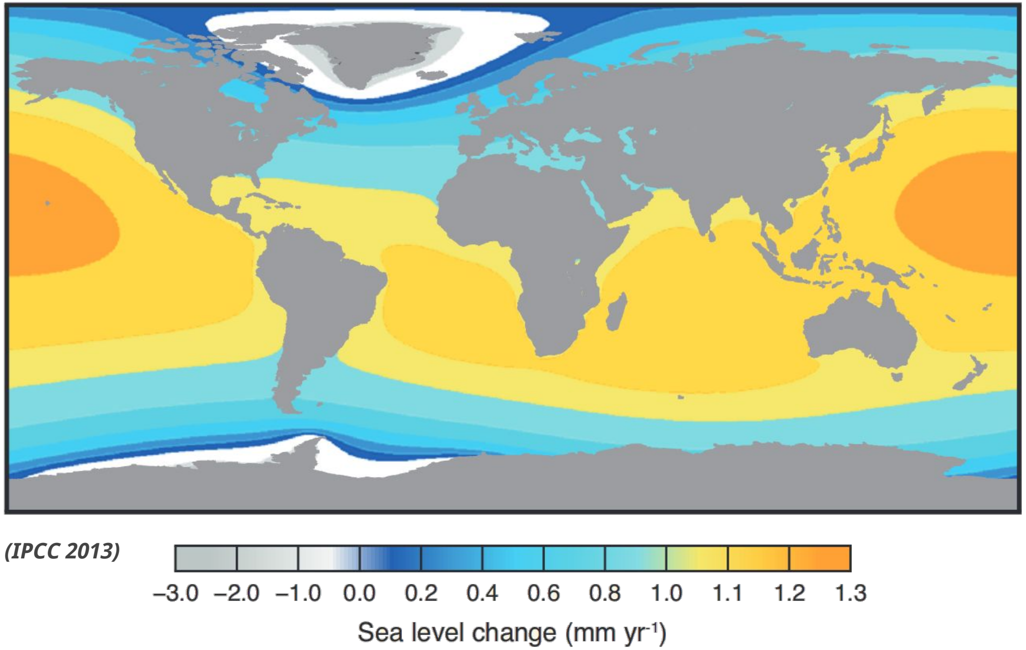
Multi-scale investigation of winter balance on alpine glaciers

Senior supervisor: Gwenn Flowers
Supervisor: Valentina Radić
Supervisor: Kirsten Zickfeld
External: Joseph Shea

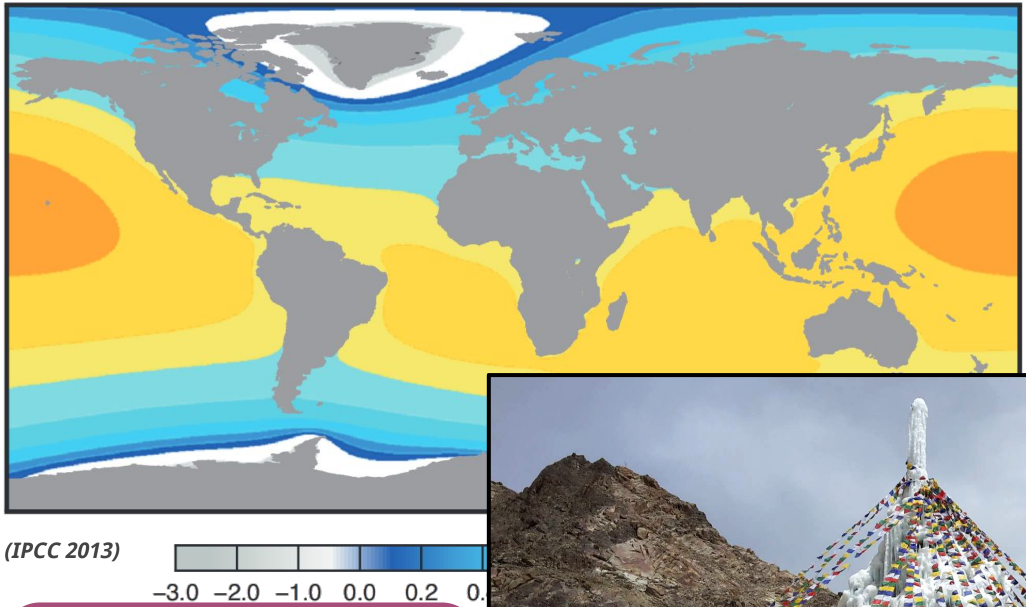
BACKGROUND



(IPCC 2013)

SEA LEVEL RISE

BACKGROUND



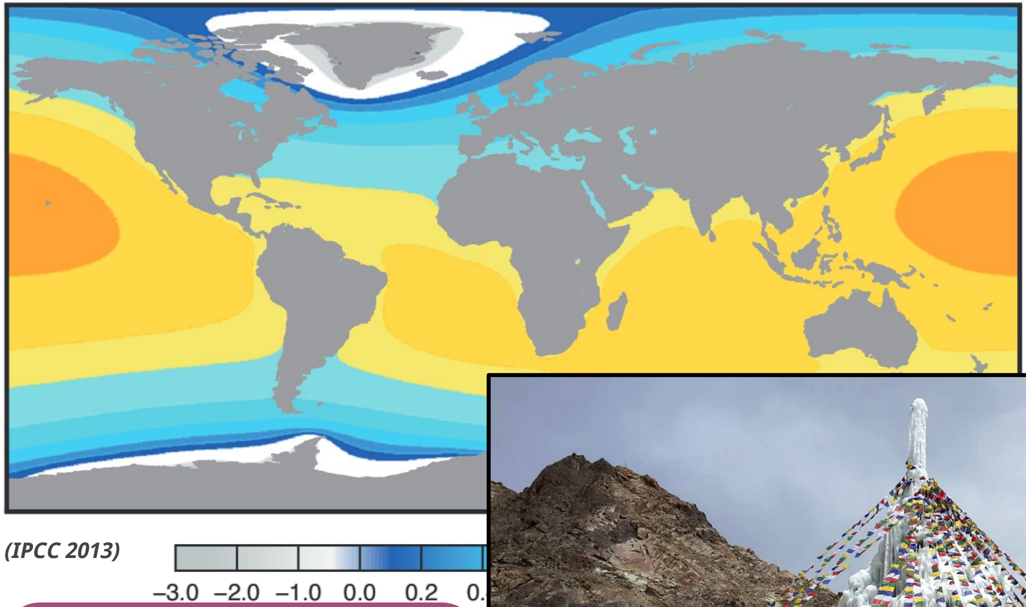
(IPCC 2013)

SEA LEVEL RISE

WATER AVAILABILITY

(icestupa.org)

BACKGROUND



(IPCC 2013)

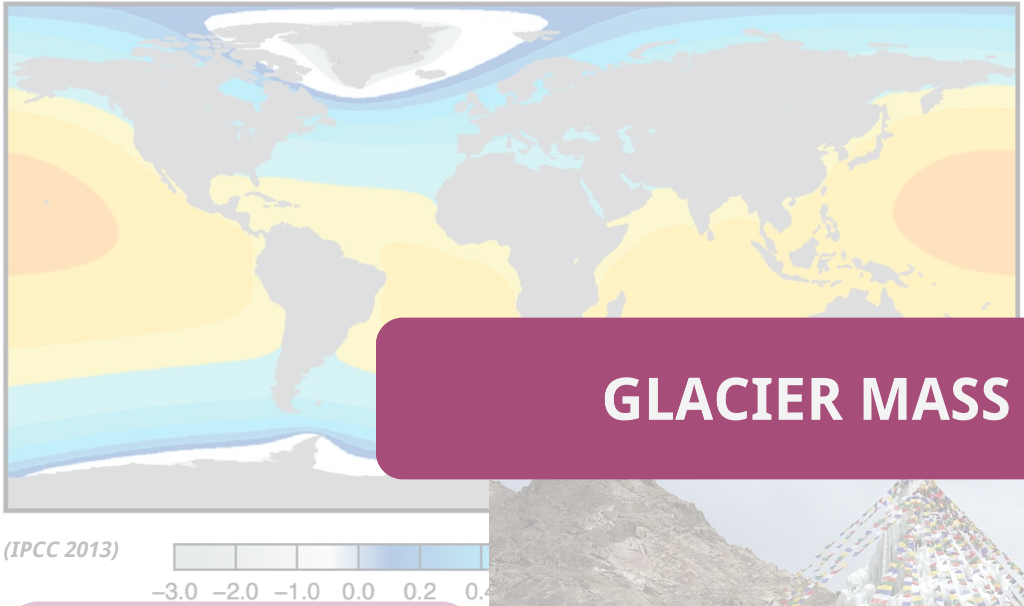
SEA LEVEL RISE

MONITOR GLACIERS

WATER AVAILABILITY

(icestupa.org)

BACKGROUND



(IPCC 2013)

SEA LEVEL RISE

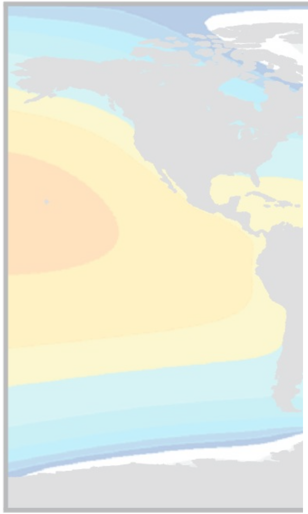
GLACIER MASS BALANCE

MONITOR GLACIERS

WATER AVAILABILITY

(icestupa.org)

BACKGROUND



(IPCC 2013)

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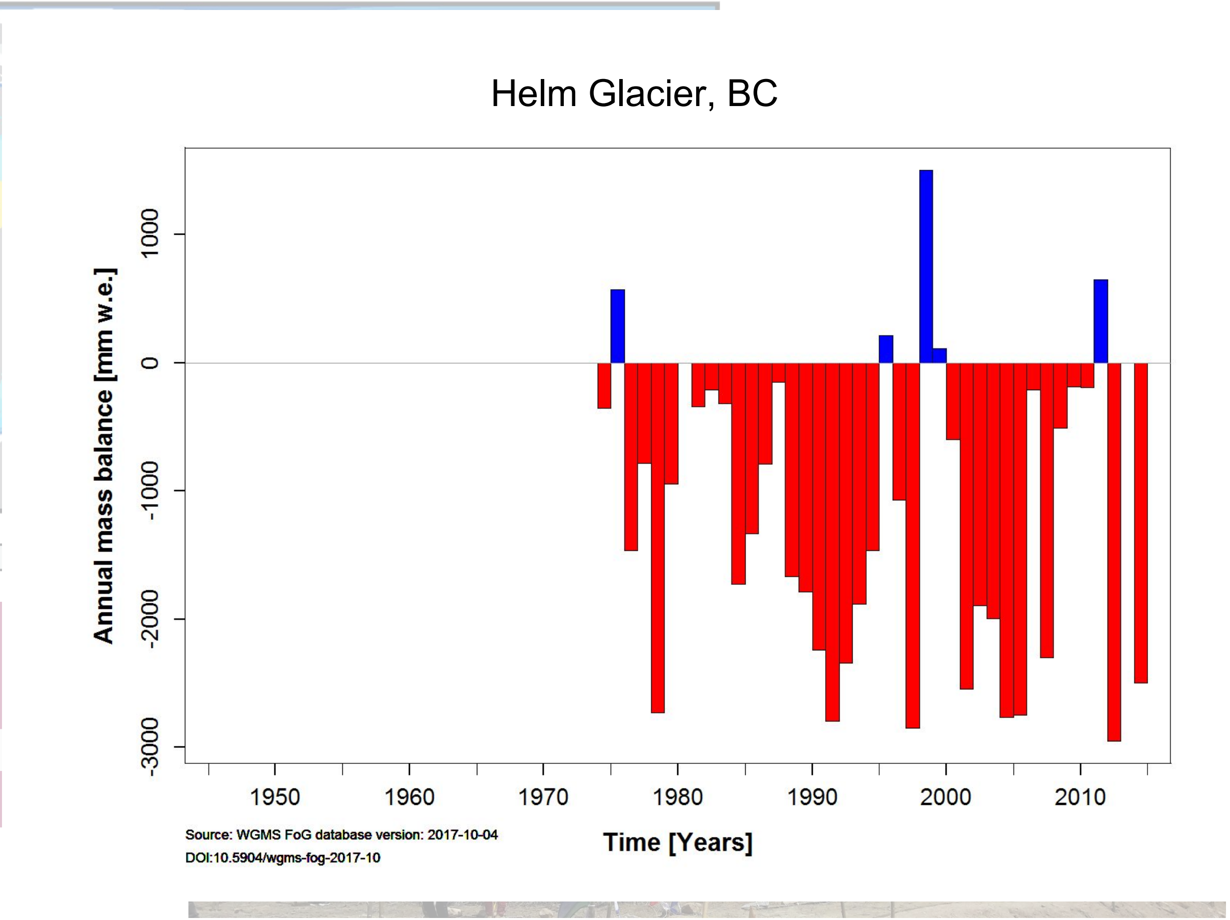
AVAILABI



MONITOR GLACIERS

BACKGROUND

WINTER BALANCE

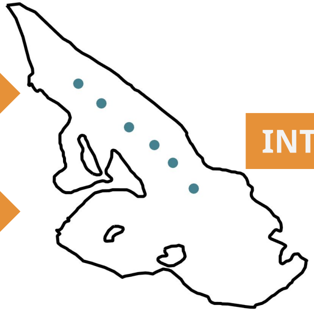
SUMMER BALANCE

BACKGROUND

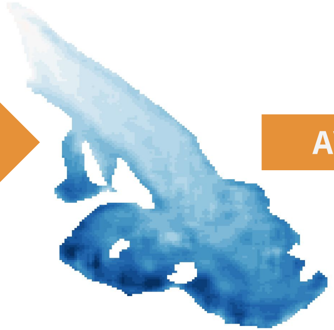
END OF WINTER

SNOW DEPTH

SNOW DENSITY



INTERPOLATE



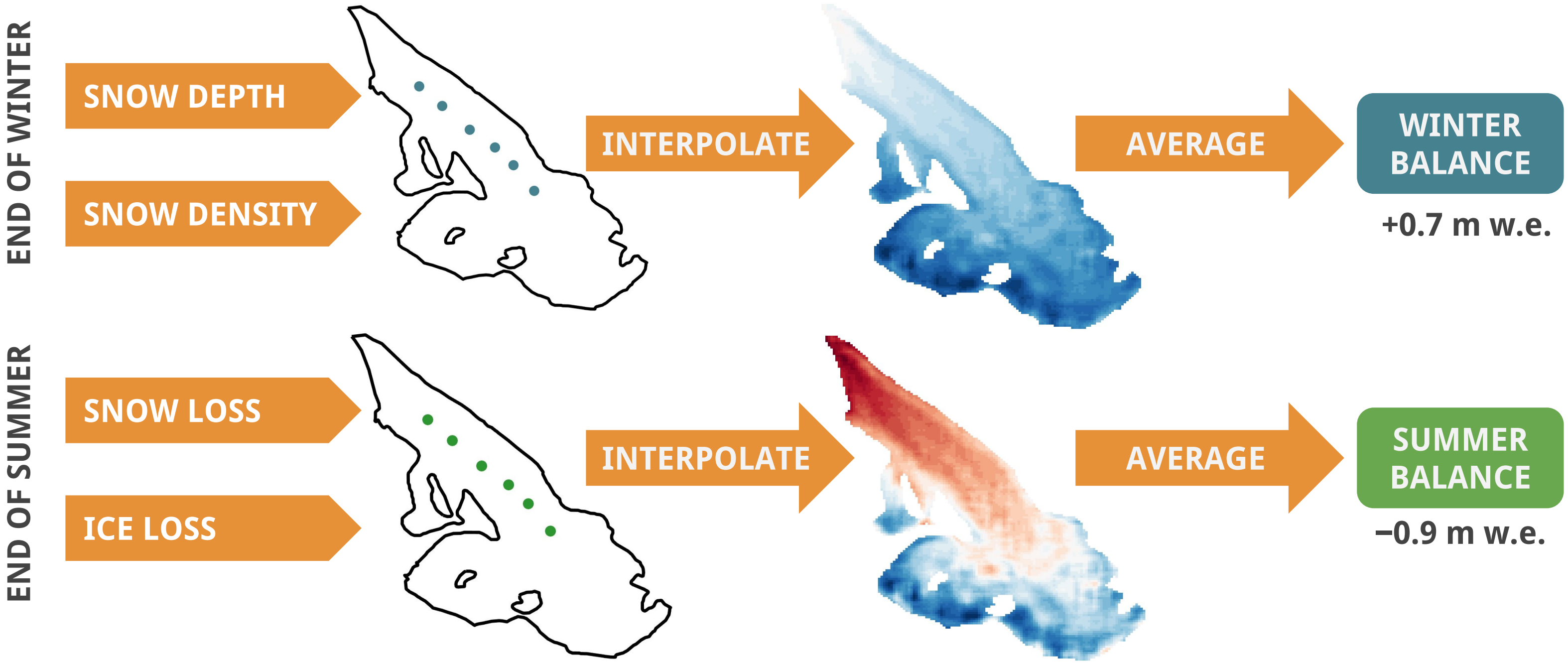
AVERAGE

WINTER BALANCE

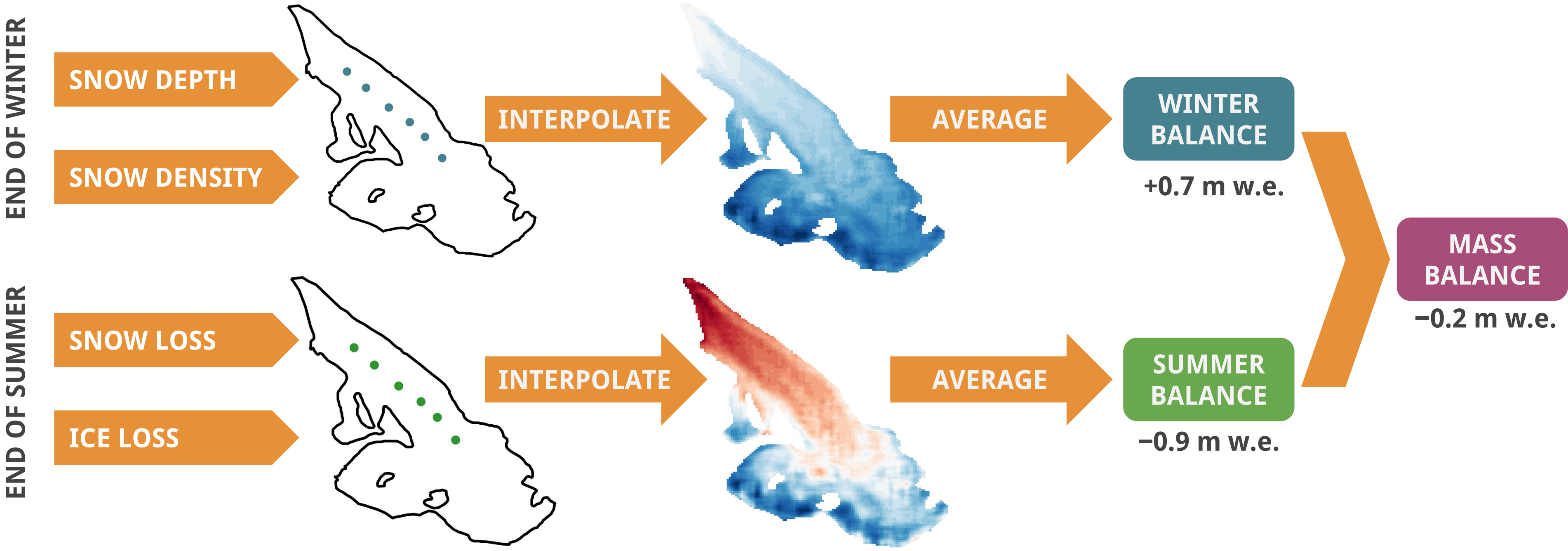
+0.7 m w.e.

