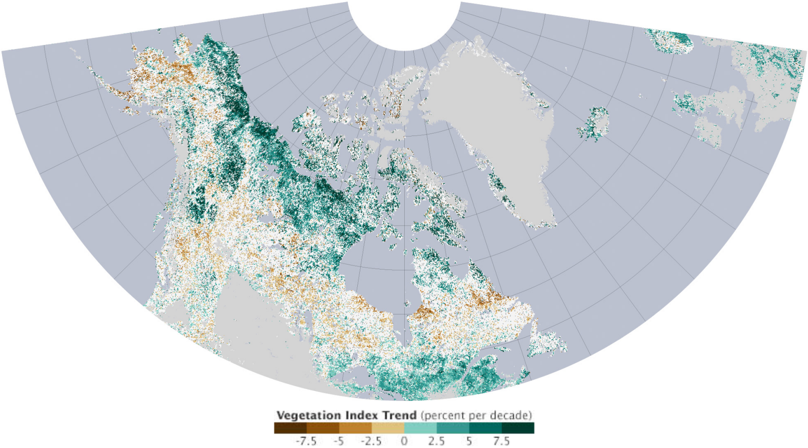
Drivers of Spring Migration in Barrenground Caribou

Elie Gurarie, Mark Hebblewhite, Sarah Davidson, Kyle Joly, Mike Suitor, Allicia Kelly, Jan Adamczewski, William F. Fagan, Natalie Boelman

North American Caribou Workshop - Oct. 2018 - Ottawa, Canada

Motivation

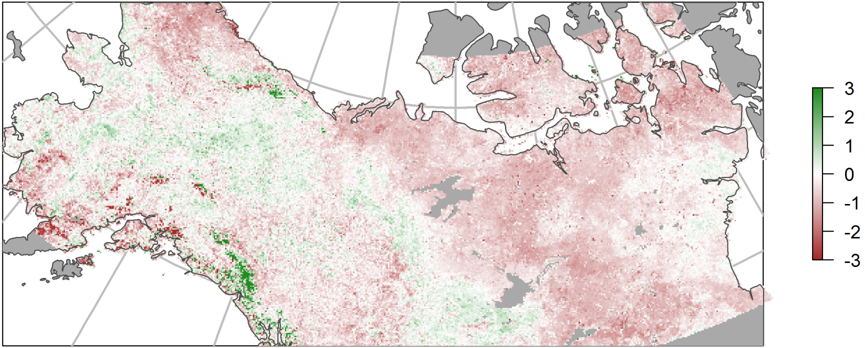
Big picture: Thing are changing in the Arctic



greening tundra vs. browning boreal forest

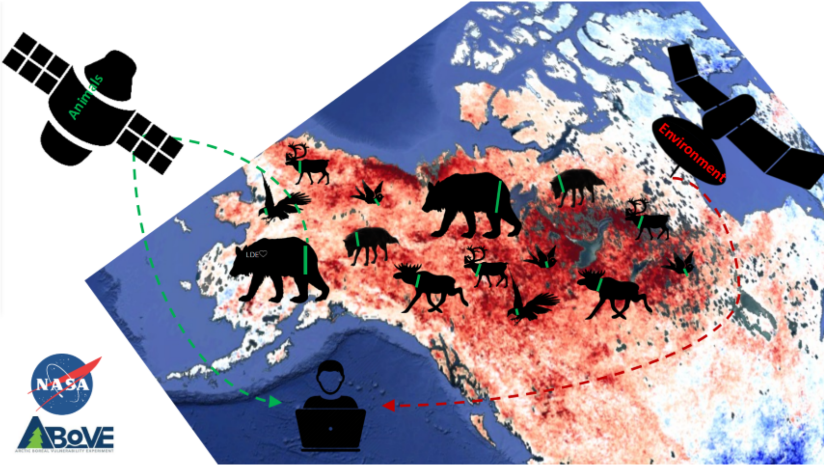
Trend in **NDVI** (1982 - 2011)

Big picture: Things are changing



Trend in **date of snowmelt** (*days* / *year*) 2002-2016.

Big Question: How are animals responding to these changes?



- NASA: Arctic Boreal Vulnerability Experiment | Animals on the Move
- Very large-scale, multi-institute/agency collaboration
- Enormous movement dataset (millions of locations / 6 species)

(only slightly) Smaller Question:

What are the environmental drivers of caribou spring migration?

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Why spring migration?

1. Globally / across taxa: spring phenological events are trending early at different rates
   - potential mismatch? (e.g. Post et al. in W. Greenland).
2. SM links boreal forest to tundra - with divergent climate trends
3. Precedes calving - may be linked to demographics?
4. Clearly identifiable mass movement

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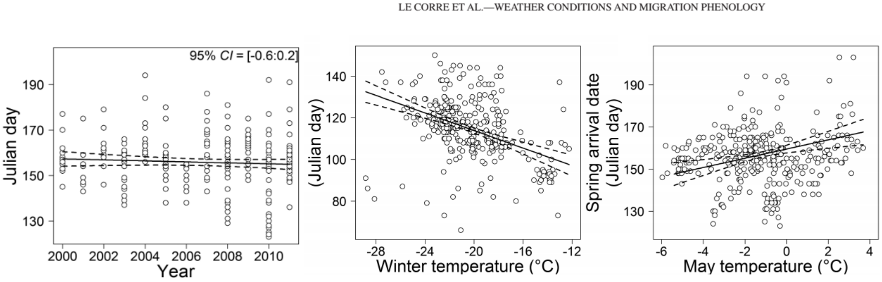
4. Clearly identifiable mass movement

and because it's **mysterious!**

Photo: Peter Mather

Known results



Rivière-George / Rivière-aux-Feuilles - Québec/Labrador

Lots of variability, no trend, some relationship with temperature (warmer = earlier) but conditioned by snow quality (wetter/more = longer migration)

