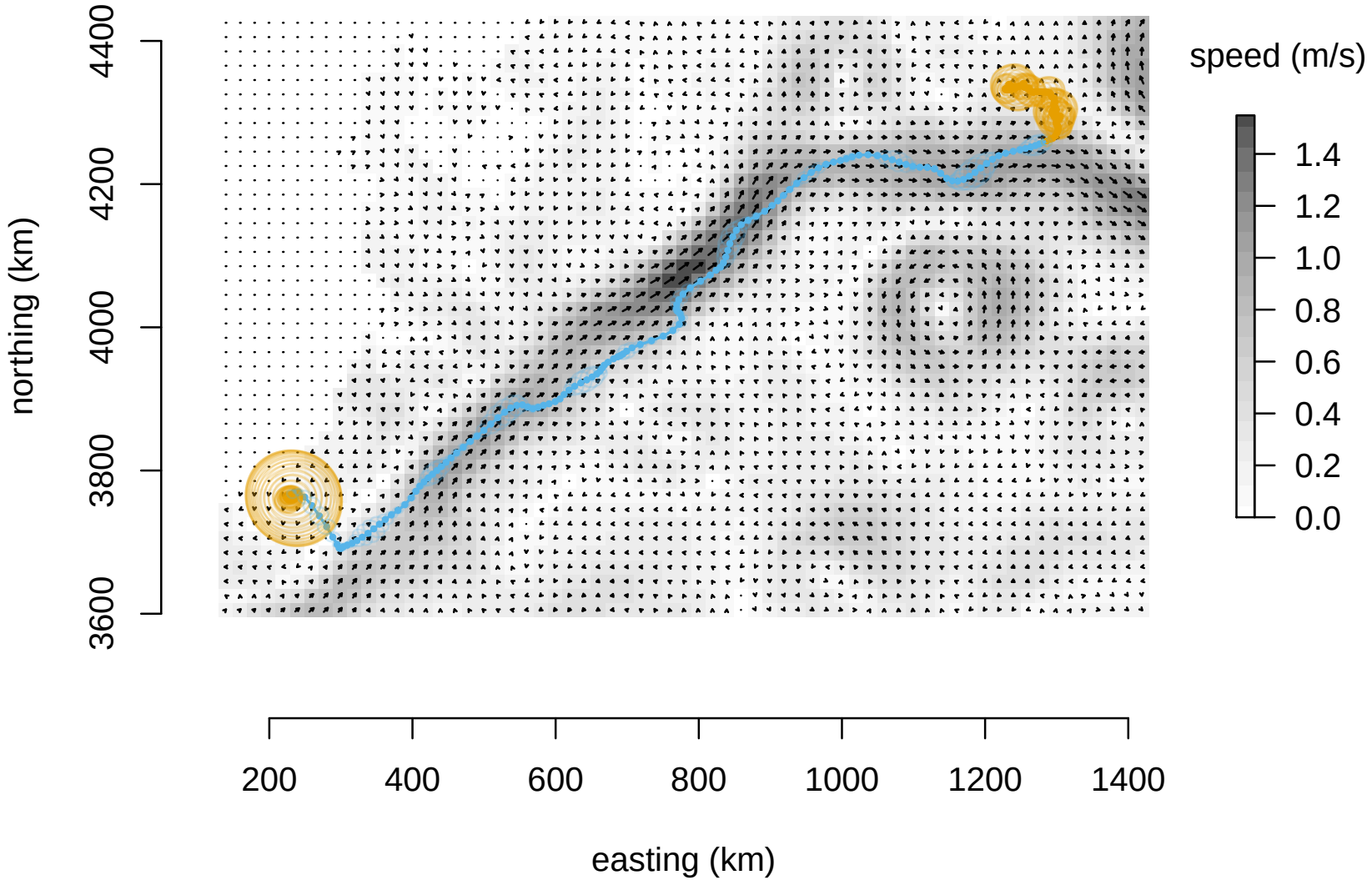
Bearded seal example: resource selection



$\longrightarrow$ Positive selection for bivalves, large shrimp, cod, sculpins, etc.

Other examples

Loggerhead turtle movements relative to ocean currents



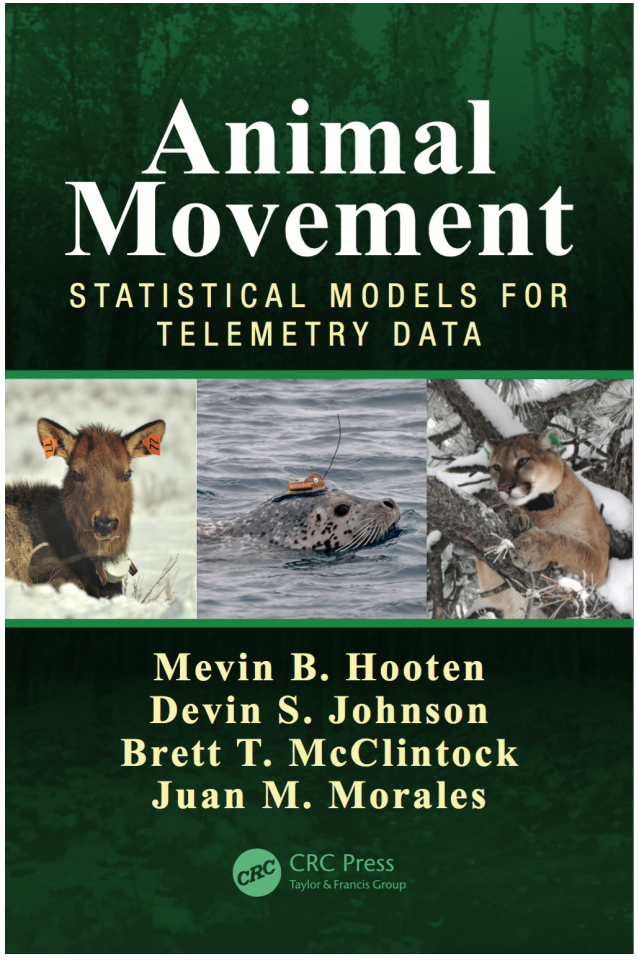
McClintock and Michelot (2018), "`momentuHMM`: R package for generalized hidden Markov models of animal movement", *M*ethods Ecol Evol.

Loggerhead turtle movements relative to ocean currents

After preparing the data, this rather complicated HMM can be specified, fitted, and visualized in only a few lines of code:

```
nbStates <- 2
dist <- list(step = "gamma", angle = "wrpcauchy")
DM <- list(step = list(mean = ~state2(w:angle_osc), sd = ~1),
           angle = list(mean = ~state2(d), concentration= ~1))
turtleFits <- MIfitHMM(miData, nbStates = nbStates, dist = dist,
                       Par0 = Par0, DM = DM,
                       estAngleMean = list(angle = TRUE),
                       circularAngleMean = list(angle = TRUE))
plot(turtleFits, plotCI = TRUE, covs = data.frame(angle_osc = cos(0)))
```

Questions?



- *Animal Movement* book available from CRS Press and Amazon