SUMMER BALANCE

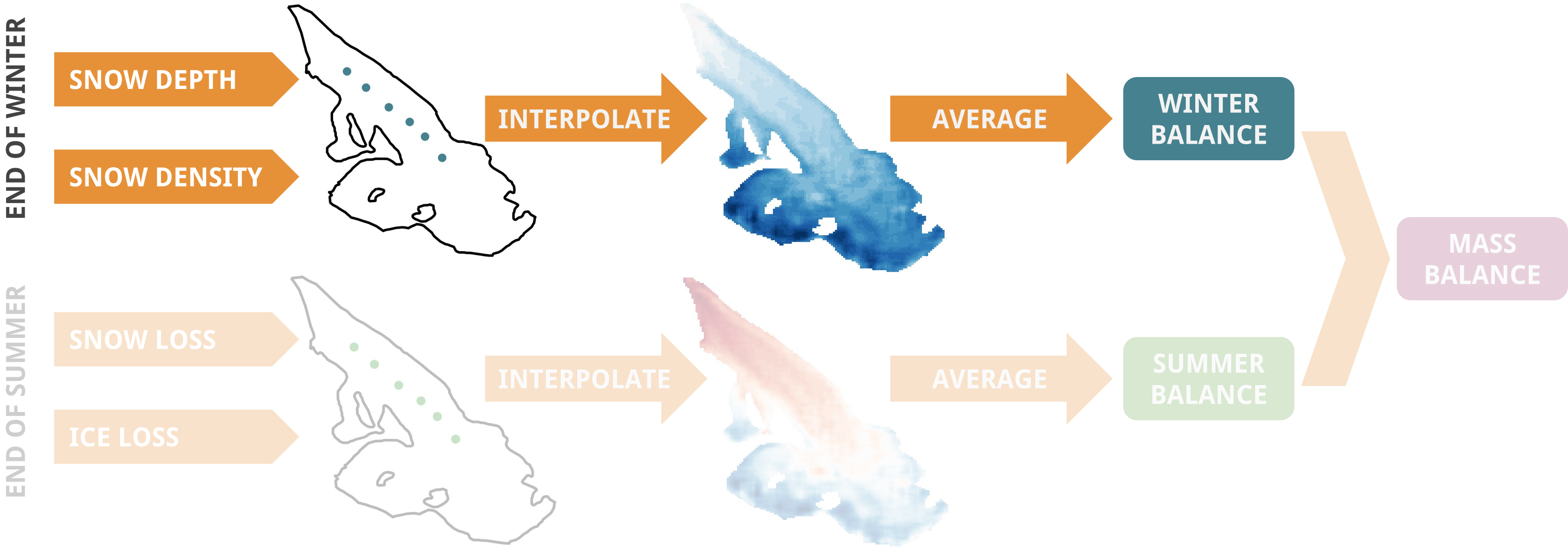
BACKGROUND


END OF WINTER
SNOW DEPTH
SNOW DENSITY
INTERPOLATE
AVERAGE
WINTER BALANCE
+0.7 m w.e.
END OF SUMMER
SNOW LOSS
ICE LOSS
INTERPOLATE
AVERAGE
SUMMER BALANCE
−0.9 m w.e.

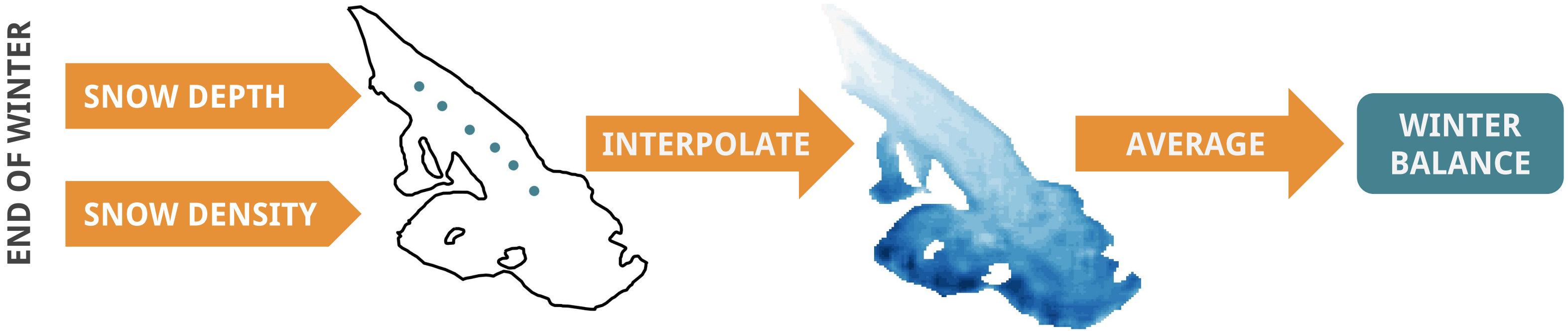
BACKGROUND


END OF WINTER
SNOW DEPTH
SNOW DENSITY
INTERPOLATE
AVERAGE
WINTER BALANCE
+0.7 m w.e.
END OF SUMMER
SNOW LOSS
ICE LOSS
INTERPOLATE
AVERAGE
SUMMER BALANCE
−0.9 m w.e.
MASS BALANCE
−0.2 m w.e.

BACKGROUND


END OF WINTER
SNOW DEPTH
SNOW DENSITY
INTERPOLATE
AVERAGE
WINTER BALANCE
END OF SUMMER
SNOW LOSS
ICE LOSS
INTERPOLATE
AVERAGE
SUMMER BALANCE
MASS BALANCE

BACKGROUND



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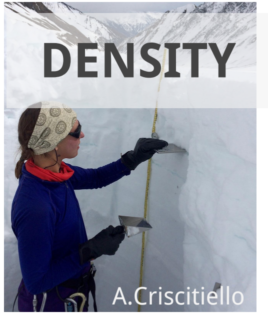
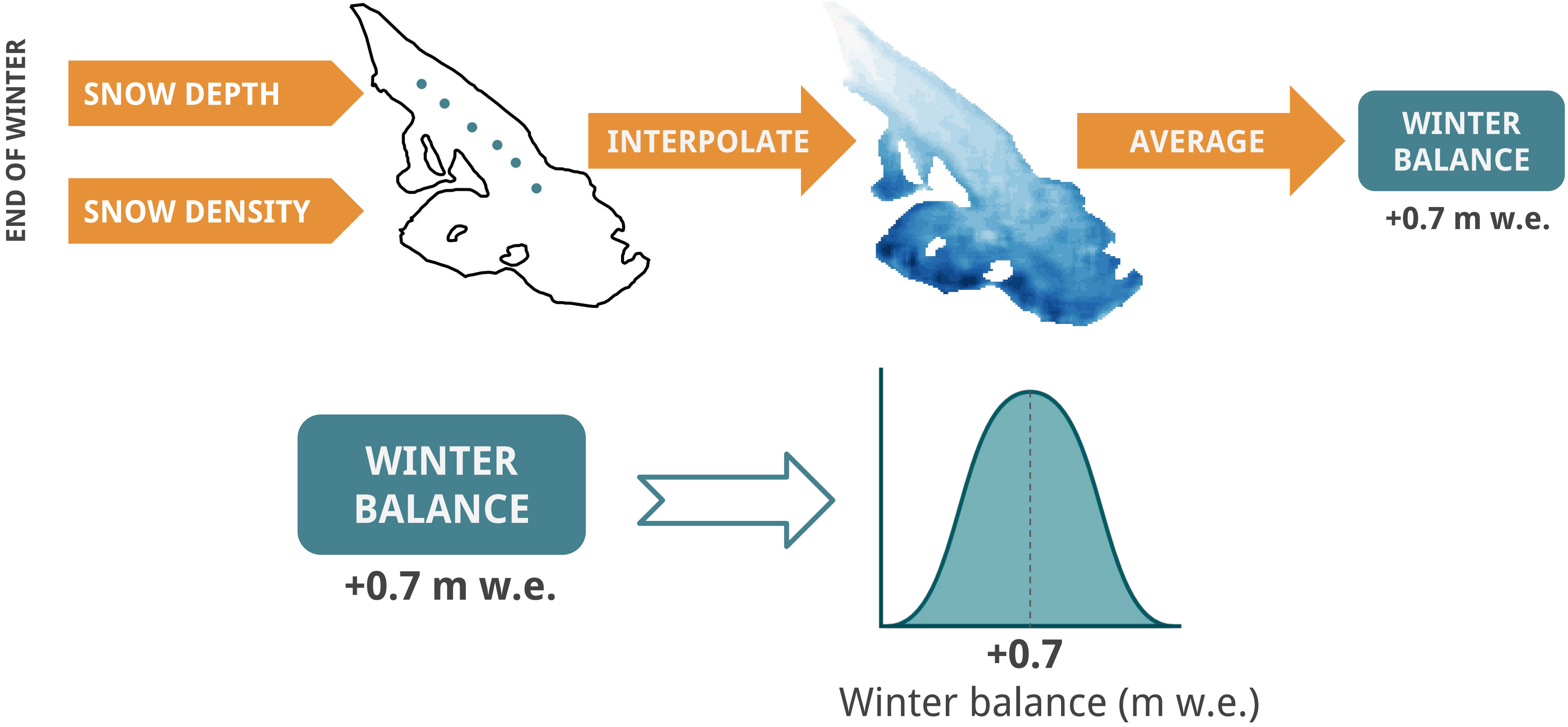


Units: meters water equivalent (m w.e.)

Probing
GPR
Repeat lidar

Snow pit
Snow core

BACKGROUND


END OF WINTER
SNOW DEPTH
SNOW DENSITY
INTERPOLATE
AVERAGE
WINTER BALANCE
+0.7 m w.e.
WINTER BALANCE
+0.7 m w.e.
+0.7
Winter balance (m w.e.)

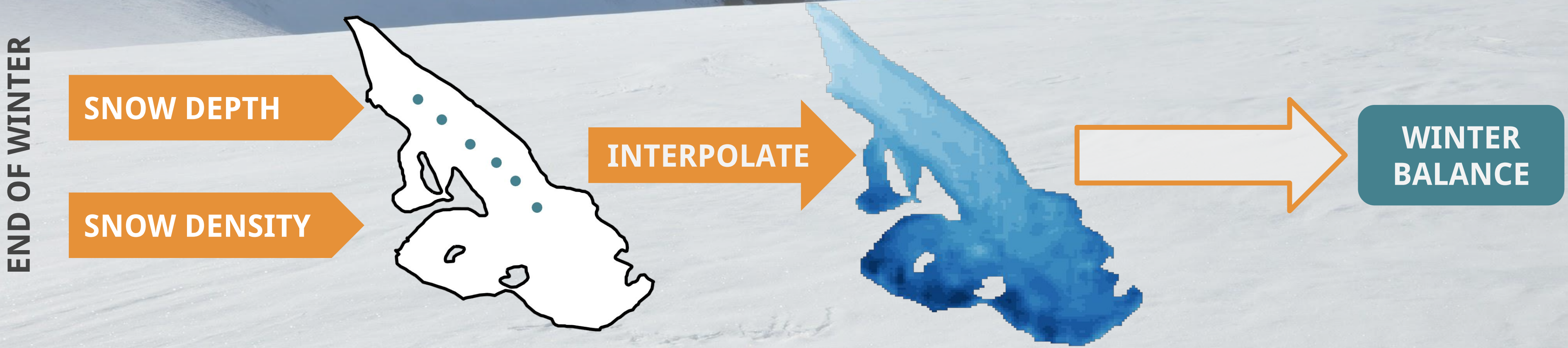
OBJECTIVES

Examine **methods** of estimating winter balance from direct measurements of snow depth and density

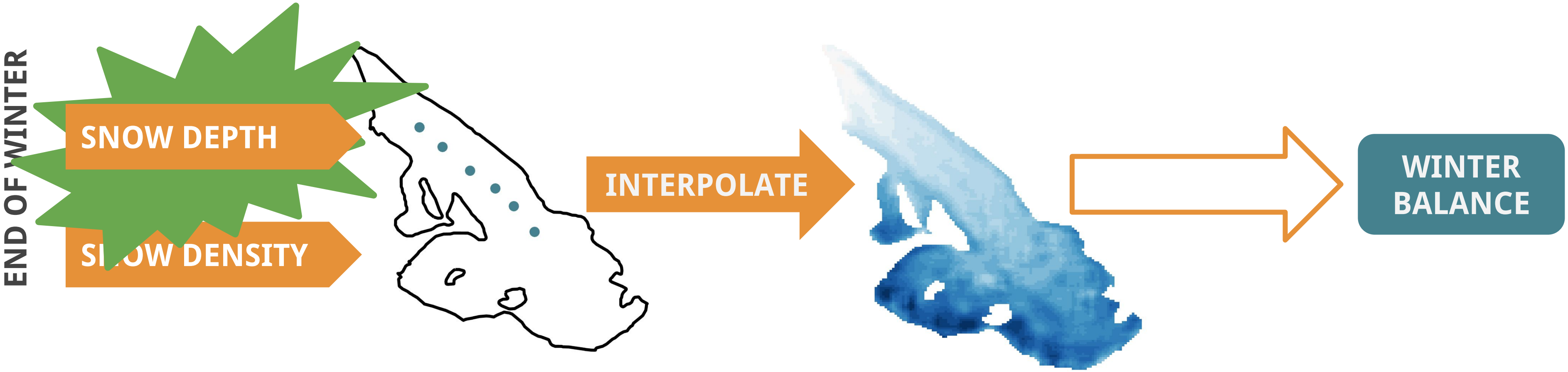
Identify and assess **sources of uncertainty**

OBJECTIVE I

Examine **methods** of estimating winter balance from direct measurements of snow depth and density