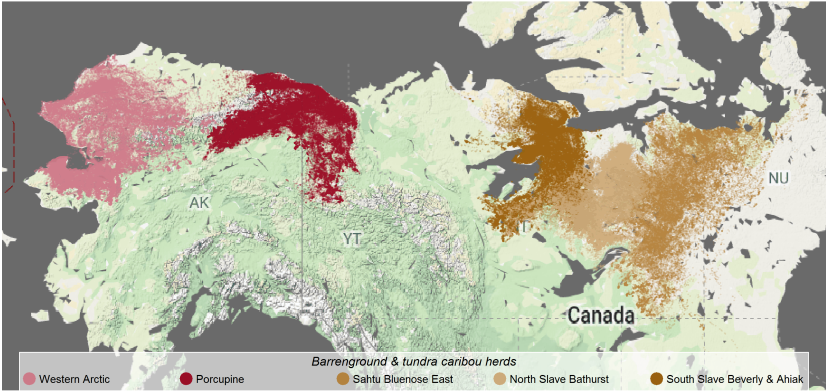
LeCorre et al 2015, Journal of Mammalogy, 98(1):260-271, 2017

Hypotheses

Spring migration phenology might ...

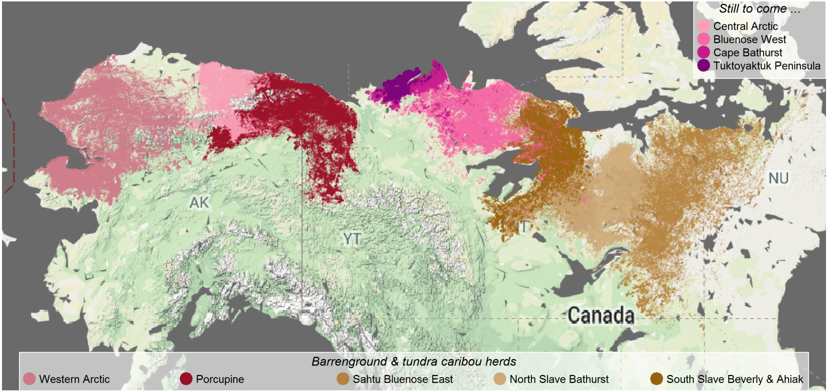
- Trending earlier
- Be linked to snowmelt timing (surfing the snow edge)
- Be linked to snow quality
- Reflect body condition / physiology

Movement Data



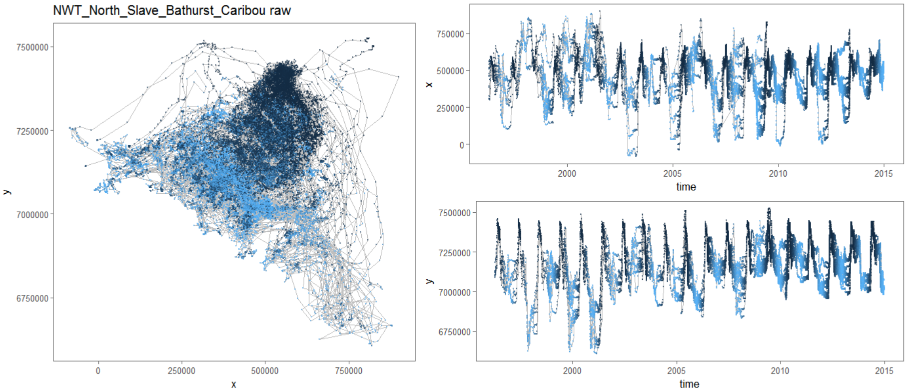
region	study	n.ind	n.obs	years	n.years
N. AK	Western Arctic	119	43 405	2010-2017	8
Yukon	Porcupine	175	77 827	1998-2017	20
NWT / Nvt	Sahtu Bluenose East	166	62 938	2005-2017	20
	North Slave Bathurst	151	40 428	1996-2017	19
	South Slave Beverly and Ahiak	124	65 492	1995-2017	10

Movement Data (recently added)



region	study	n.ind	n.obs	years	n.years
N. AK.	Central Arctic	54	33 899	2003-2007	5
NWT	Bluenose West	159	83144	1996-2017	22
	Cape Bathurst	83	56775	1996-2017	22
	Tuktoyaktuk Peninsula	46	27430	2006-2016	11

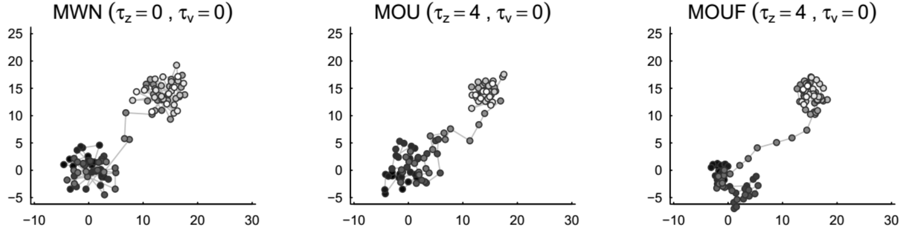
Long time series!