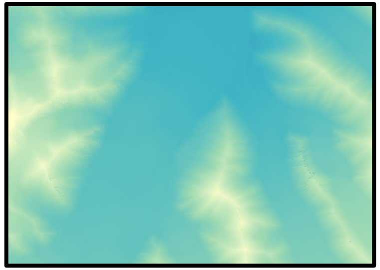
OBJECTIVE I

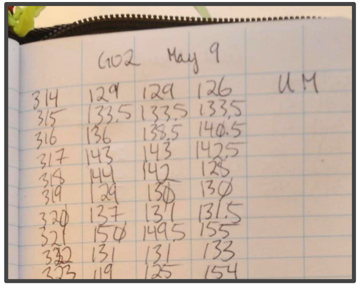

END OF WINTER
SNOW DEPTH
SNOW DENSITY
INTERPOLATE
WINTER BALANCE

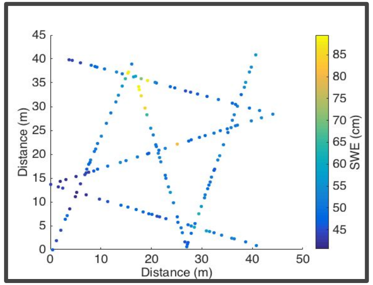
SNOW DEPTH - METHODS

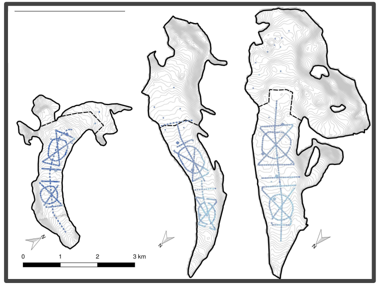
SCALES OF VARIABILITY

Point scale	Gridcell scale	Basin scale	Regional scale

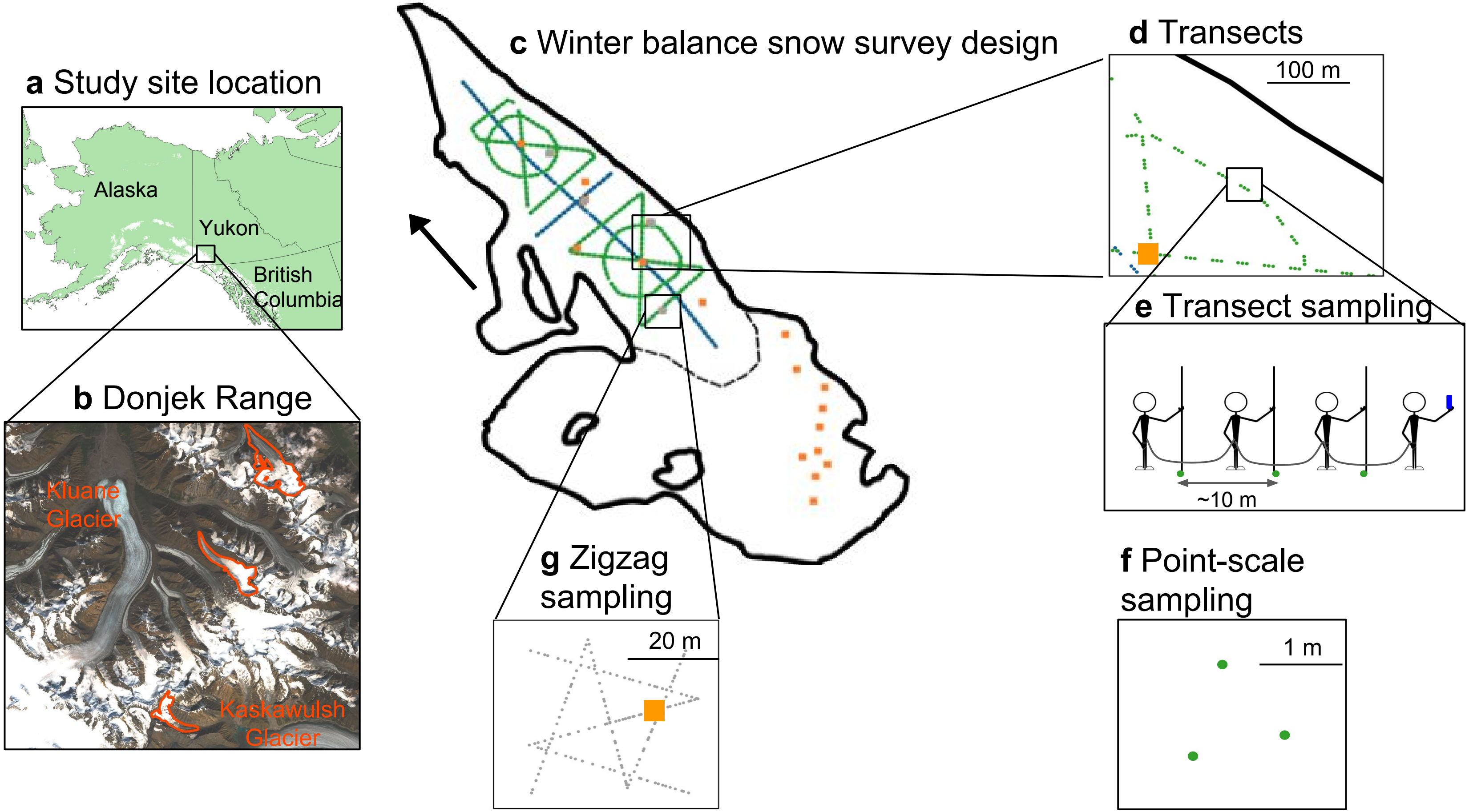




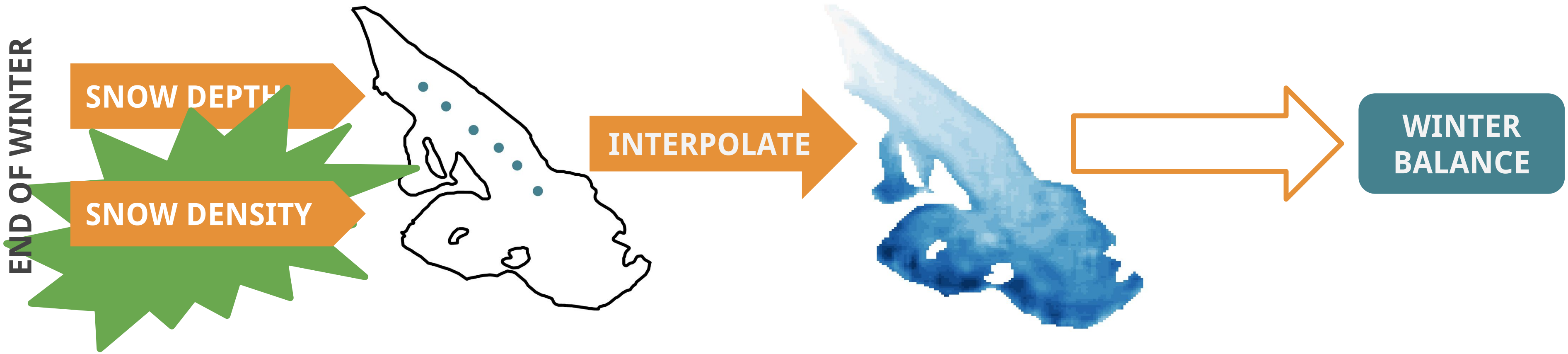




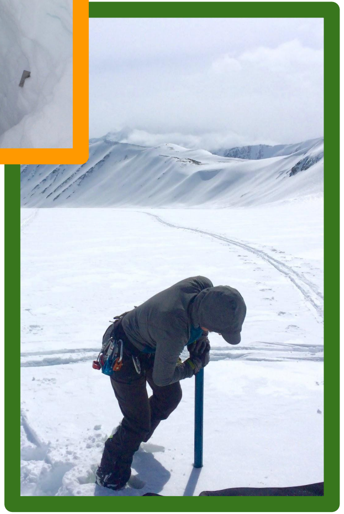
SNOW DEPTH - METHODS

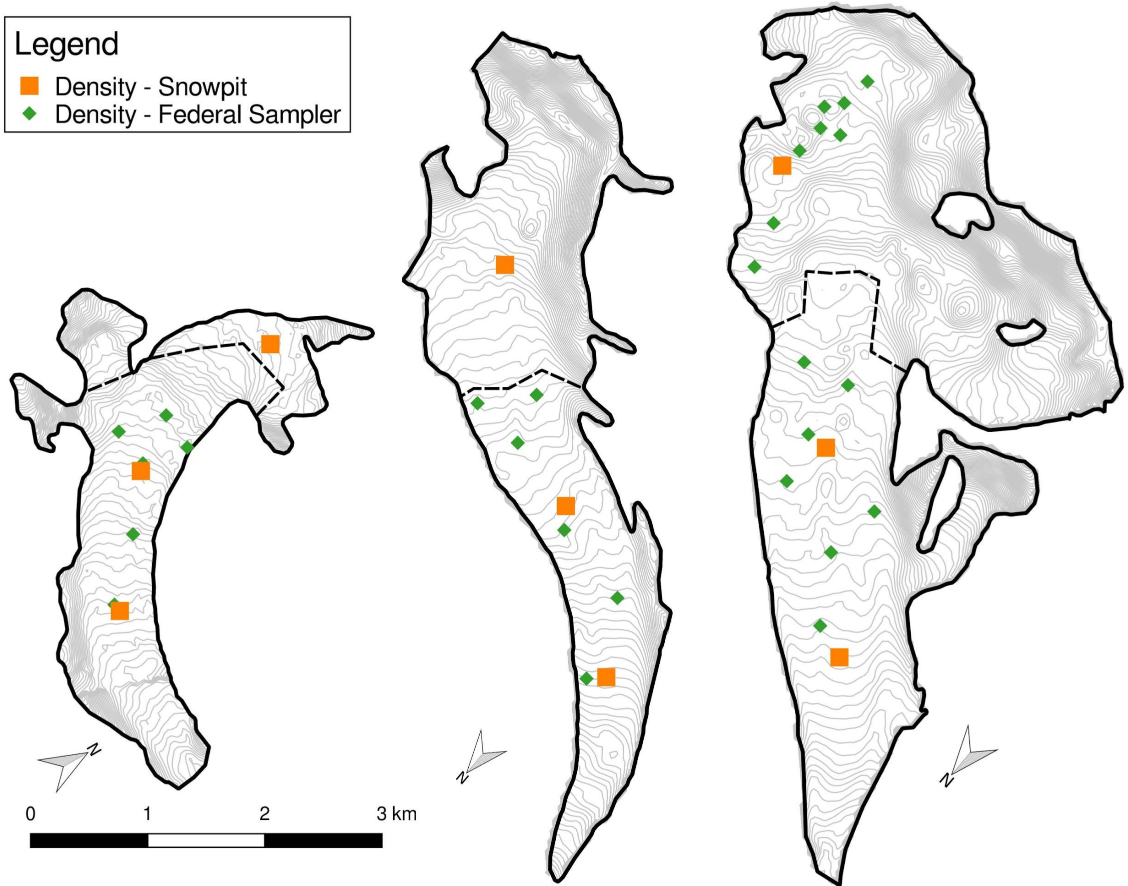


OBJECTIVE I

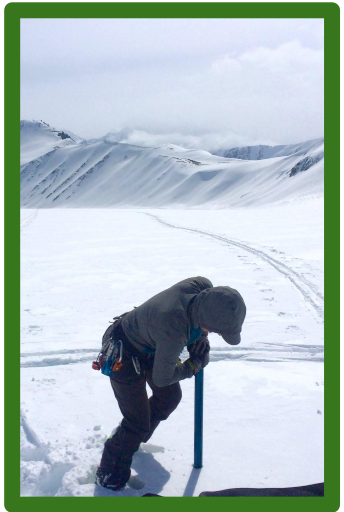

END OF WINTER
SNOW DEPTH
SNOW DENSITY
INTERPOLATE
WINTER BALANCE

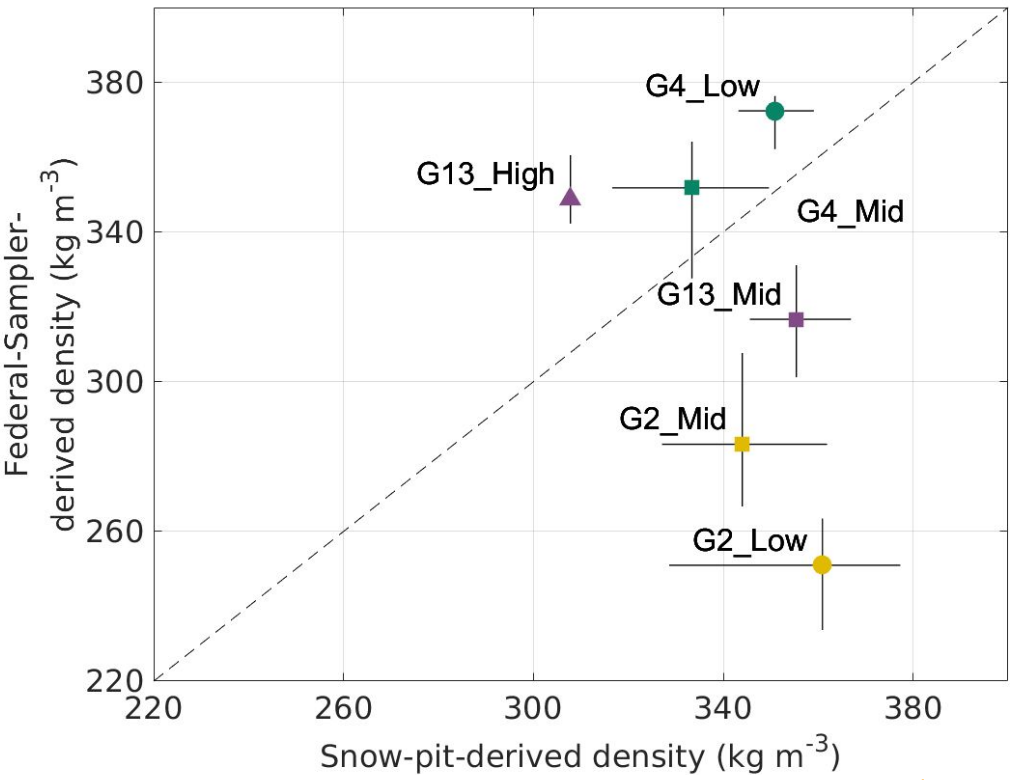
SNOW DEPTH - METHODS





SNOW DENSITY - RESULTS



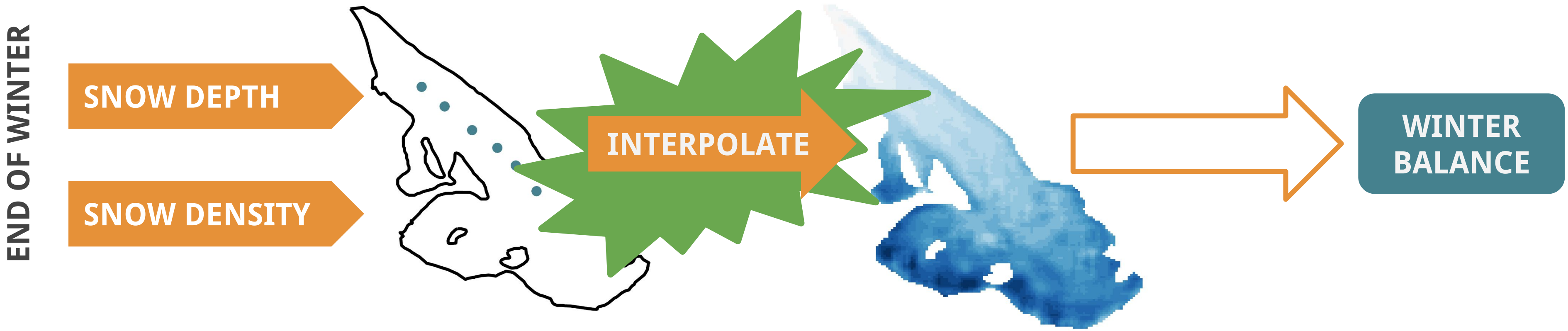


SNOW DENSITY - RESULTS

EIGHT METHODS OF ESTIMATING DENSITY

Source of measured snow density		Density assignment method
Snow pit	*Federal Sampler*	
❄	❄	Mean of measurements across all glaciers
❄	❄	Mean of measurements for each glacier
❄	❄	Regression of density on elevation for a glacier
❄	❄	Inverse distance weighted mean for a glacier

OBJECTIVE I


END OF WINTER
SNOW DEPTH
SNOW DENSITY
INTERPOLATE
WINTER BALANCE

INTERPOLATION - METHODS

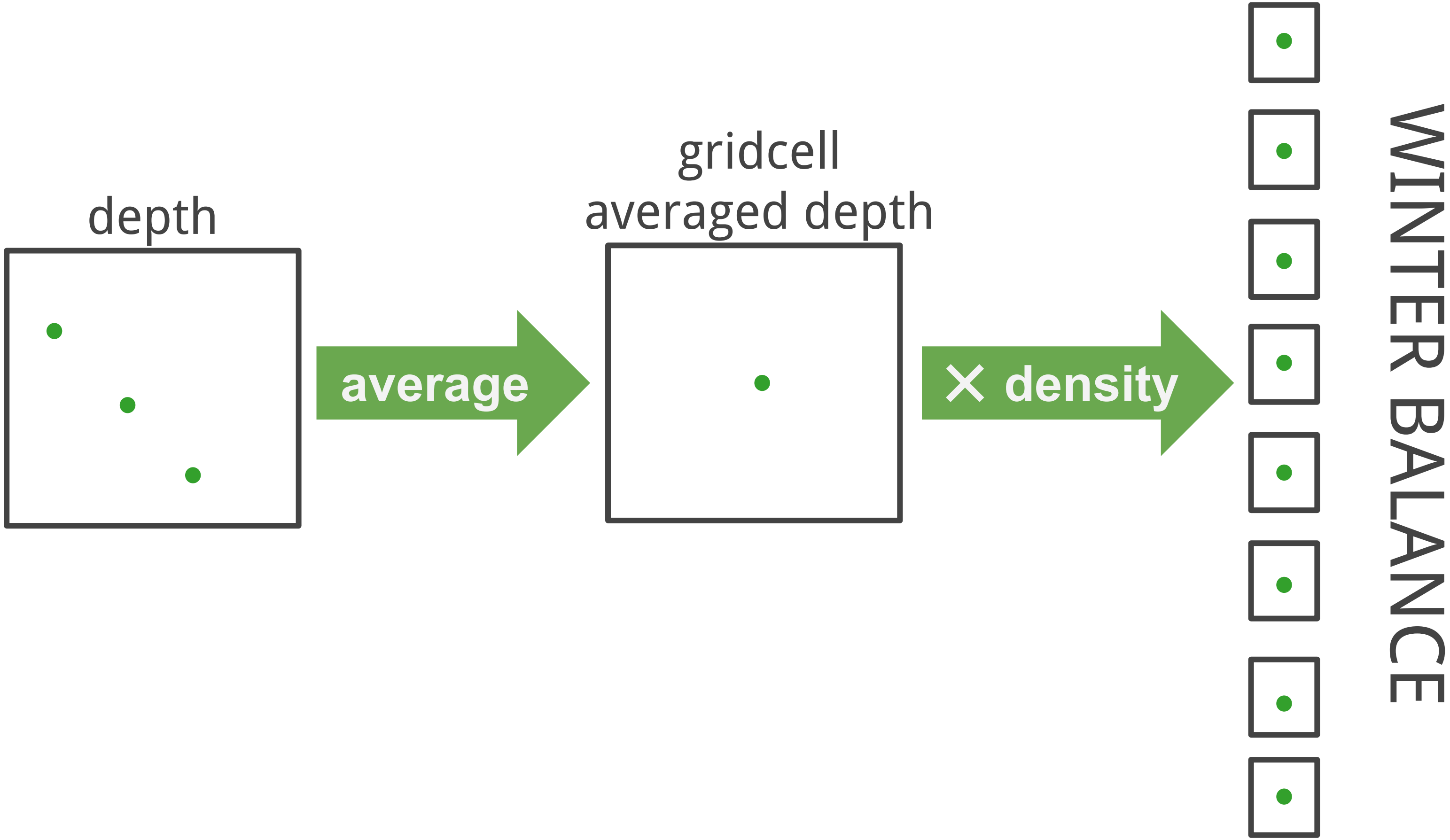
LINEAR REGRESSION

- Multiple linear regression of winter balance on topographic parameters derived from SPOT-5 DEM (40 m)
- Cross-validation and model averaging (BIC)

SIMPLE KRIGING

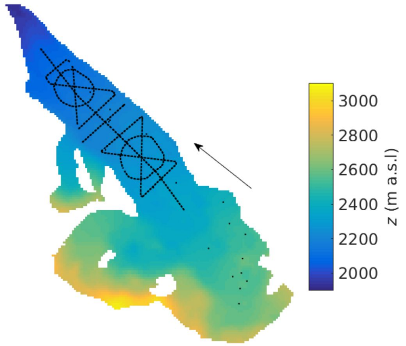
REGRESSION KRIGING

INTERPOLATION - INPUT DATA

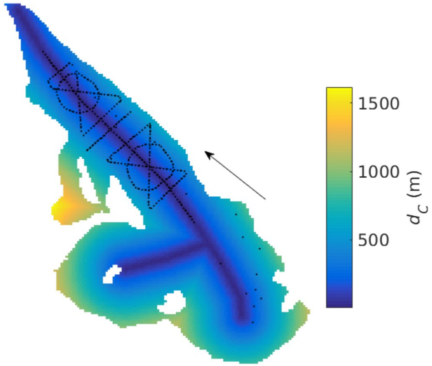


INTERPOLATION - INPUT DATA

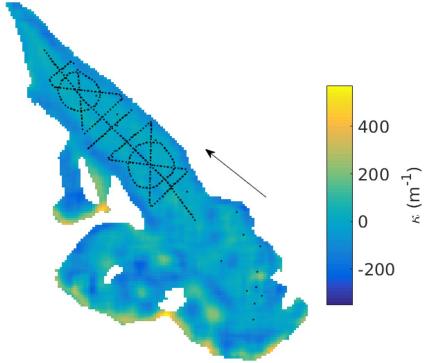
Elevation



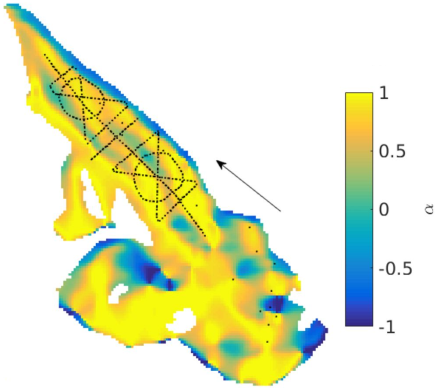
Distance from centreline



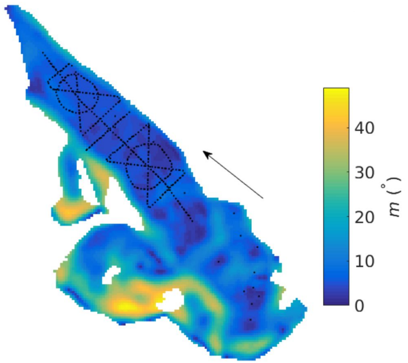
Curvature



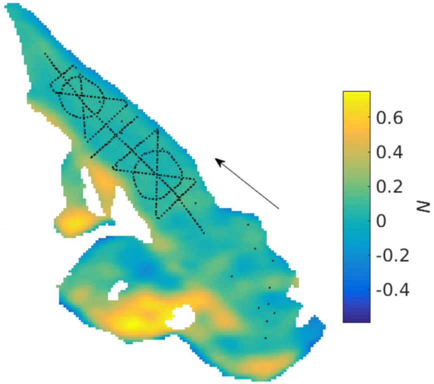
Aspect



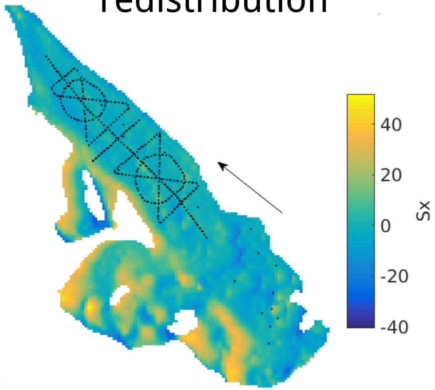
Slope



Northness

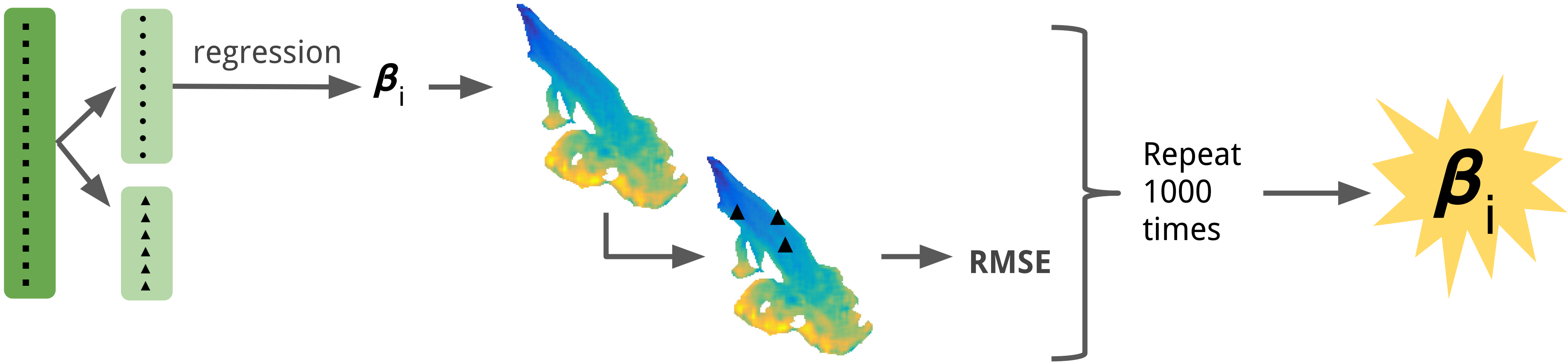


Measure of wind redistribution



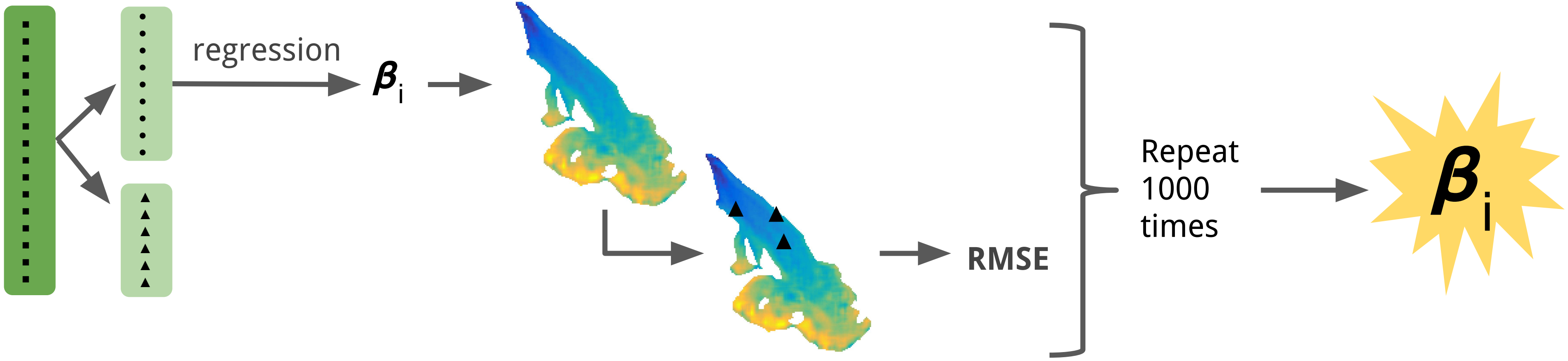
INTERPOLATION - METHODS

CROSS VALIDATION



INTERPOLATION - METHODS

CROSS VALIDATION

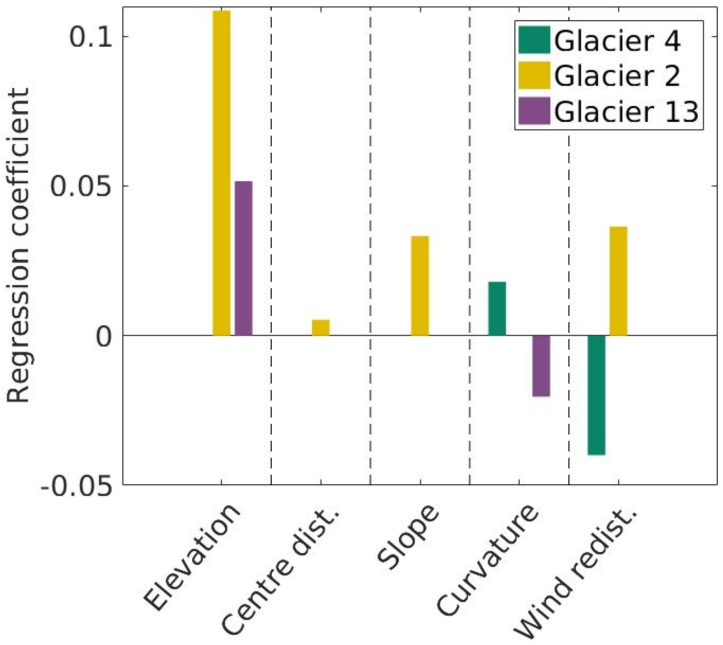


MODEL AVERAGING

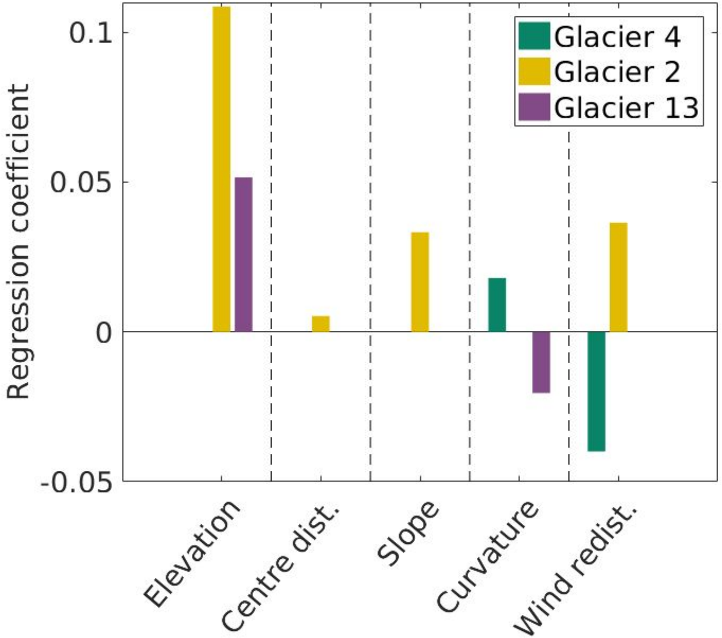
β_1 β_1, β_2 $\beta_1, \beta_2, \beta_3$ β_2, β_3 $\beta_2, \beta_3, \beta_4$ $\beta_1, \beta_2, \beta_3, \beta_4$ … $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7$

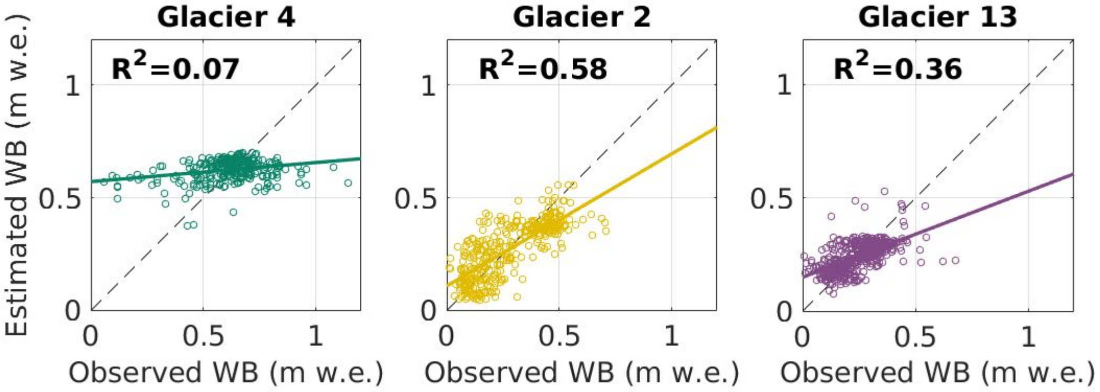
⇒ **Bayesian information criterion (BIC) weighting**

INTERPOLATION - RESULTS

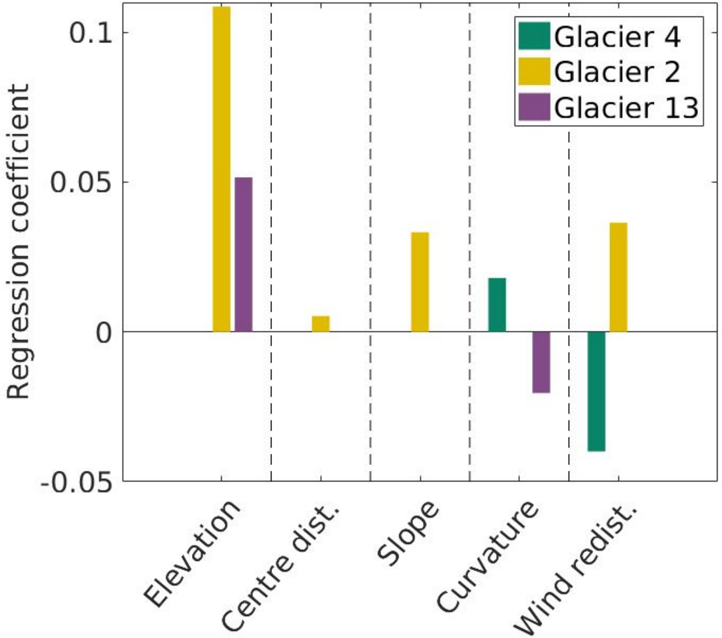


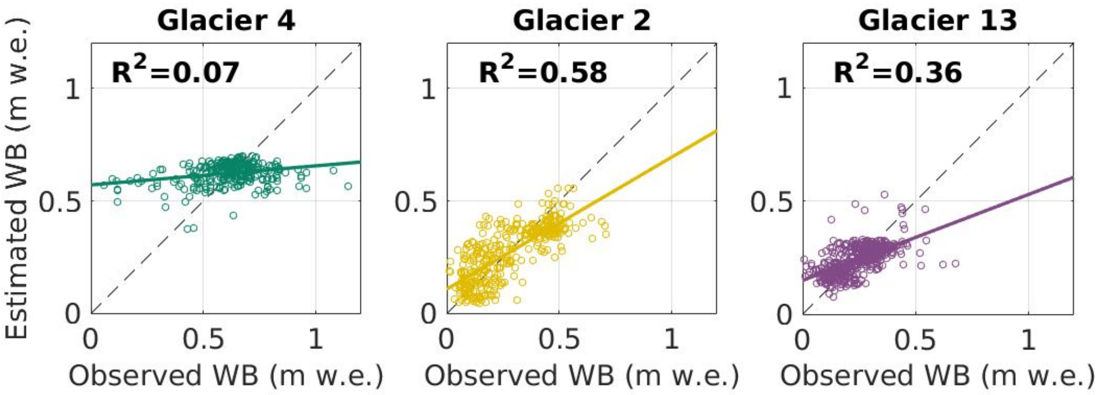
INTERPOLATION - RESULTS





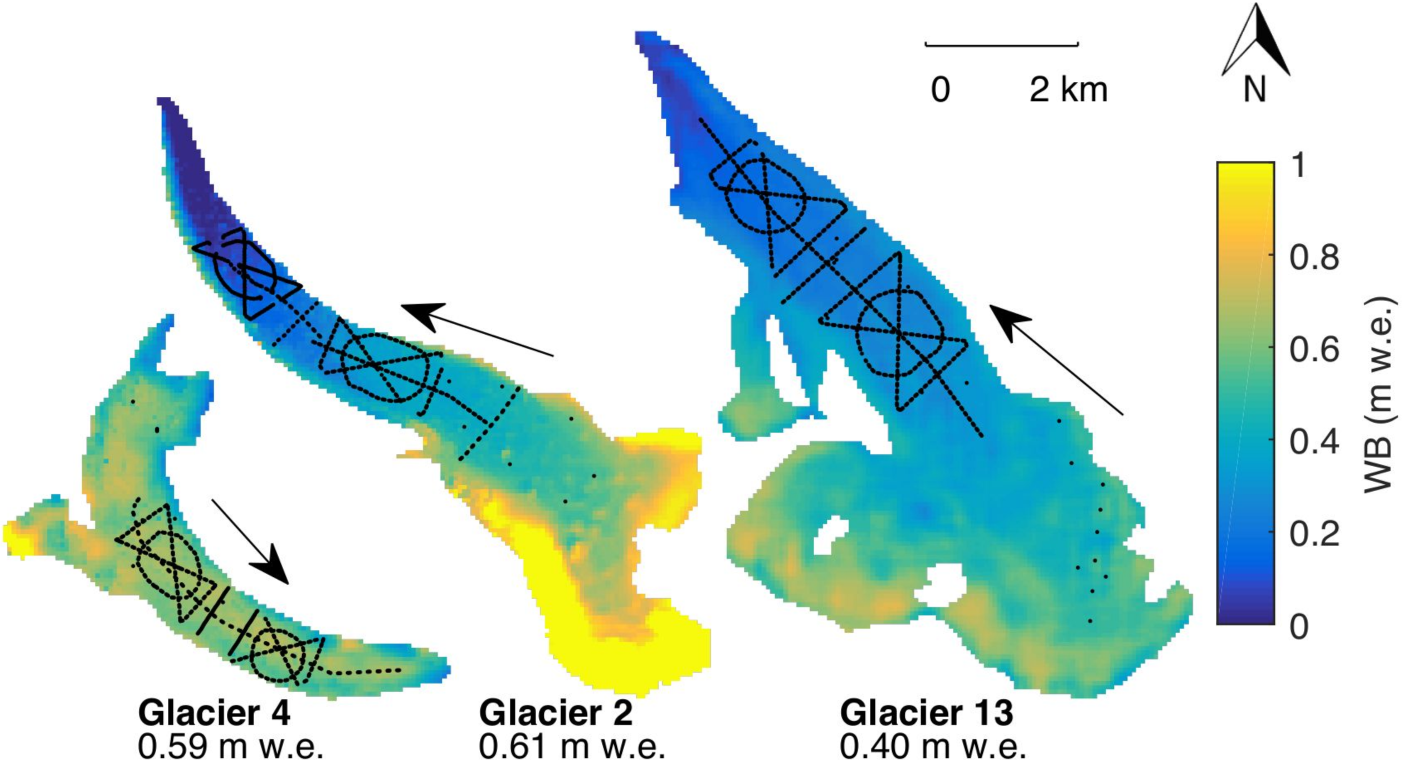
INTERPOLATION - RESULTS





- Processes governing winter balance differ between glaciers
  - Elevation dominates
  - Wind processes likely important but not adequately captured

DISTRIBUTED WINTER BALANCE



EIGHT REALIZATIONS DUE TO DENSITY ESTIMATES

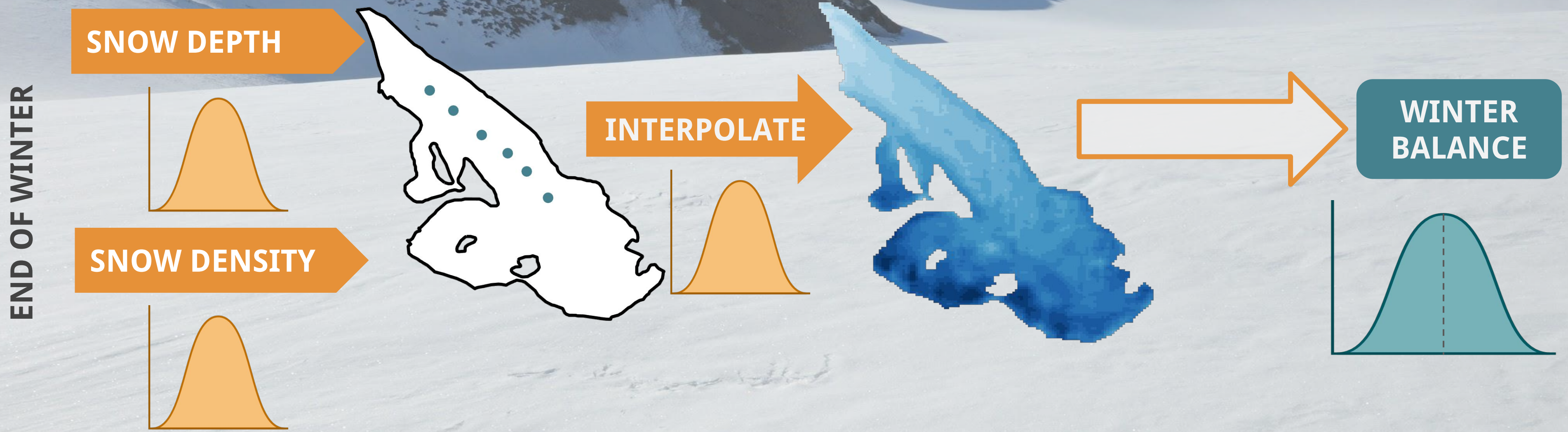
OBJECTIVES

Examine **methods** of estimating winter balance from direct measurements of snow depth and density

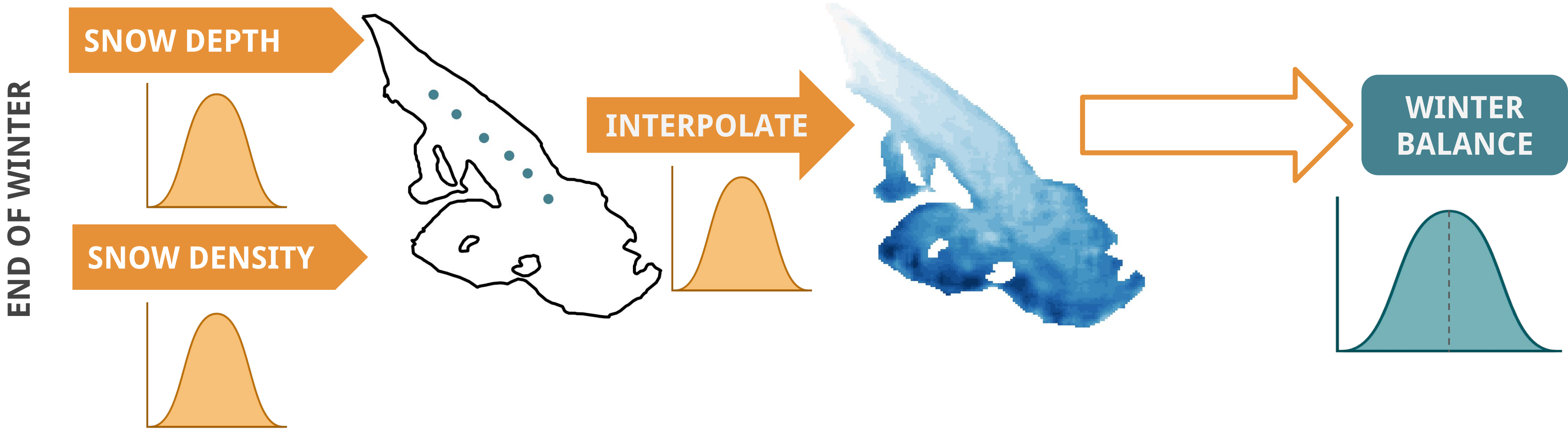
Identify and assess **sources of uncertainty**

OBJECTIVE II

Identify and assess **sources of uncertainty**

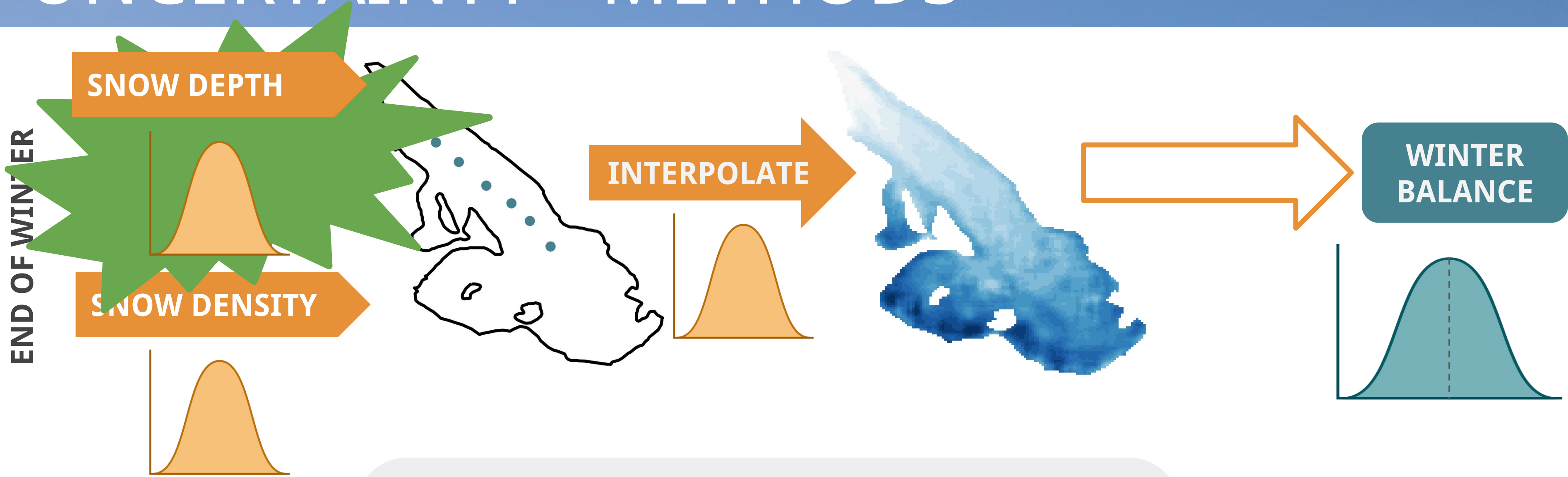


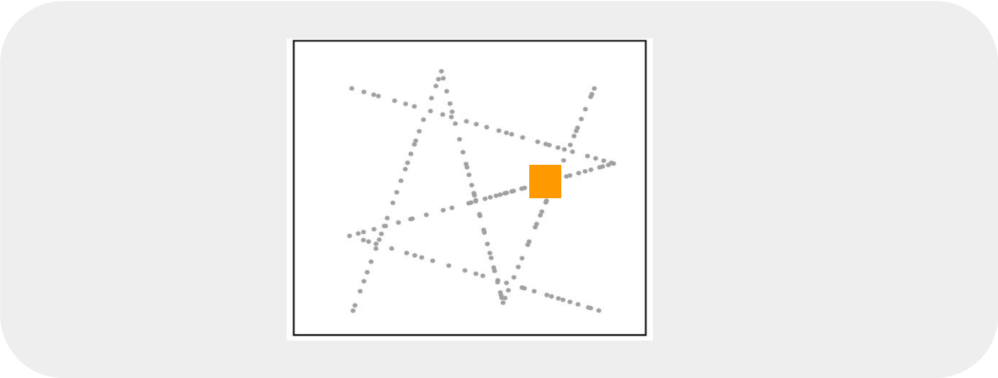
UNCERTAINTY - METHODS



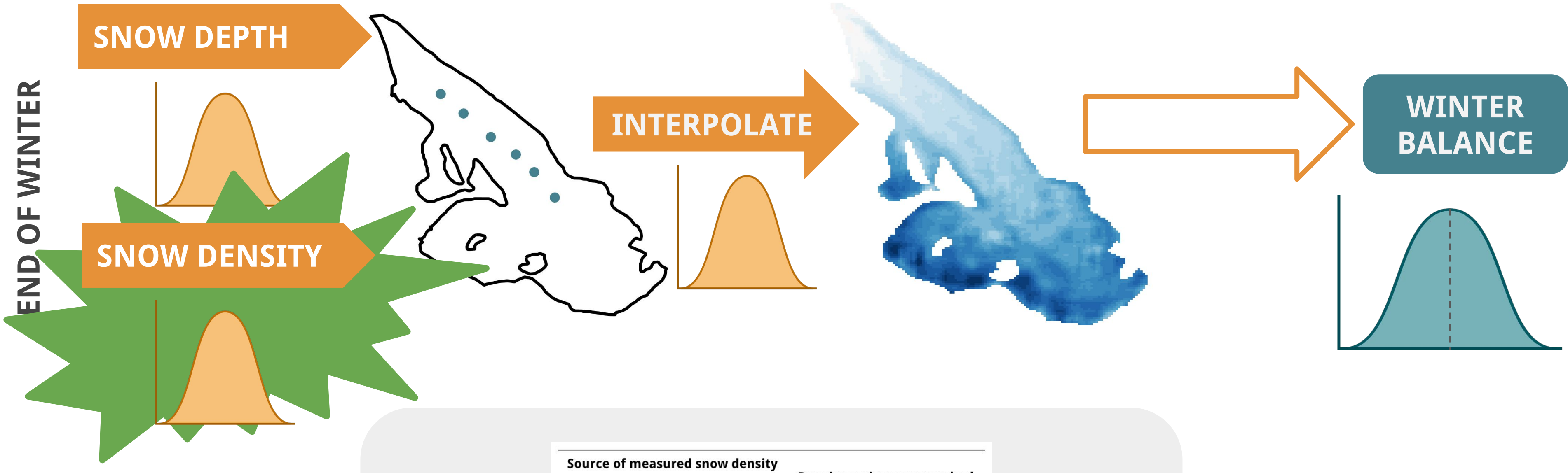
MONTE CARLO METHOD

UNCERTAINTY - METHODS





UNCERTAINTY - METHODS



Source of measured snow density		Density assignment method
Snow pit	*Federal Sampler*	
❄	❄	Mean of measurements across all glaciers
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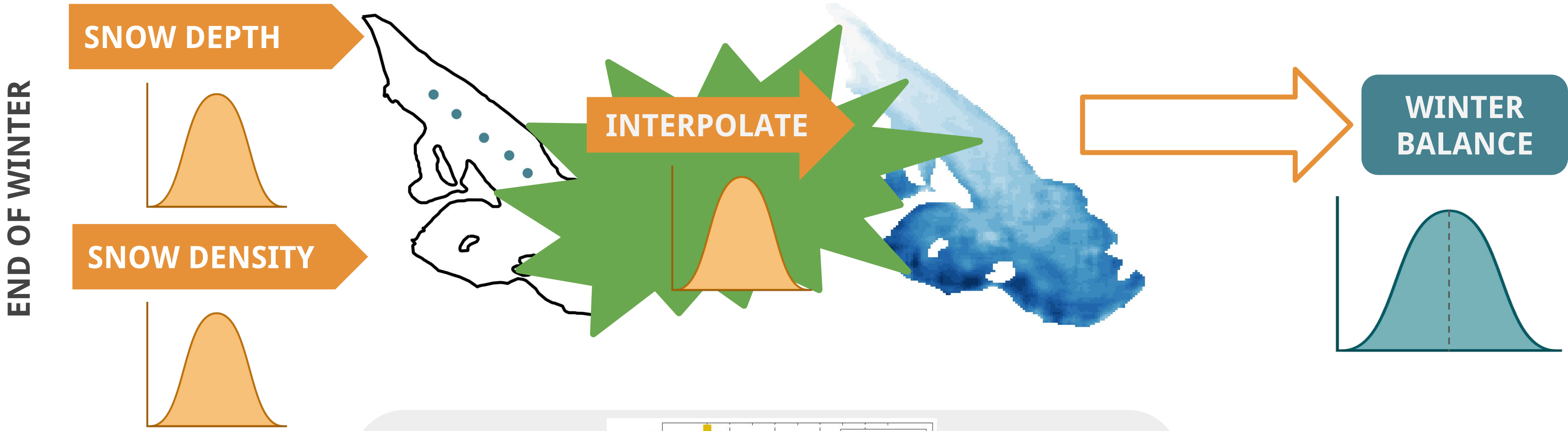
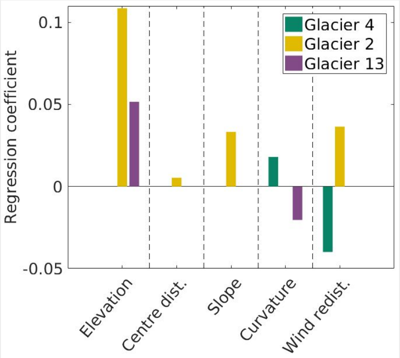
UNCERTAINTY - METHODS