Estimating migration

Migratory/Range Shift Analysis model

$$\mathbf{z}(t) = \mu(t) + \mathbf{r}(t)$$



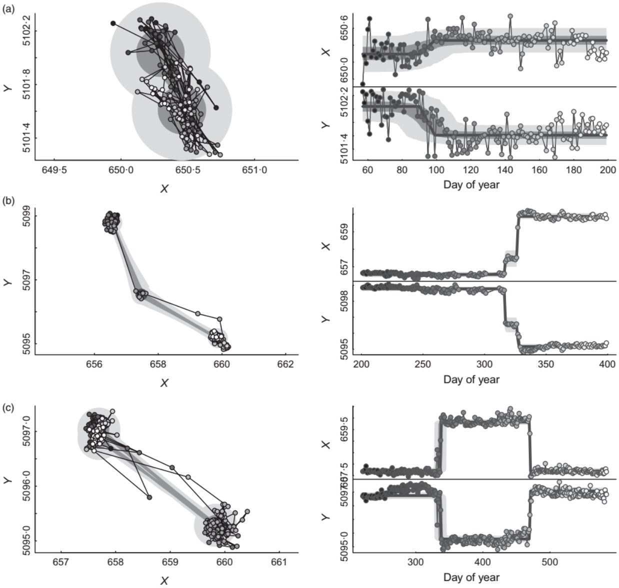
Mean process

Ranging

- uncorrelated (WN)
- position correlated (OU)
- position-velocity correlated (OUF)

$$\mu(t) = \begin{cases} \mu_1 & t < t_1 \\ \mu_1 + \beta(t - t_1) & t_1 < t < t_2 \\ \mu_2 & t > t_2 \end{cases}$$

MRSA: applied to individual tracks[1]



Estimates (with CI's):

- timing
- ranging locations
- ranging areas

Rigorous tests of:

- range shift
- stop-overs
- site-fidelity

R package:

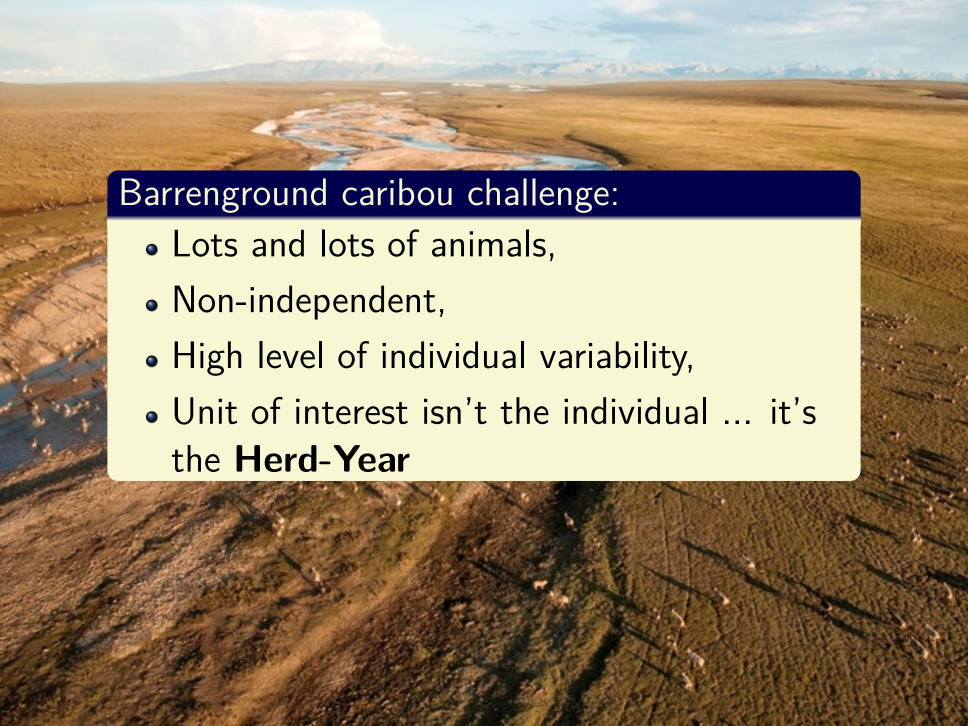
`marcher`


Journal of Animal Ecology
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]

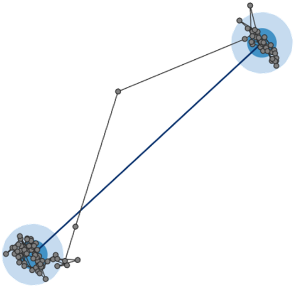
[1]Gurarie et al. 2017



Barrenground caribou challenge:

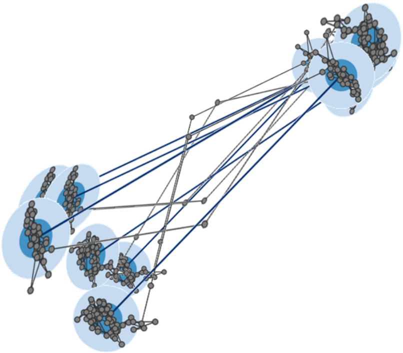
- Lots and lots of animals,
- Non-independent,
- High level of individual variability,
- Unit of interest isn't the individual ... it's the **Herd-Year**

Hierarchical spring migration model



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

Hierarchical spring migration model



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Lots of individuals!