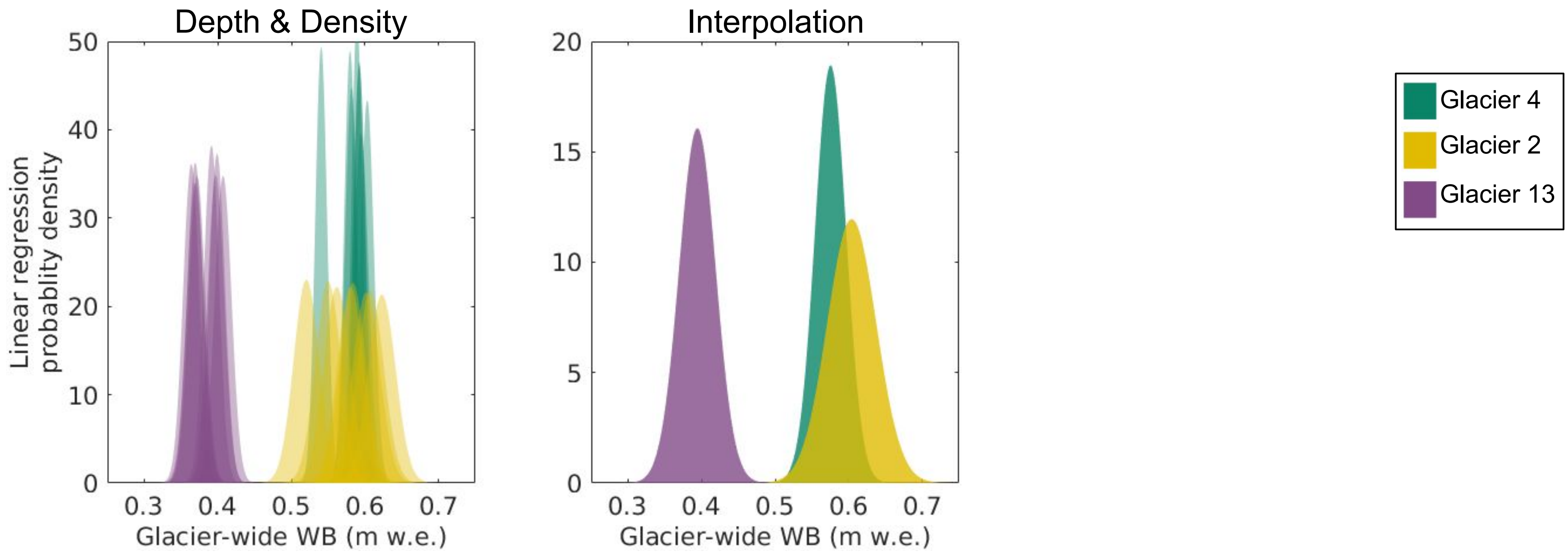




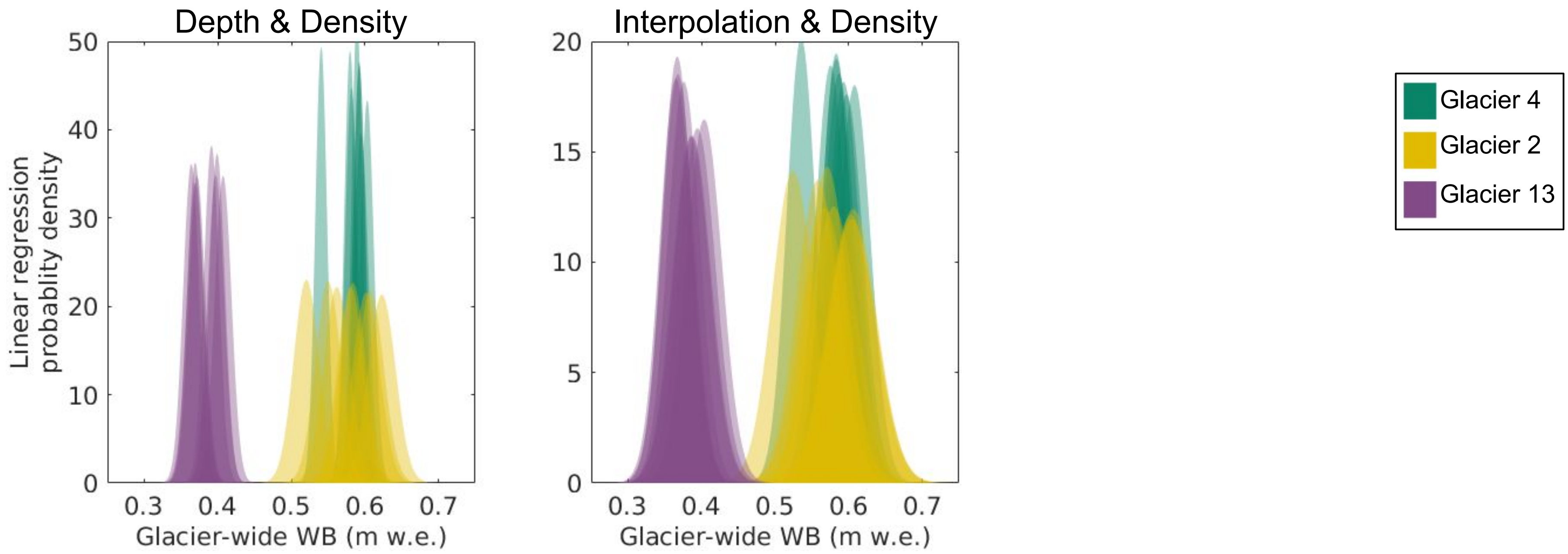
UNCERTAINTY - RESULTS

UNCERTAINTY - RESULTS

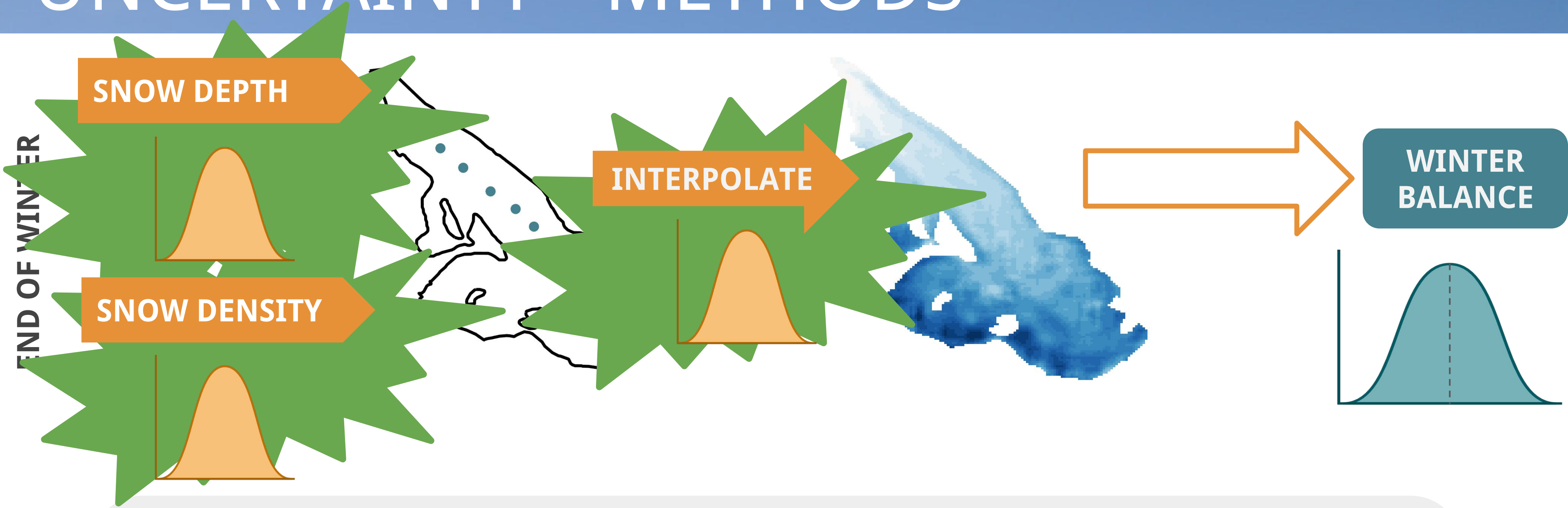
RESULTS - UNCERTAINTY

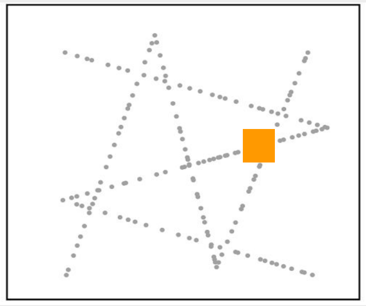


UNCERTAINTY - RESULTS



UNCERTAINTY - METHODS





Source of measured snow density: Snow pit	Federal Sampler	Density assignment method
❄	❄	Mean of measurements across all glaciers
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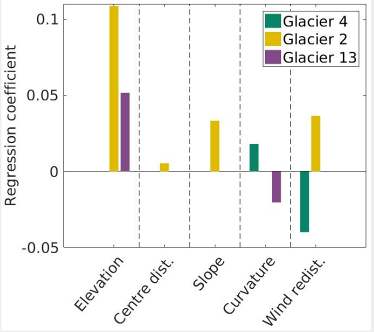
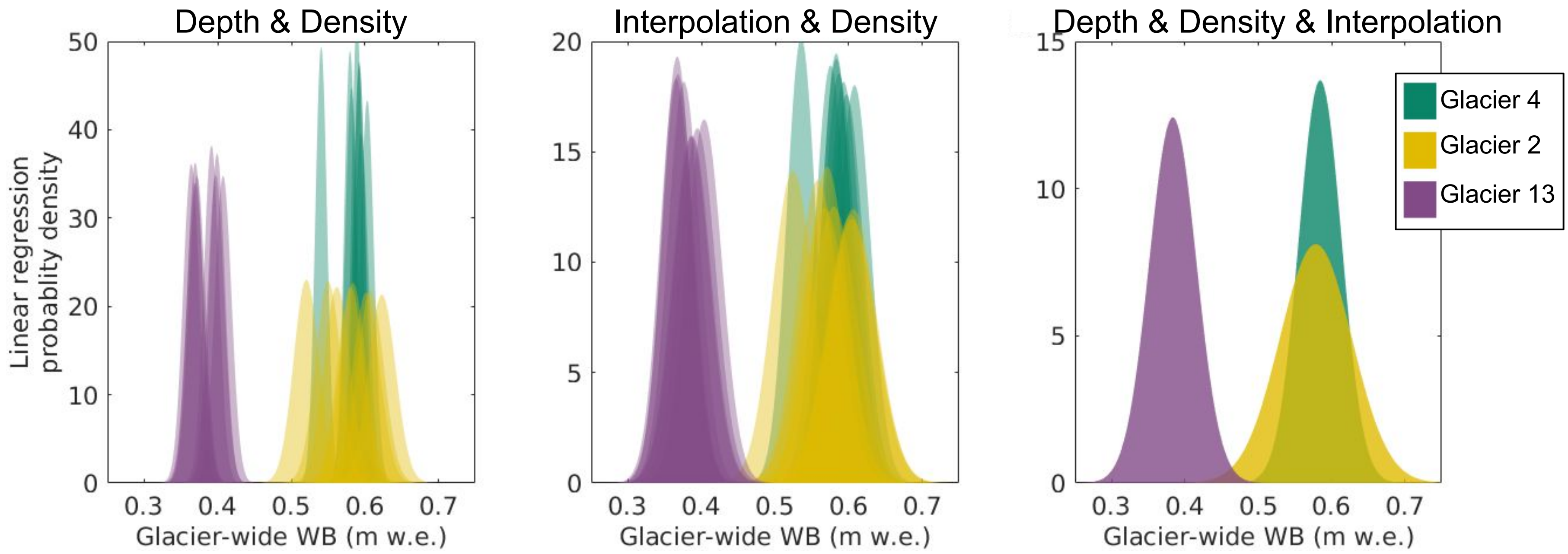
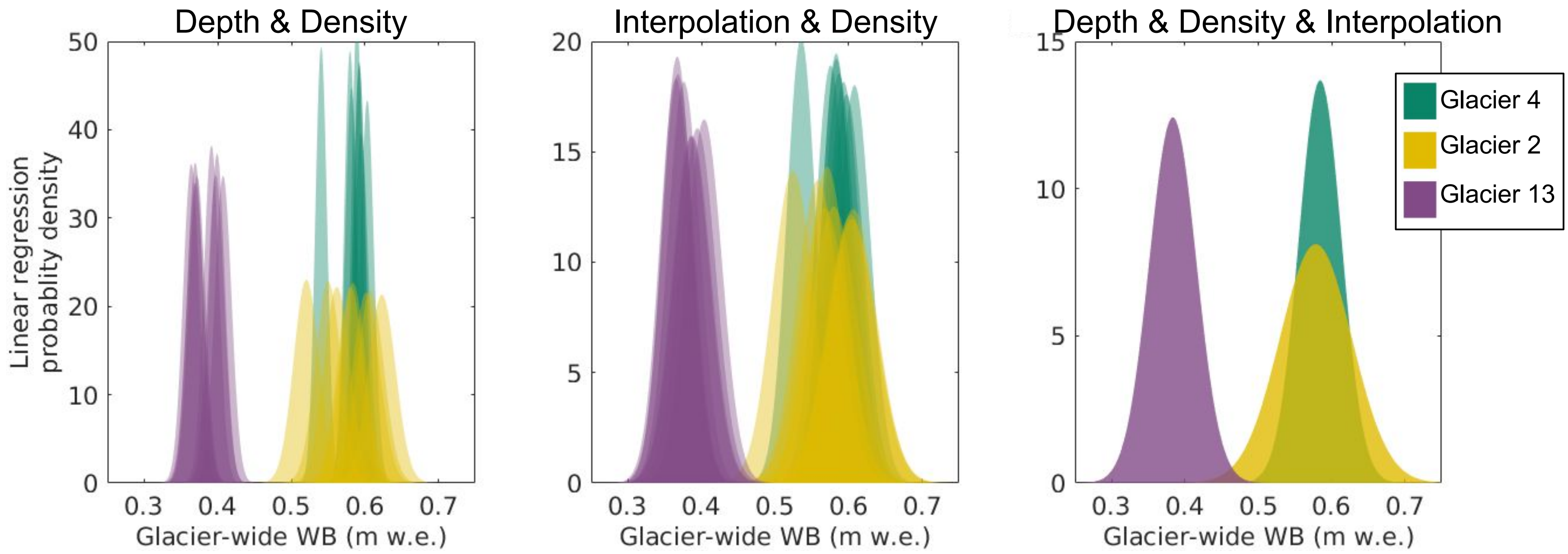


UNCERTAINTY - RESULTS



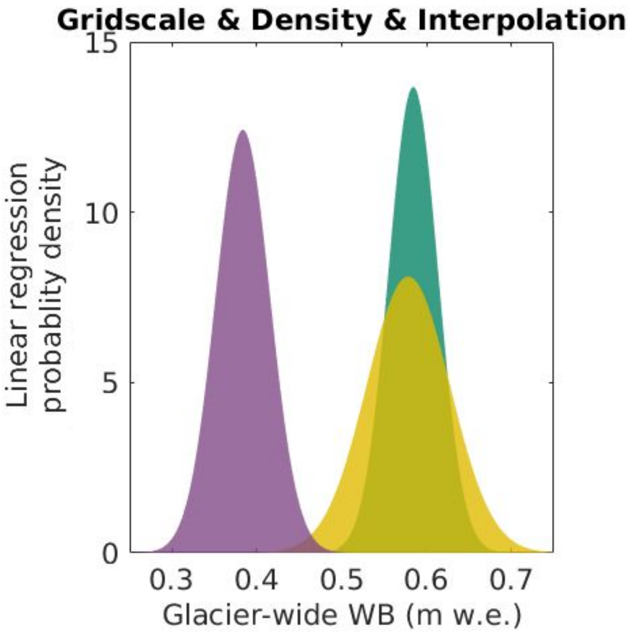
UNCERTAINTY - RESULTS

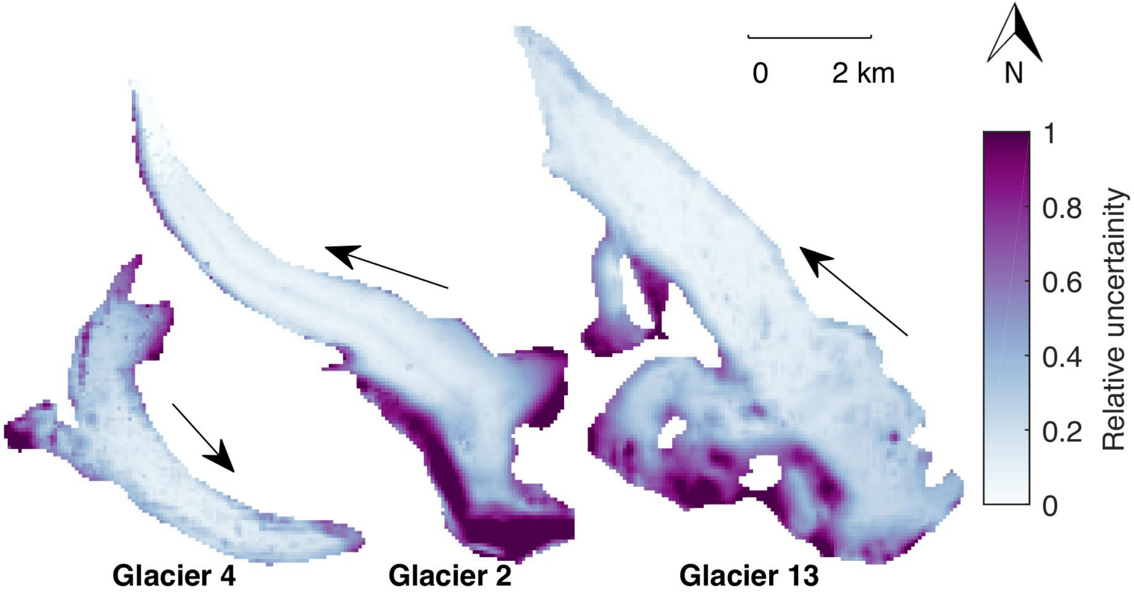


❄ Interpolation is the largest assessed source of uncertainty in winter balance → use interpolated values with caution

❄ Uncertainty from snow depth and density measurement is low

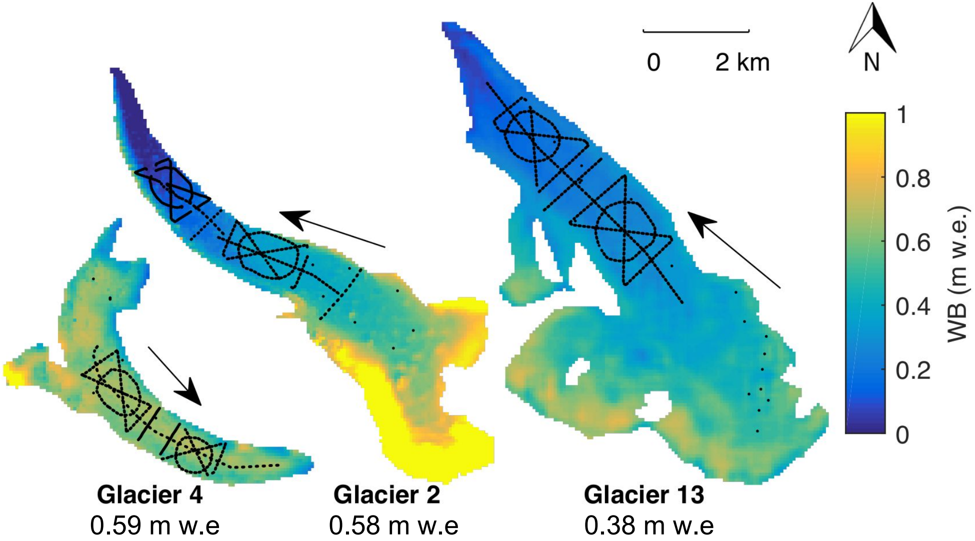
UNCERTAINTY - RESULTS



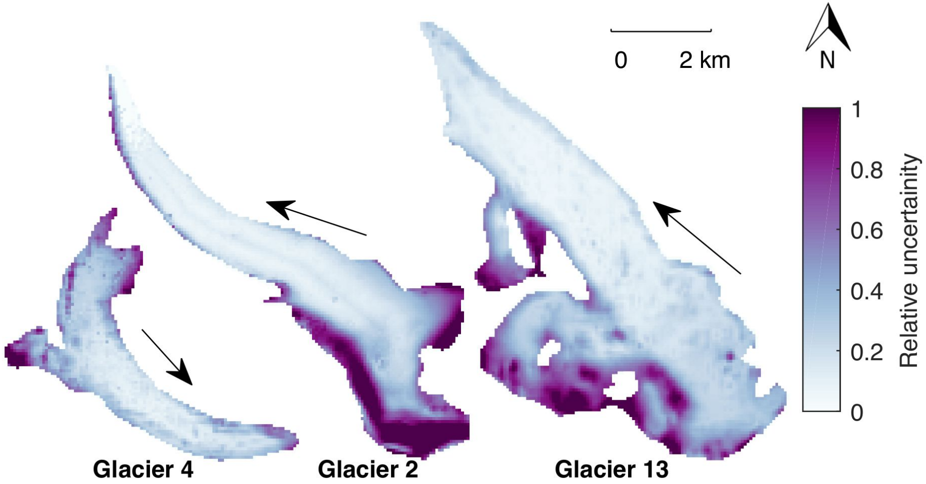


DISTRIBUTED WINTER BALANCE

WINTER BALANCE

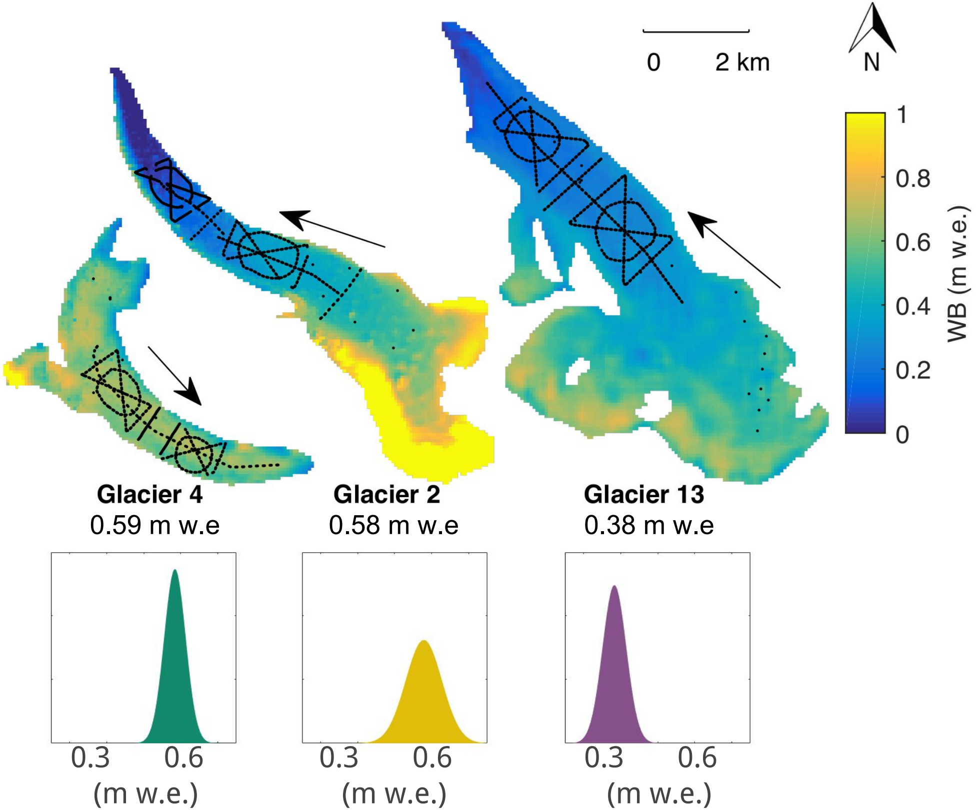


RELATIVE UNCERTAINTY

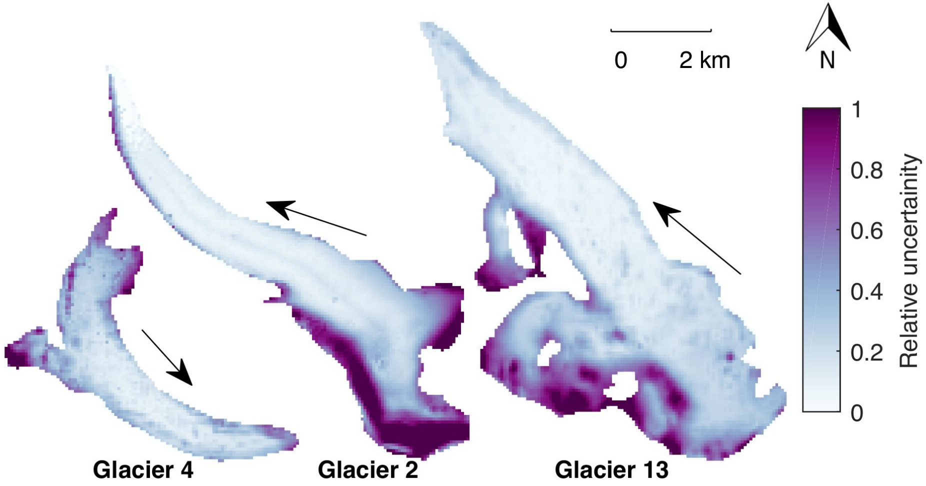


DISTRIBUTED WINTER BALANCE

WINTER BALANCE



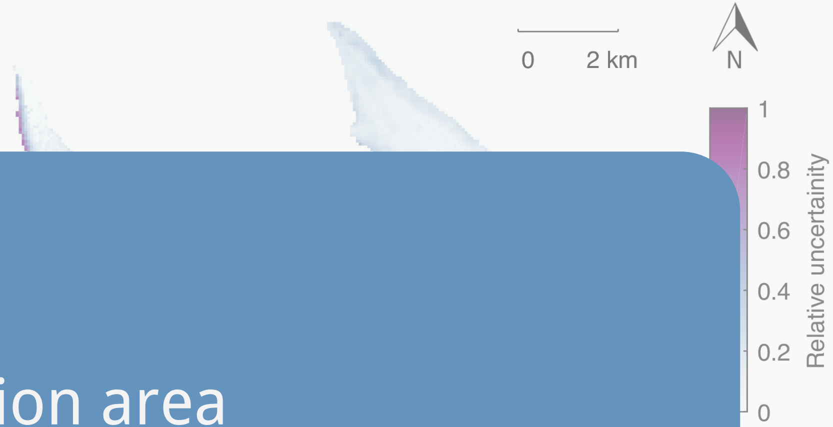
RELATIVE UNCERTAINTY



DISTRIBUTED WINTER BALANCE

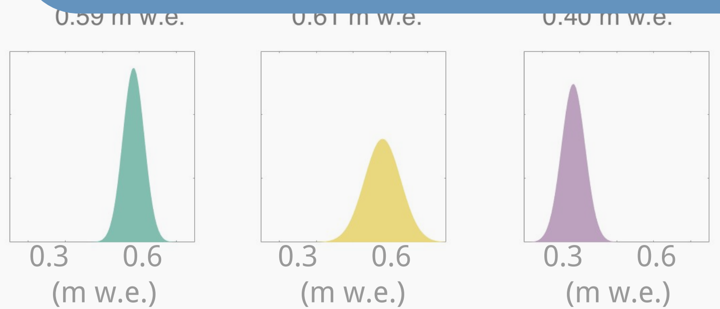
WINTER BALANCE

RELATIVE UNCERTAINTY



MAIN LIMITATIONS

- ❄ Data restricted to single year
- ❄ Minimal sampling in accumulation area



SUMMARY

METHODS

- ❄ Multiscale snow-depth and density measurements
- ❄ Linear regression and Monte Carlo analysis used to estimate winter balance

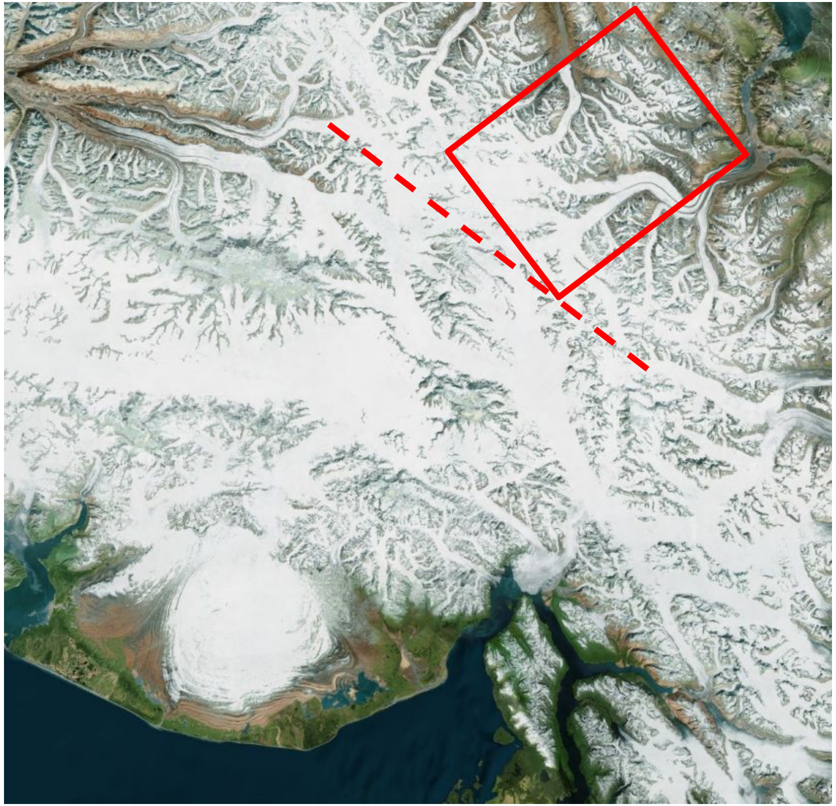
RESULTS

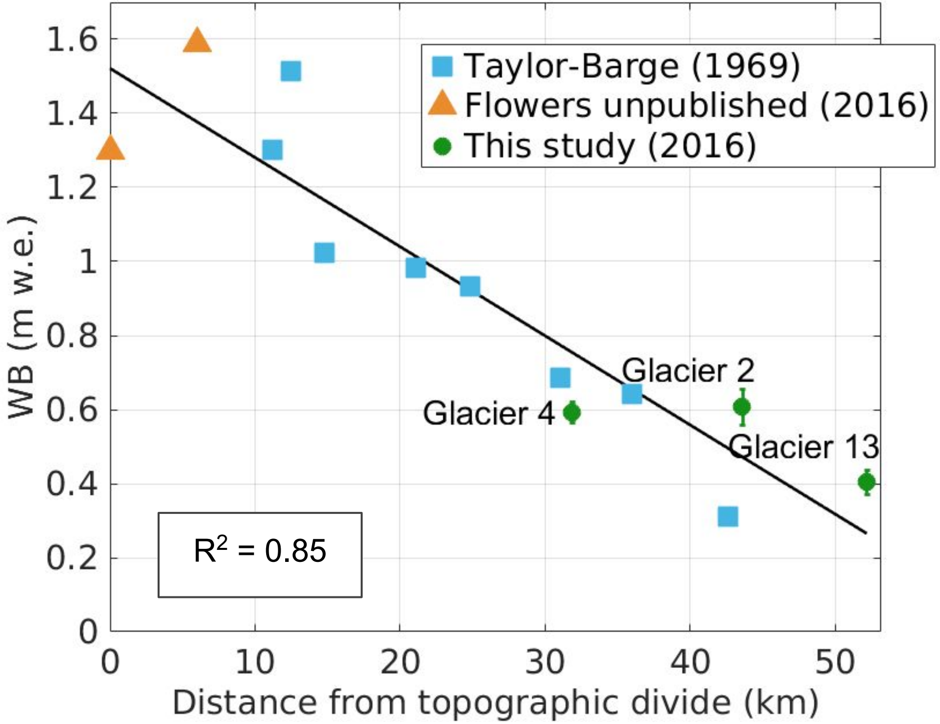
- ❄ Processes governing winter balance differ between glaciers
- ❄ Sources of uncertainty: **interpolation**, *depth & density*
- ❄ Basin coverage more important than high resolution sampling

LIMITATIONS

- ❄ Multi-year data and accumulation area measurements needed

REGIONAL WINTER BALANCE GRADIENT



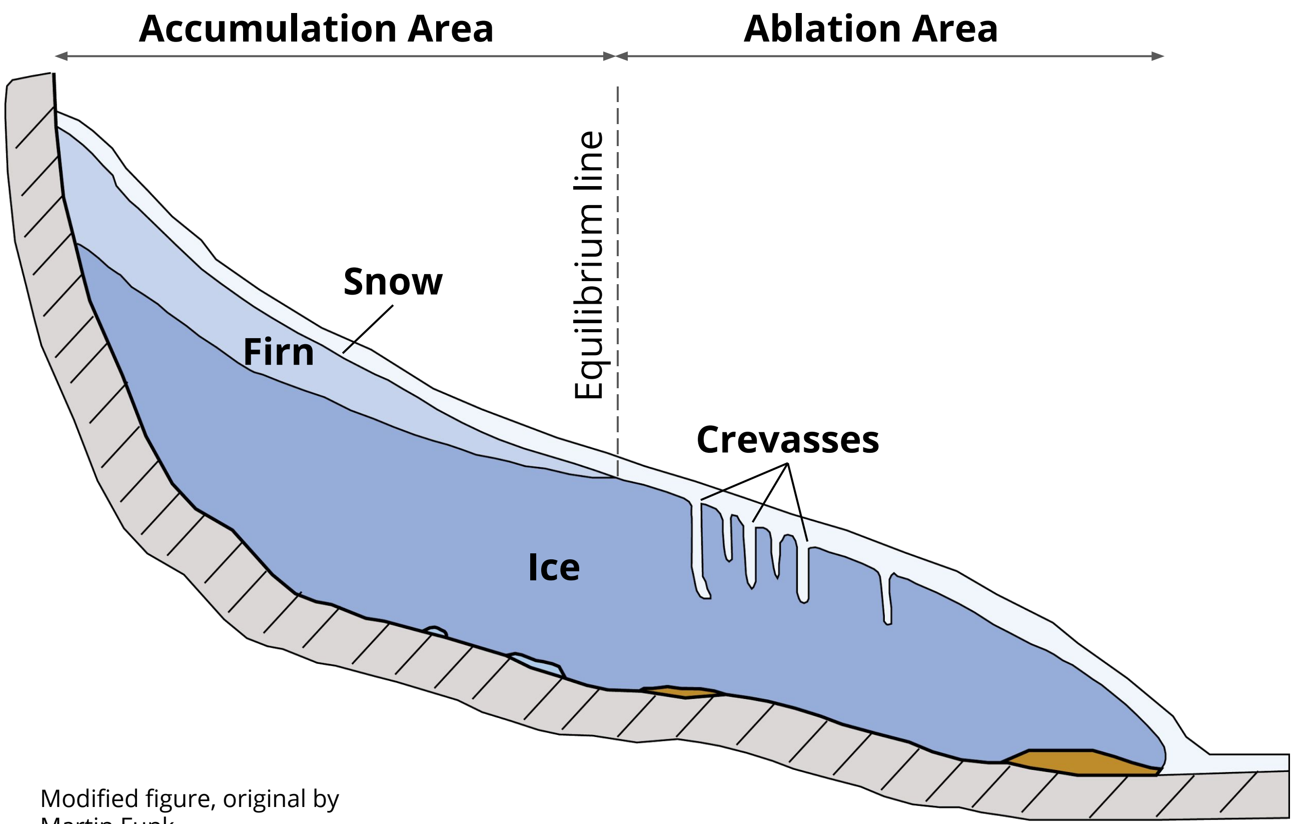


STUDY GLACIERS

Table 1.2: Physical characteristics of the study glaciers and May 2016 winter-balance survey details, including number of snow-depth measurement locations along transects (n_T), total length of transects (d_T), number of combined snow pit and Federal Sampler density measurement locations (n_ρ) and number of zigzag surveys (n_{zz}).

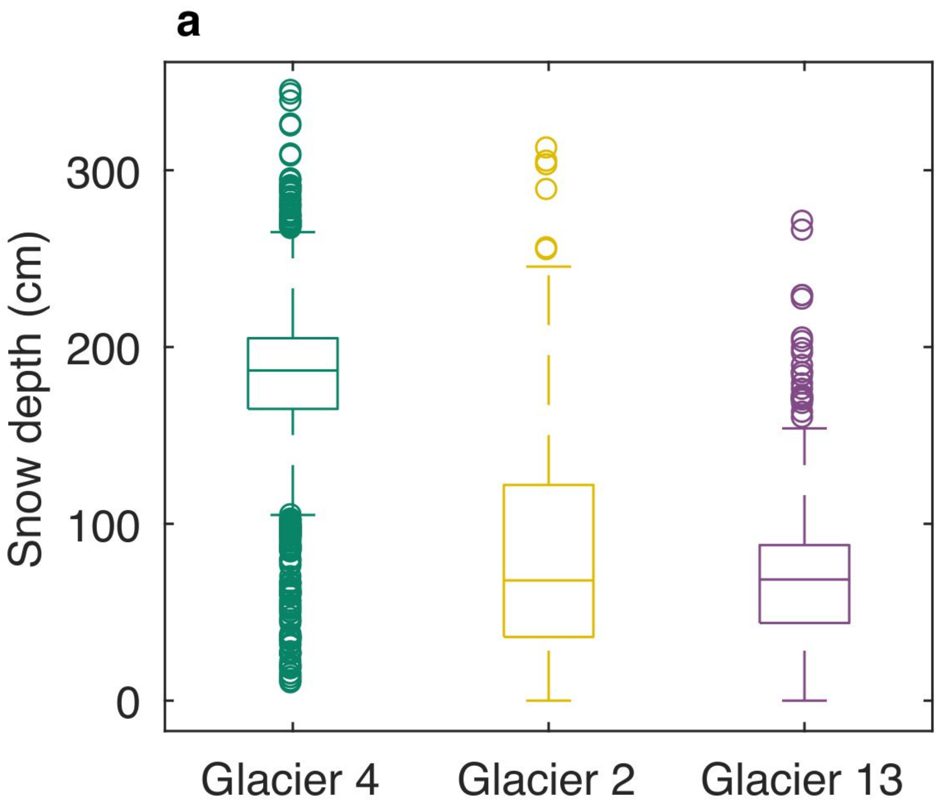
	Location	**Elevation (m a.s.l)**			**Slope (°)**	**Area**	**Survey**	**Survey Details**			
	UTM Zone 7	*Mean*	*Range*	*ELA*	*Mean*	**(km^2)**	**Dates**	n_T	d_T (km)	n_ρ	n_{zz}
Glacier 4	595470 E 6740730 N	2344	1958–2809	~2500	12.8	3.8	4–7 May 2016	649	13.1	10	3
Glacier 2	601160 E 6753785 N	2495	1899–3103	~2500	13.0	7.0	8–11 May 2016	762	13.6	11	3
Glacier 13	604602 E 6763400 N	2428	1923–3067	~2380	13.4	12.6	12–15 May 2016	941	18.1	20	4