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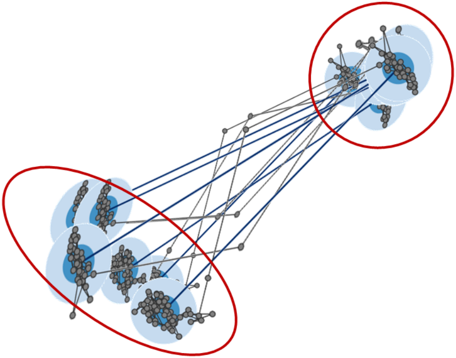


Each individual:
MWN(A, m_1, m_2, t_1, dt)

Lots of individuals!

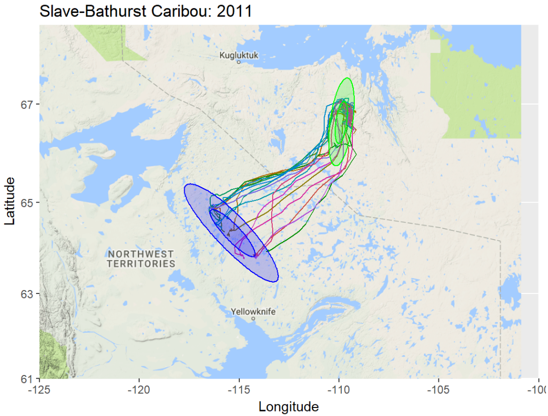
Herd Range:
winter: $M_1 \sim \text{BivarNormal}(\mu_1, \Sigma_1)$
calving $M_2 \sim \text{BivarNormal}(\mu_2, \Sigma_2)$

Migration Timing:
start: $t^\star \sim \mathcal{N}(\mu_t, \sigma_t)$
duration: $\Delta t^\star \sim \mathcal{N}(\mu_{\Delta t}, \sigma_\Delta)$.

Fitted model: 2011

Herd Ranges:

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



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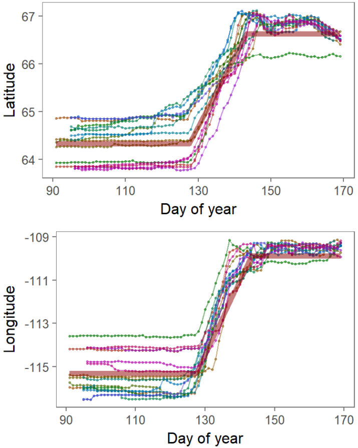
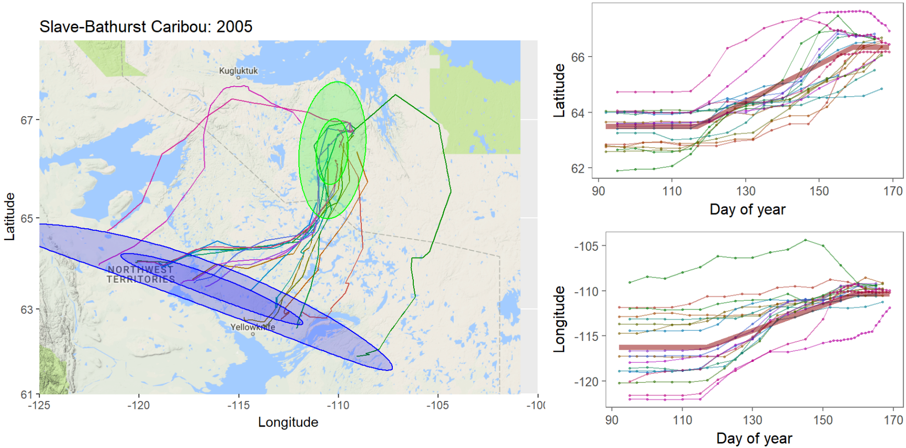
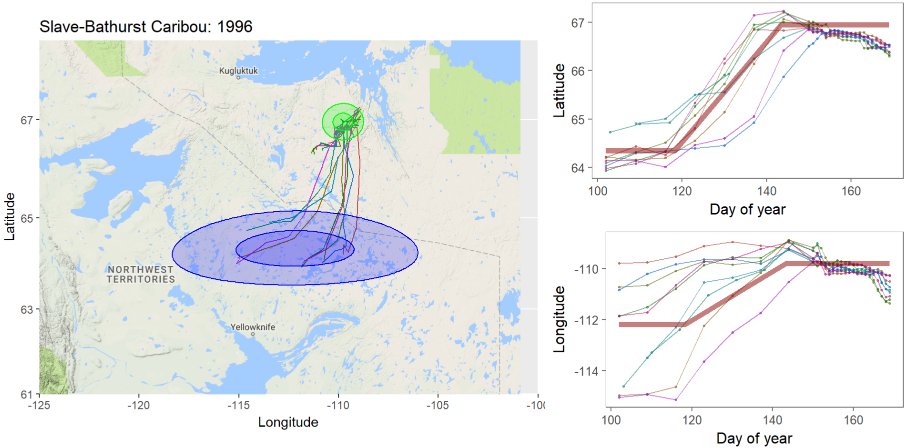