ALPINE GLACIER

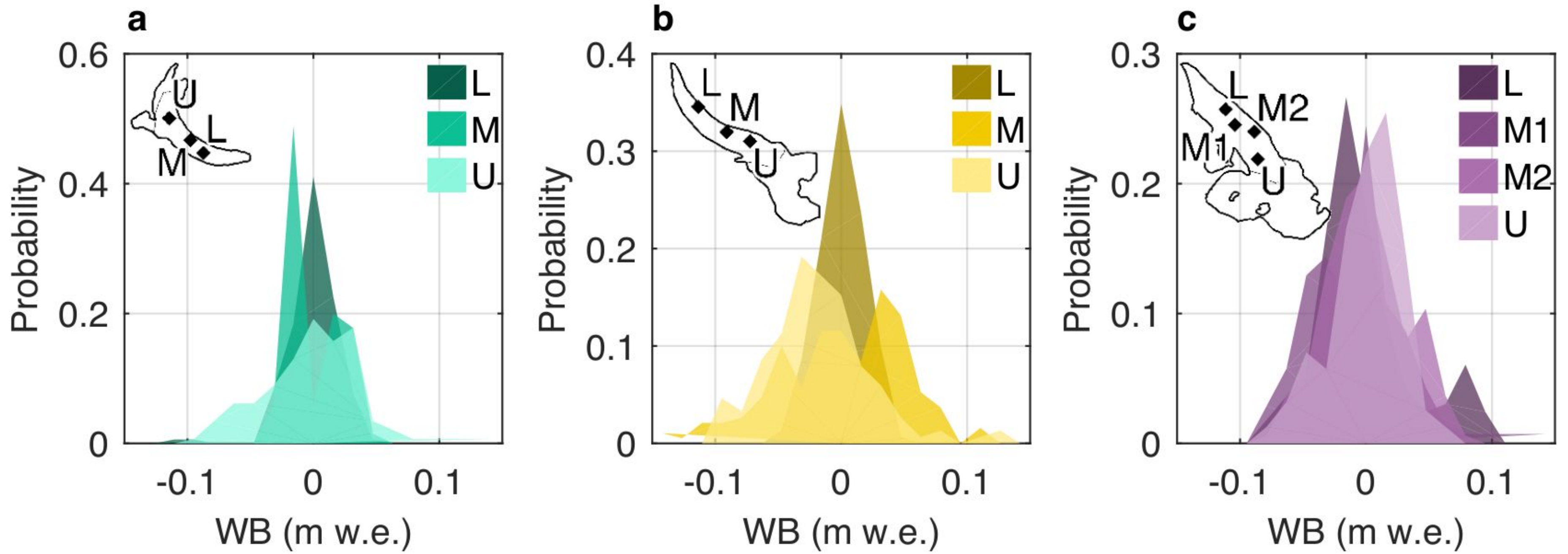


Modified figure, original by
Martin Funk

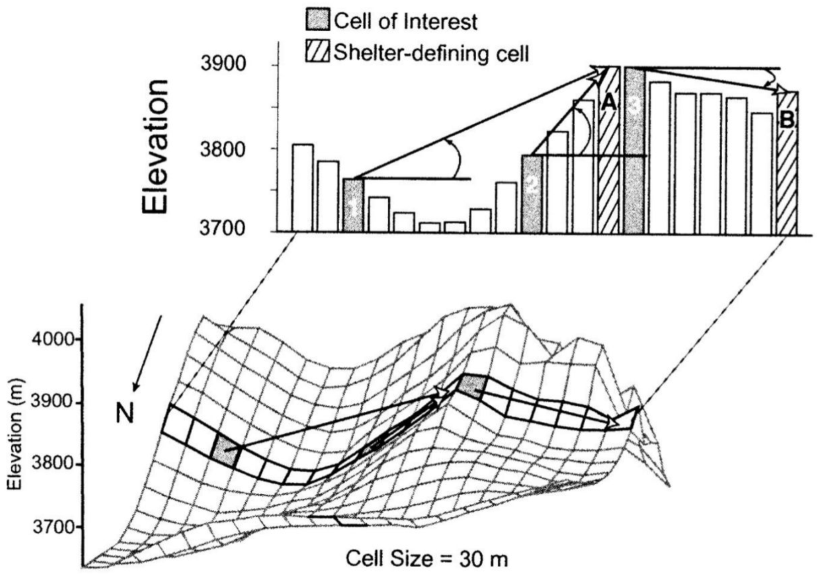
SNOW DEPTH



ZIGZAG PDFs

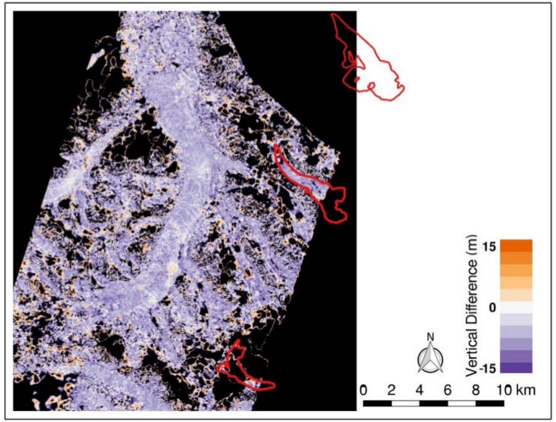


WIND REDISTRIBUTION PARAMETER (*Sx*)

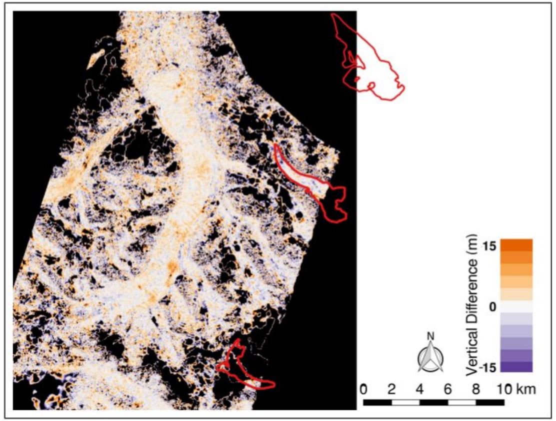


Example of Sx calculations for three cells of interest along a 270 ◦ search vector. As depicted, with dmax set equal to 300 m, the shelter-defining cell for cells 1 and 2 is cell A, producing positive Sx values. The shelter-defining cell for cell 3 is cell B, producing a negative Sx. Had dmax been equal to 100 m, the search for the shelter-defining cell for cell 1 would not extend across the valley, thus producing a negative Sx for cell 1, while Sx for cell 2 would remain the same and that for cell 3 would be slightly lower. Image and description from (Winstral and others, 2002).

DEM CORRECTIONS



(a) Difference between original DEMs



(b) Difference between corrected DEMs.

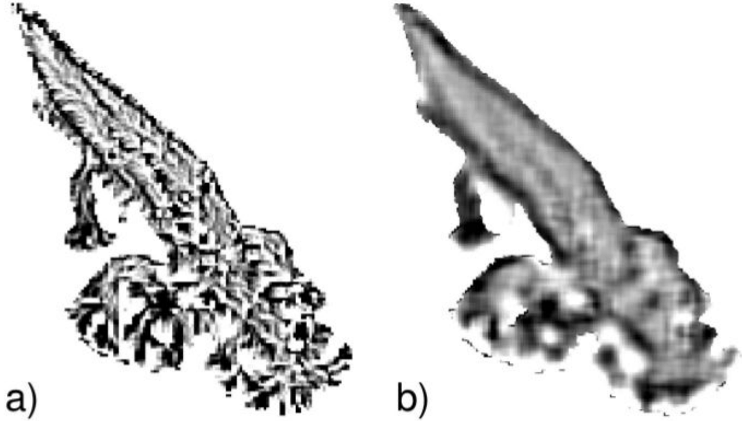
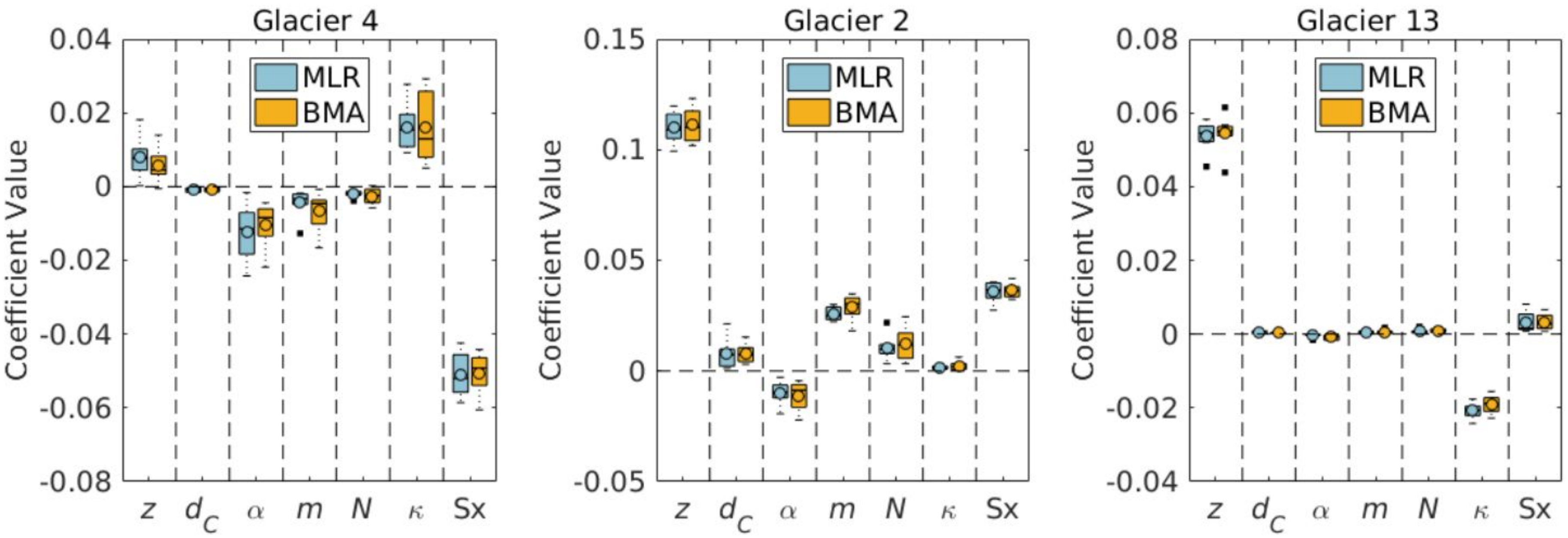


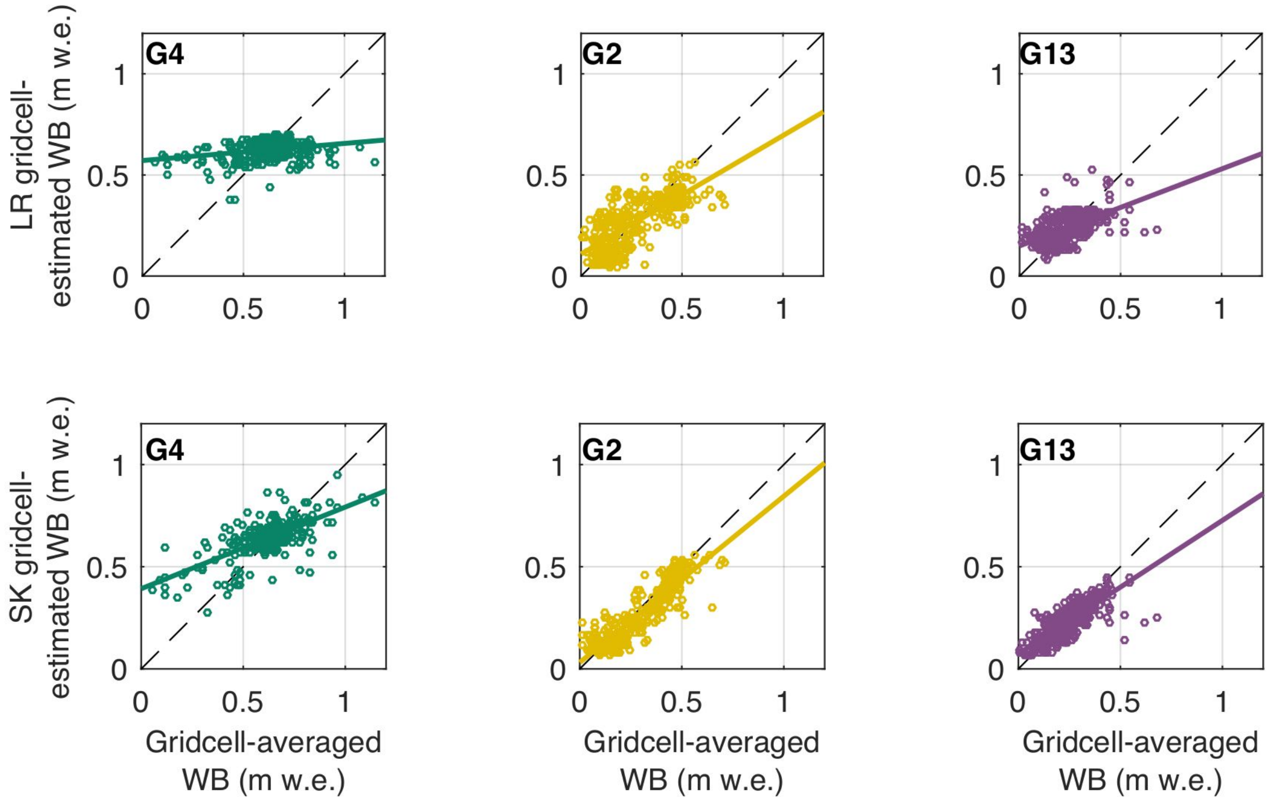
Figure 4.8: (a) Curvature found using the original DEM. (b) Curvature found using the smoothed (7×7 window moving average) DEM.

LR - MLR vs BMA

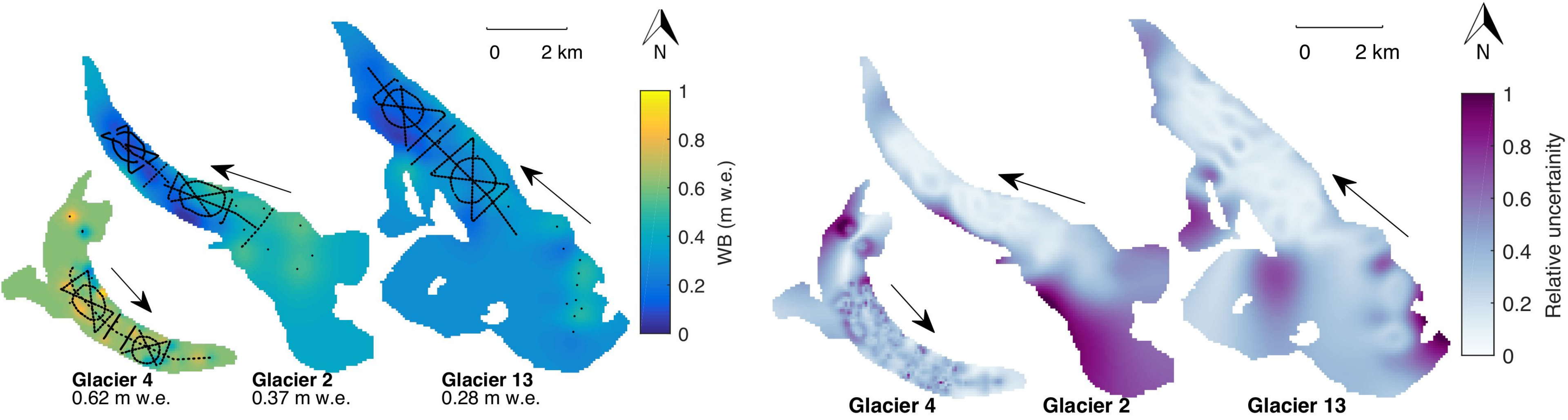


Glacier 4
Glacier 2
Glacier 13
Coefficient Value
MLR
BMA
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0.15
0.1
0.05
-0.05
0.08
0.06
z
d_C
α
m
N
κ
Sx