Fitted model: 2005



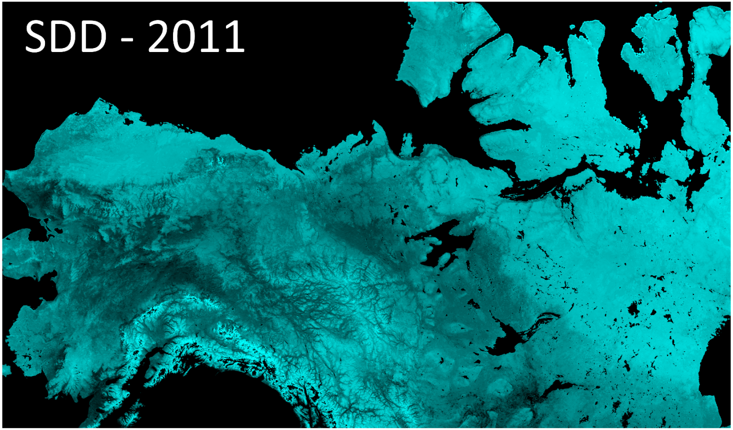
Fitted model: 1996



Covariates

1. **Intrinsic:** estimates in migration model
2. **Phenology:** spatially explicit, 1 measurement per year
3. **Climate**: single variable time series (monthly)
4. **Weather**: location + time specific

Phenology: Snow Departure Day [2]

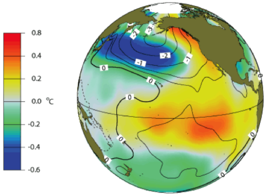


- gap-filled and smoothed measure of last day a pixel was snow-covered
- reduces complex dynamic snow cover data to a single variable.
- collected for each Herd-Year in Winter and Calving range

[2] courtesy Anne Nolin, Oregon State University

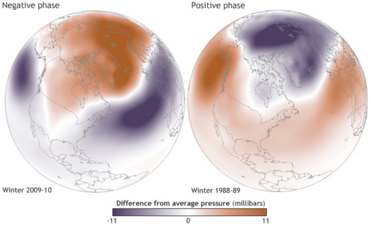
Climate indices

PDO



Warm Phase PDO

AO / NAO



Strength of differences in atmospheric pressure / oceanic temperature, high / lows. Mainly associated with winter conditions, but measured monthly.

Pacific Decadal Oscillation:
+ = warm, wet winters in AK
Arctic Oscillation:
+ = more severe winter in northern N. America
North Atlantic Oscillation:
+ = Cold dry winters in N. Canada

Linked to: Pacific salmon (Mantua et al. 1997), songbirds (Ballard et al. 2003), mountain caribou (Hegel et al. 2010), Greenland caribou (Post and Forchhammer 2002), more.

Weather variables

What did the caribou actually experience?

- **Temperature**, **Precipitation**, **Snow-water Equivalent**
  - NASA-ORNL Daymet V3
  - daily summaries 1km $\times$ 1km.
- **Wind speed**
  - NASA GLDAS-2: Global Land Data Assimilation System
  - 0.25 $\times$ 0.25 arc degrees

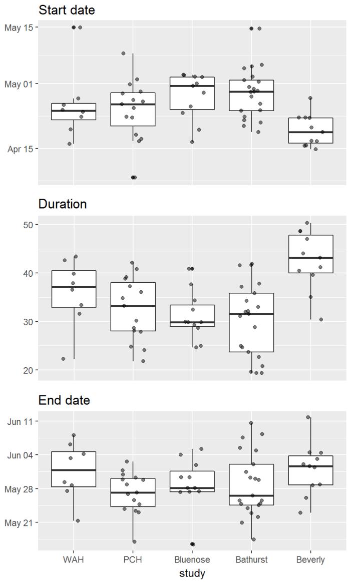
All (daily mean) caribou locations *annotated*.

Variables: Broken down seasonally

			n. vars.
Response / Intrinsic			*n. vars.*
Migration:	**Start** (T_{start}); **Duration** (dT); **End** (T_{end}); **Distance**		4
Predictors			
Climate:	**PDO, NAO, AO**		
	(season)	*(definition)*	
	prev. summer	Jul & Aug	3
	winter	Jan & Feb	3
	spring	Apr	3
Weather:	**Temp, Precip, SWE, Wind**		
	prev. summer	Jul 15 to Aug 31	4
	winter	Jan 1 to Feb 28	4
	spring	Mar 15 to (T_{start} - 14 d)	4
	pre-migration	(T_{start} - 14 d) to T_{start}	4
	migration	T_{start} to T_{end}	4
Phenology:	**Snow departure day (SDD)**		
	winter range	75% MCP 14 d. pre-migration locs.	1
	calving range	75% MCP 14 d. post-migration locs.	1