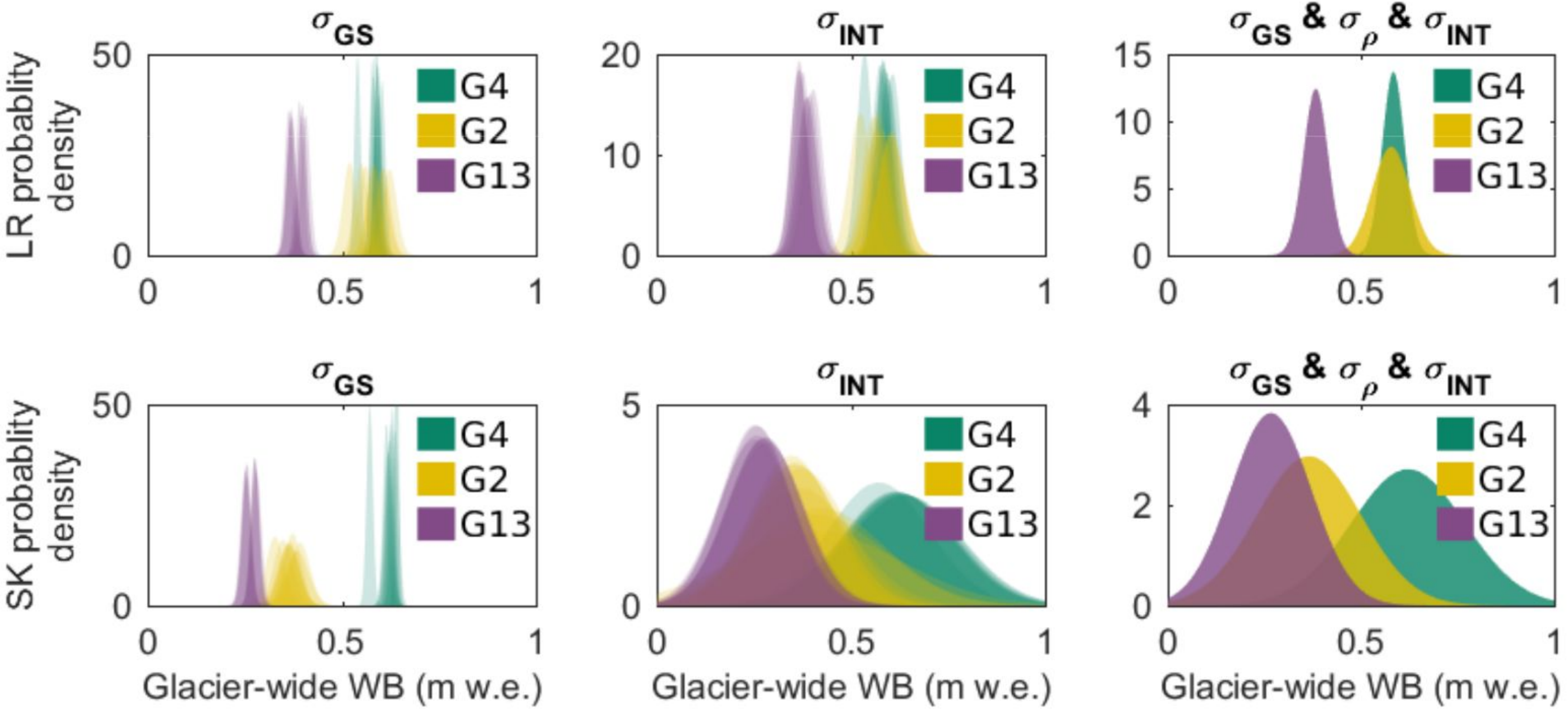
LR AND SK ESTIMATES - GOF



SIMPLE KRIGING



WB PDFs FOR LR AND SK



COMPARISON OF INTERPOLATIONS

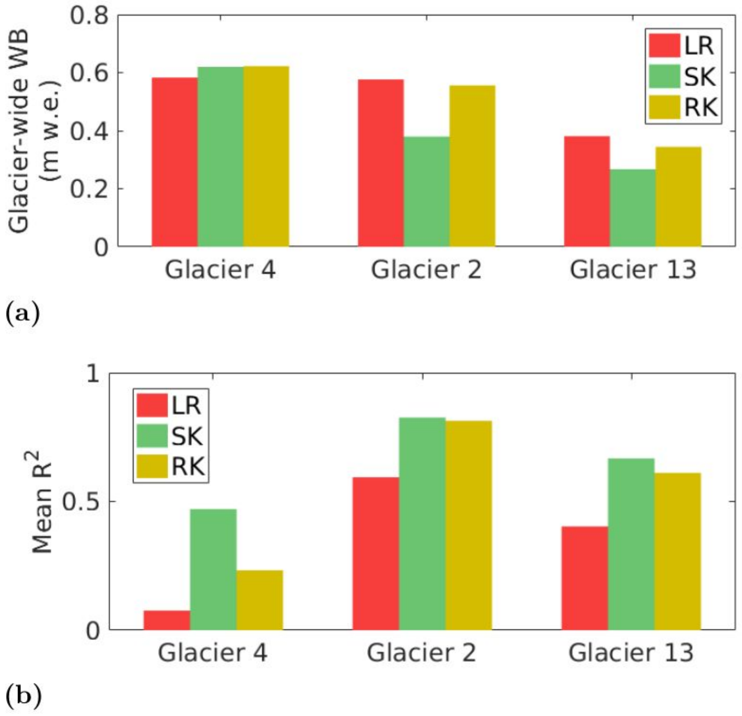
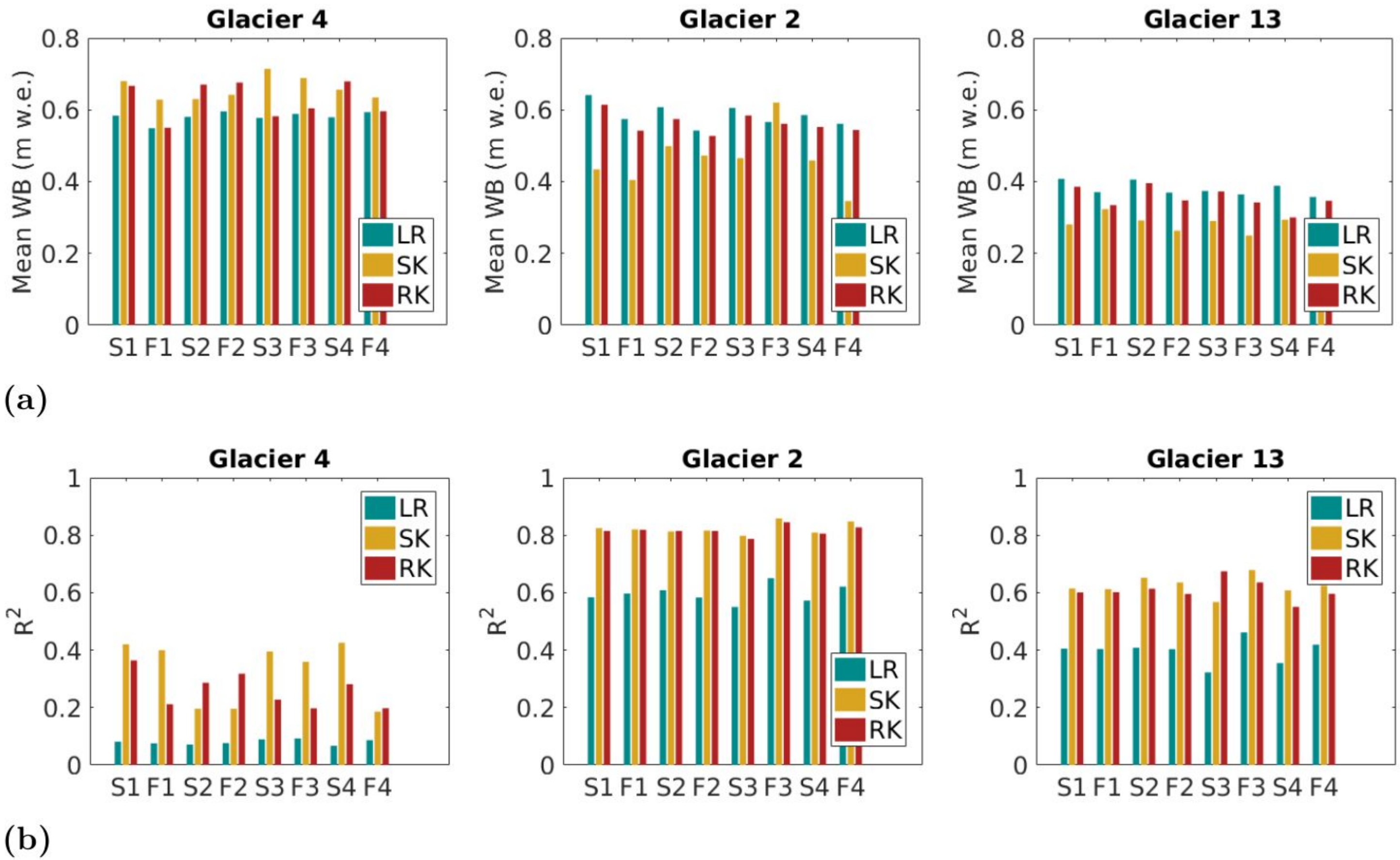
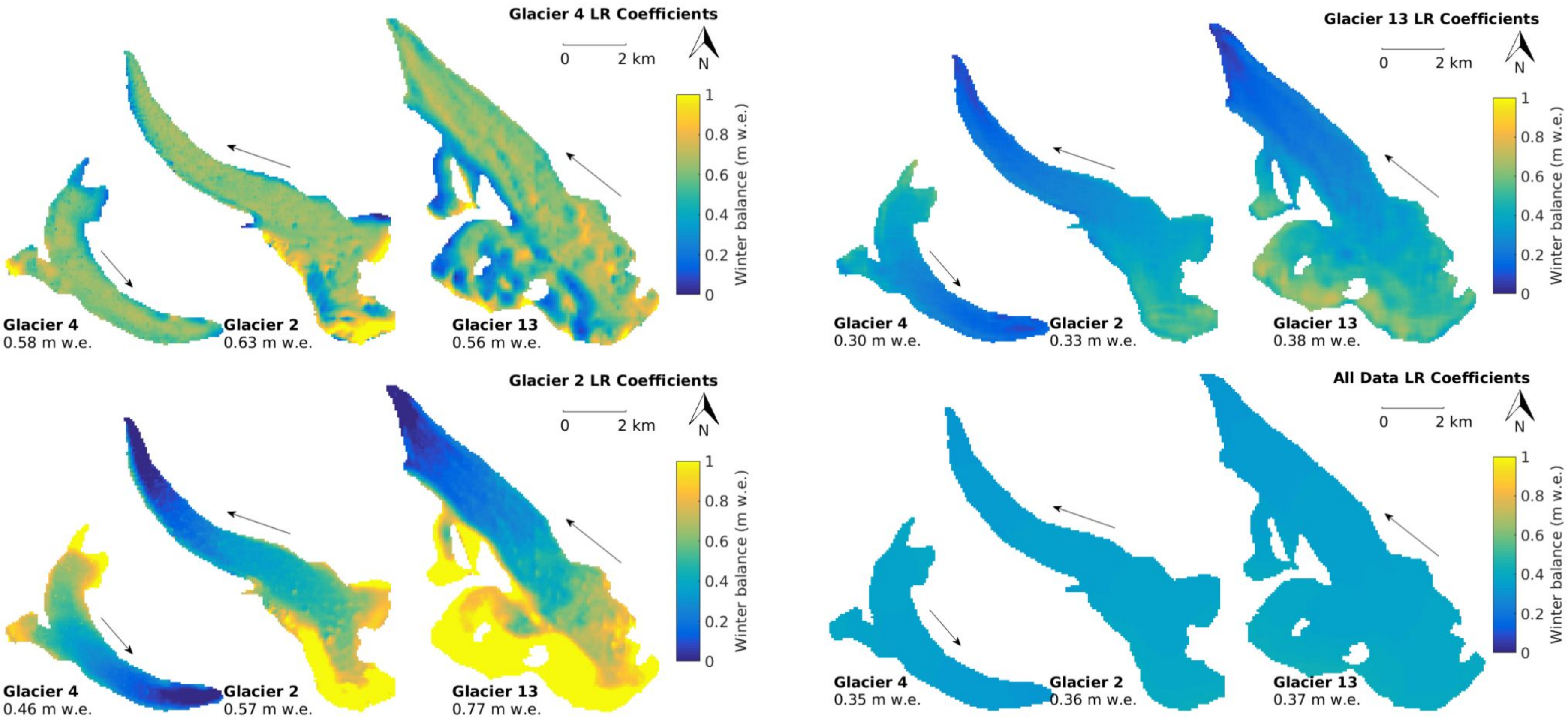


Figure 5.33: Comparison of winter balance (WB) and R^2 for topographic regression (LR), simple kriging (SK) and regression kriging (RK), averaged over density assignment methods. (a) Glacier-wide WB. (b) Mean correlation coefficient (R^2) between observed winter balance and estimated winter balance at sampling locations.

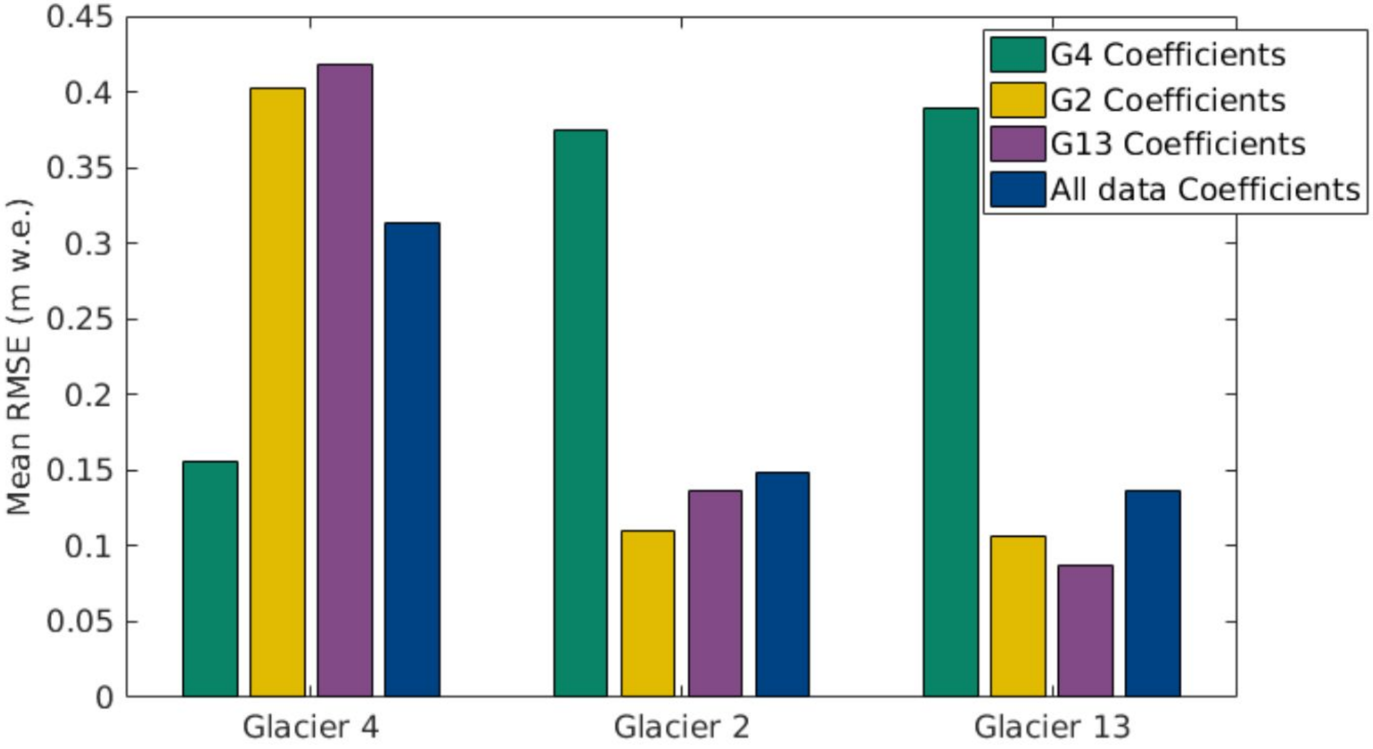
COMPARISON OF INTERPOLATION WITH DENSITY



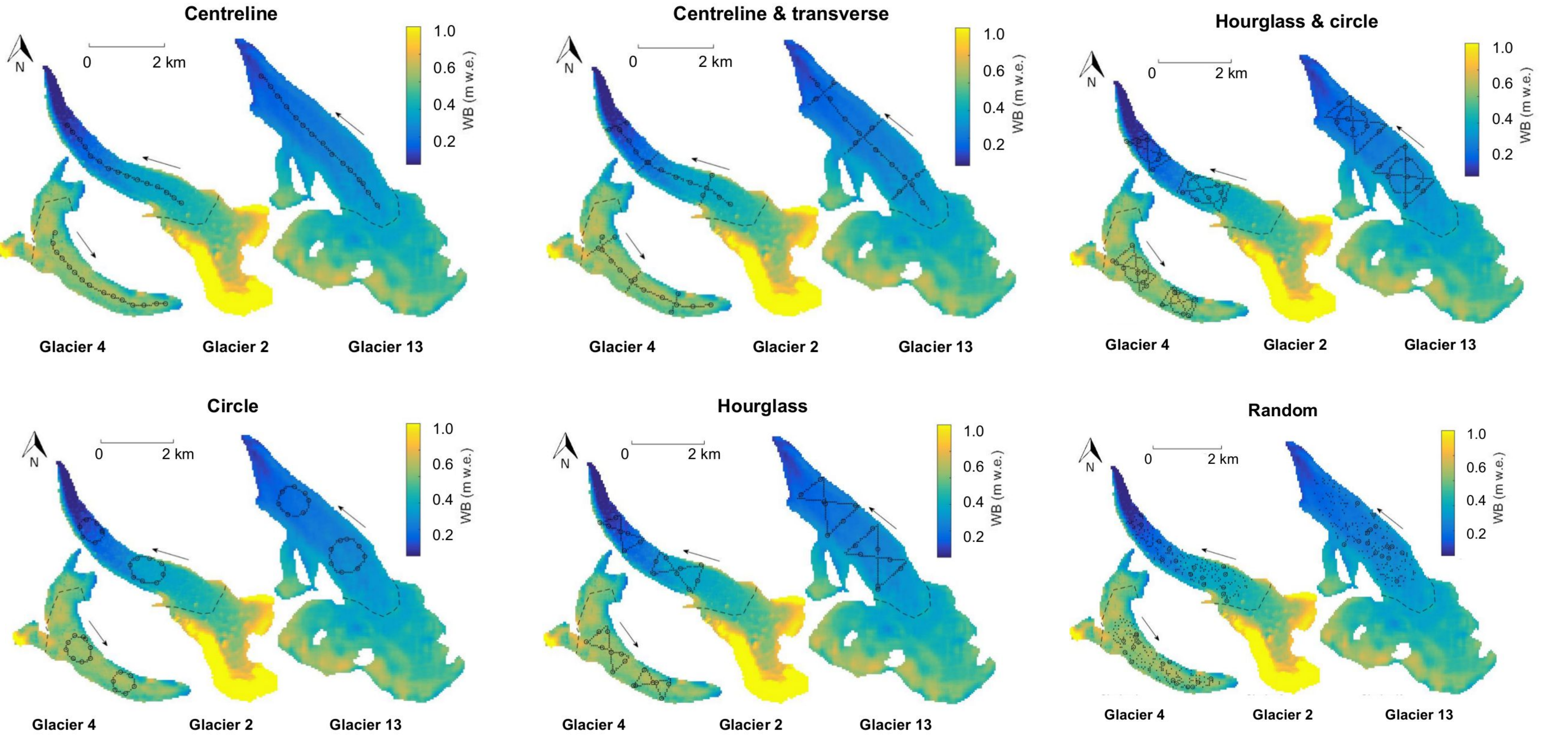
LR TRANSFERABILITY



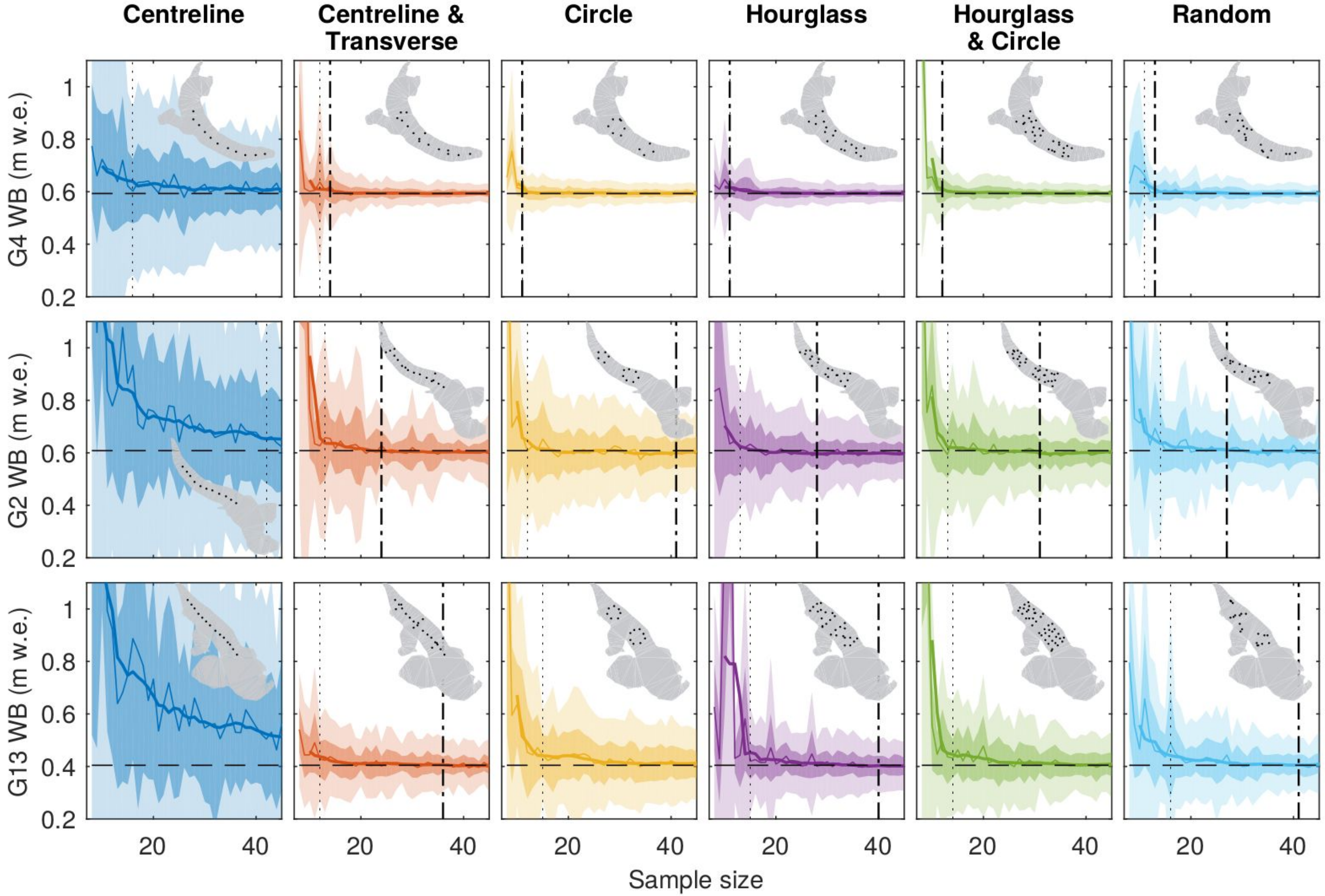
TRANSFERABILITY ERROR



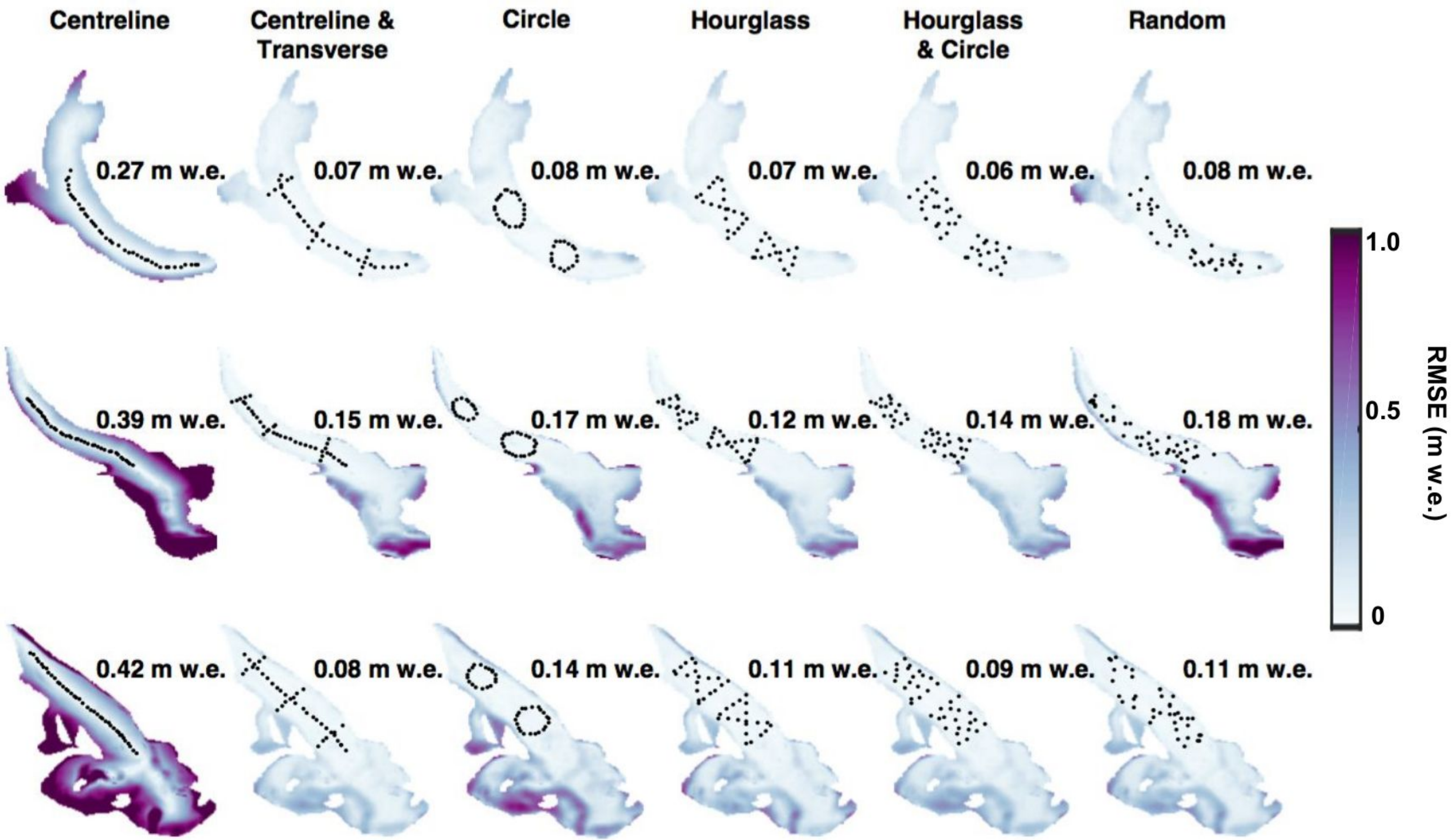
SAMPLING SCHEMES



SYNTHETIC DATA - SAMPLING DESIGN



SYNTHETIC DATA ERROR



REAL DATA SAMPLING DESIGN WB