Results

Basic summaries

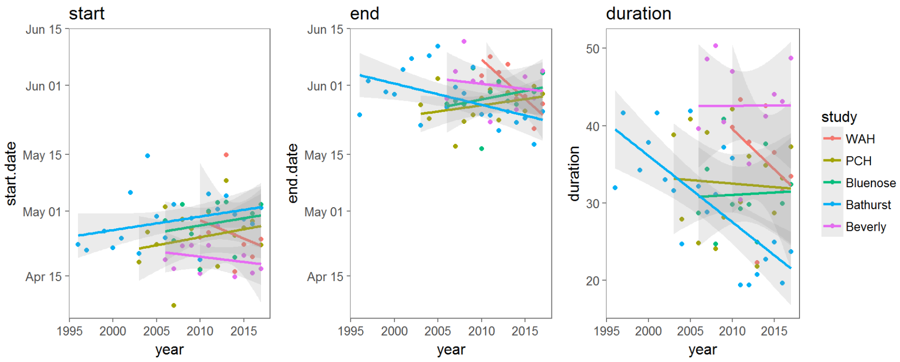


66 herd-year estimates obtained (all available years / herds except where sample size less than 5 ind.)

study	start	(sd)	dur.	(sd)	end	(sd)
WAH	4-25	8.53	35.93	6.87	5-31	5.90
PCH	4-24	7.44	32.52	6.50	5-27	4.30
Bluenose	4-27	5.80	31.13	4.94	5-29	5.24
Bathurst	4-28	6.15	30.19	7.63	5-28	6.63
Beverly	4-19	3.95	42.59	6.13	6-01	5.33

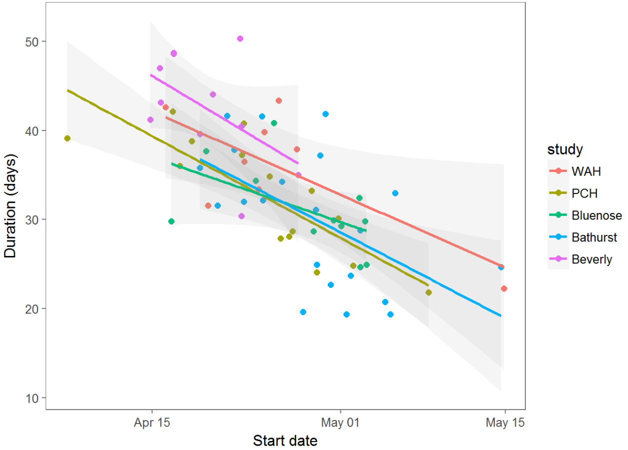
- Mean start Date: variable (April 19 - April 29)
- Mean end date: consistent (May 28-June 1)
- Only one significantly earlier / longer herd.

Trends



Basically NONE. Definitely not EARLIER (as hypothesized).

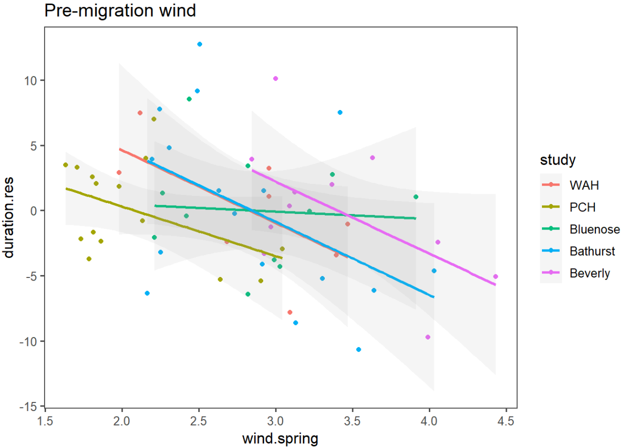
Late start = fast migration



Duration of migration can compensate for a late start, VERY consistently across all herds.

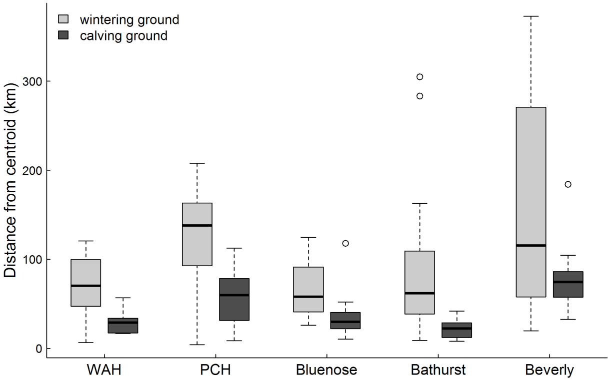
More wind = fast migration

Modeling residuals of the Start Time v. Duration regression:



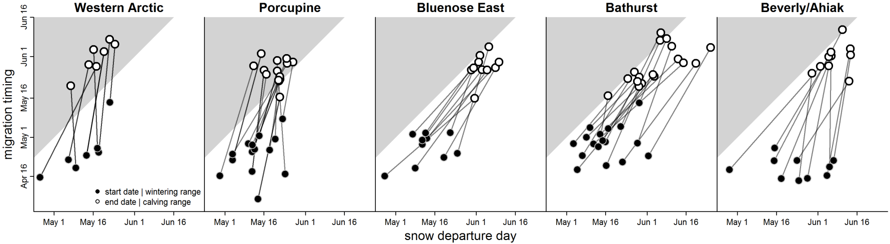
Windier conditions = **faster migrations**, beating out all other variables.

Shifting of ranges



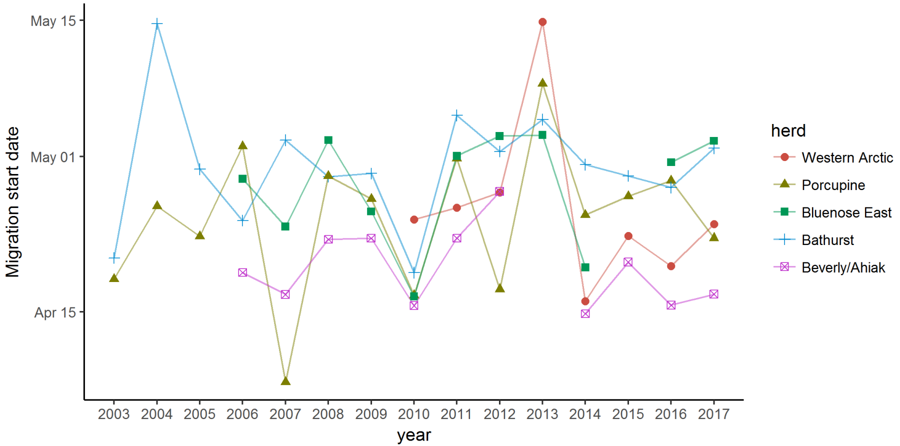
Pretty consistent calving ranges, wintering ranges move around quite a bit.

SDD v. start time

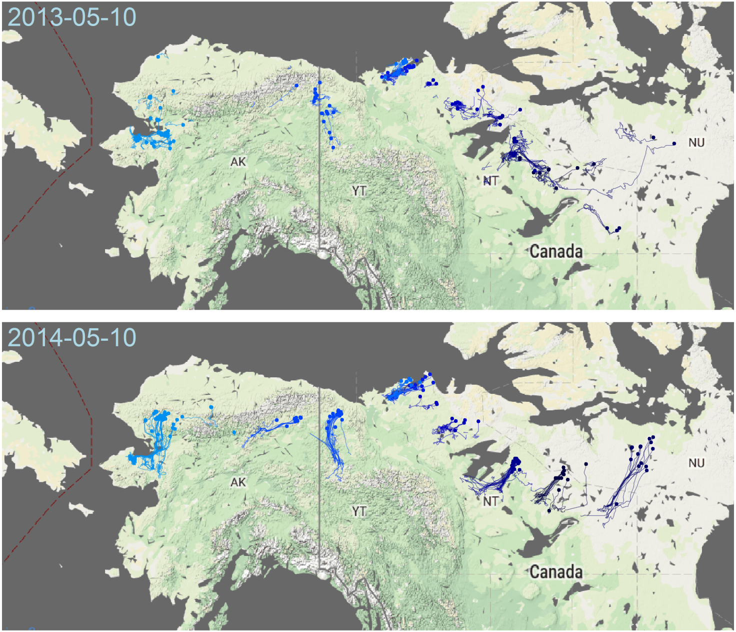


- Start dates always before snow melt.
- Arrival time: split
- Very weak relationship between **Start date / Winter SDD** or **End data / Calving SDD**
  - (except for WAH)

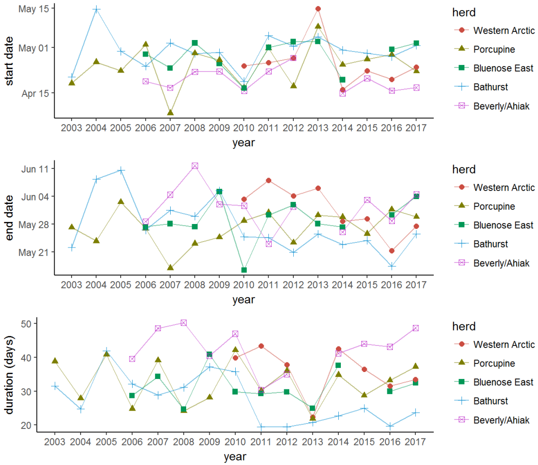
Key Discovery: Very high synchrony



Unbiased cross-correlation coefficient: 0.44 (p-value = 0.0002)

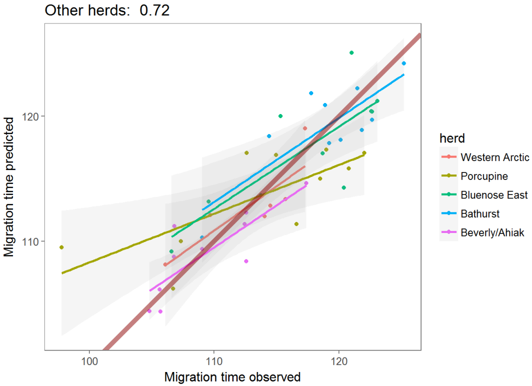

2013-05-10
AK
YT
NT
NU
Canada
2014-05-10
AK
YT
NT
NU
Canada

- but ONLY for start date



event	$\widehat{\rho}$	p.value
start	0.44	0.0002
duration	0.26	0.02
end	-0.04	0.61

Prediction plot

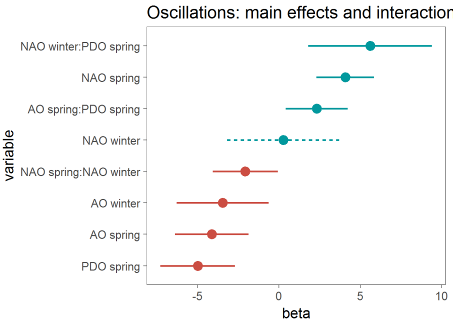


Using only other herds as a predictor, $r^2 = 0.72$.

Puts an onus on finding a way to explain the variability in start timing with environmental covariates.

Large scale oscillations model

Coefficients:

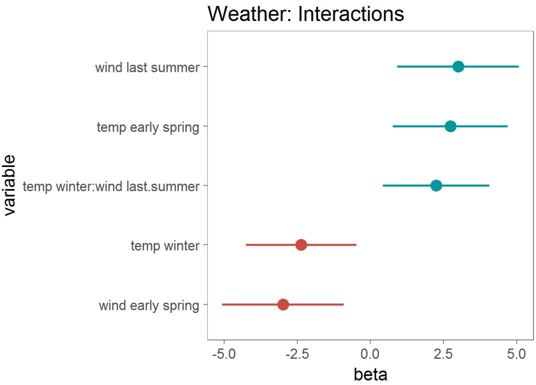


- high spring PDO = more snow = earlier migration
- positive winter and spring AO = ? = earlier migration
- but spring NAO = later migration (unless high winter NAO) ....

$$r^2 = 0.55$$

Weather model

Coefficients:



Very few significant predictors across herds, but:

- Colder winter leads to LATER migration ...
- Windy early spring leads to EARLIER migration ...
- Windy previous summer leads to LATER migration ...

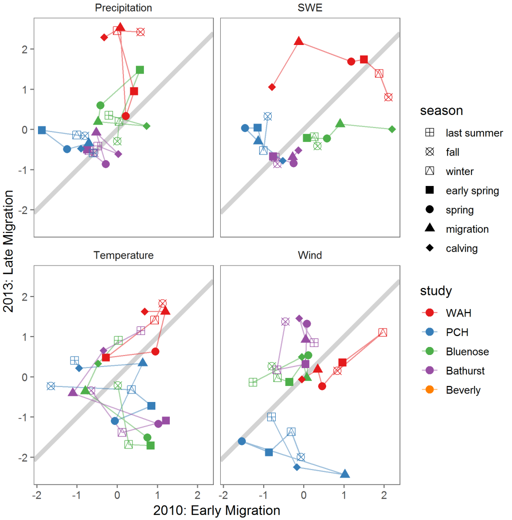
$$r^2 = 0.40$$

On balance:

$$\text{Synchrony } (r^2 = 0.69) >$$
$$\text{Climate } (r^2 = 0.55) >$$
$$\text{Weather } (r^2 = 0.39)$$

NOT what I would have expected!

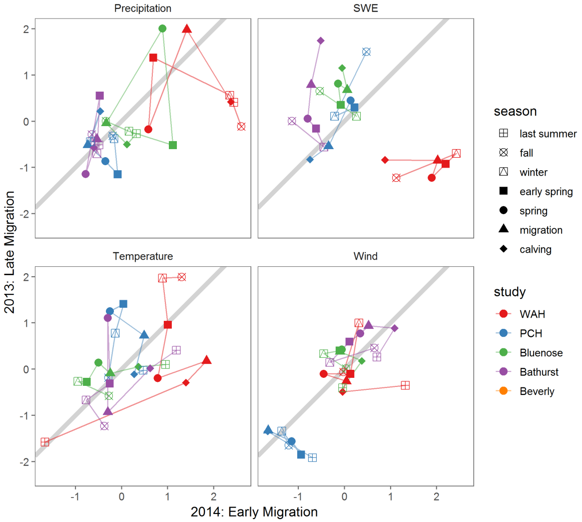
What did the caribou experience?



Early Migration Year vs. Late Migration Year

Higher temperatures and more precipitation in *late* year

What did the caribou experience?



Early Migration Year vs. Late Migration Year

(Mostly) just more snow

Conclusions

Caribou ...

Migrations remain Mysterious!

Caribou ...

Migrations remain Mysterious!

but they:

- seem pretty driven by the need to calve / are good at making up lost time
- don't seem to care much about, e.g., quantity of snow or precipitation
- move better under windier conditions (related to snow quality? forage availability?)
- possibly influenced by previous summer conditions, notably: windier, wetter (i.e. better because more bug-free?) lead to *later* migration times.

Number 1 outstanding questions

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How to explain migration synchrony!?

- Perhaps more hypothesis driven predictors rather than trolling for results? If so, what hypotheses?
- Analyze against "experienced" NDVI - proxy of productivity.
- Energetic interpretations? Reserves / Expenditure?

or ...

Number 1 outstanding questions

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- Perhaps more hypothesis driven predictors rather than trolling for results? If so, what hypotheses?
- Analyze against "experienced" NDVI - proxy of productivity.
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or ...

- Just go with the most parsimonious solution: They use their antlers as **antennae** to communicate across herds and **sails** to take advantage of the wind?

Future directions ....

Linking to populations ...

- Estimate calving times / rates from movement data
- Link to population estimates / survey reports
- **IDEA:** *Could migration timing tell us something about animal condition or predict reproductive success?*
- Relate to population dynamics (which may also show some synchrony in some places?)

Inverse pyramid of collaboration

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- U. of Maryland
- U. of Montana
- Columbia U.
- Ohio State U.
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