

Design of an optimal snow observation network to estimate snowpack thickness matching ground data, digital terrain models and satellite observations.

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**WORKSHOP: SNOW MONITORING AND MODELING INITIATIVES IN SPAIN
BASED ON GROUND AND SATELLITE DATA. COST ES1404 ACTION.**

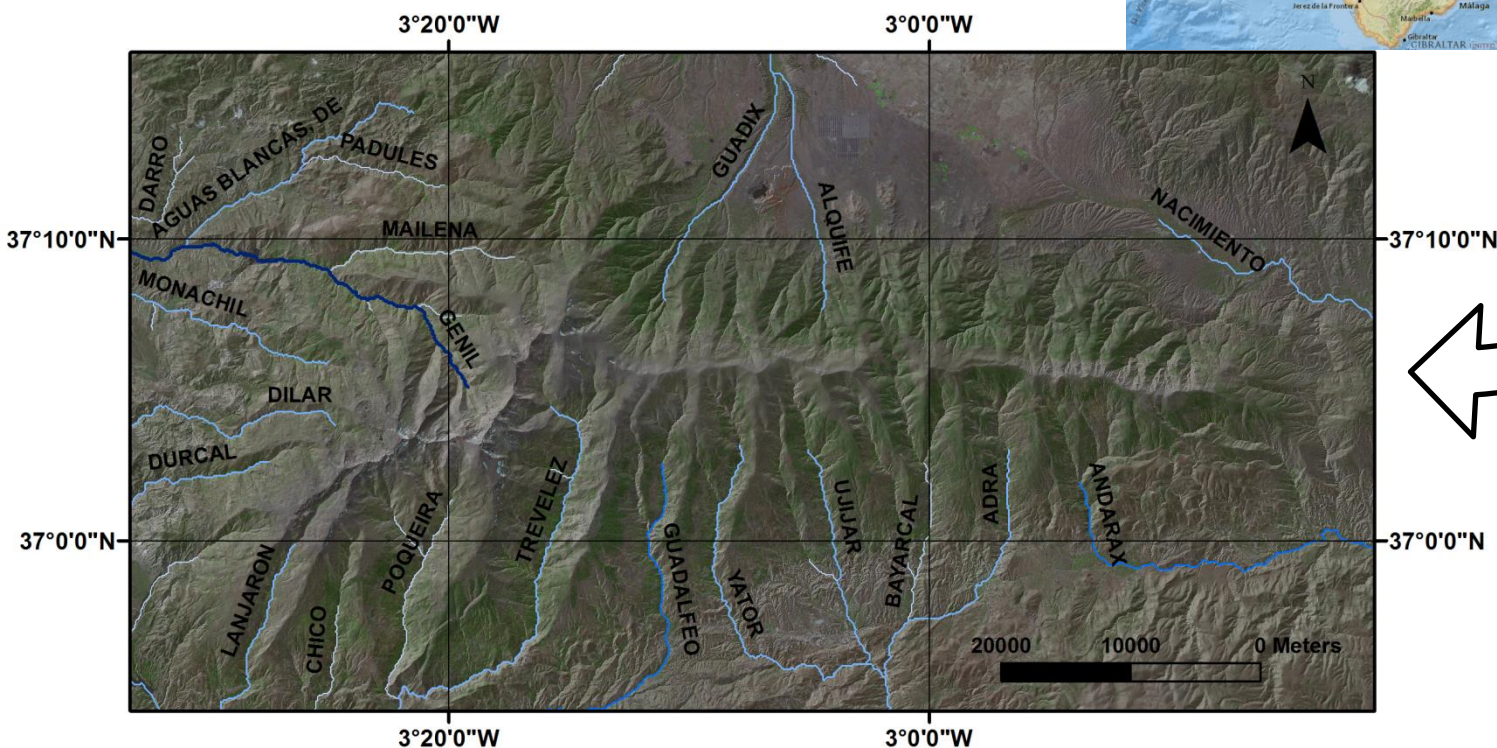
Granada 2nd November 2016



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1. LOCATION OF THE STUDY AREA AND DATA

- The Sierra Nevada mountain range is located in south of Spain.
- Important to the region:
 - Economic: ski station
 - **Water resources:** Melt season with important input to the reservoirs

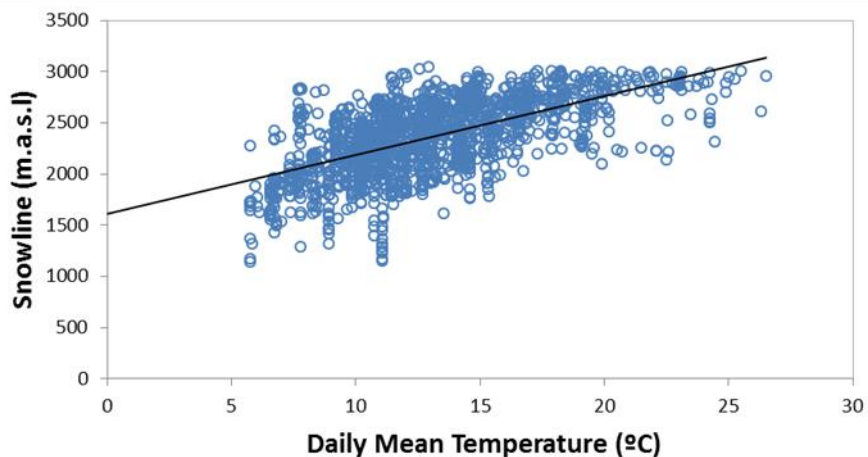
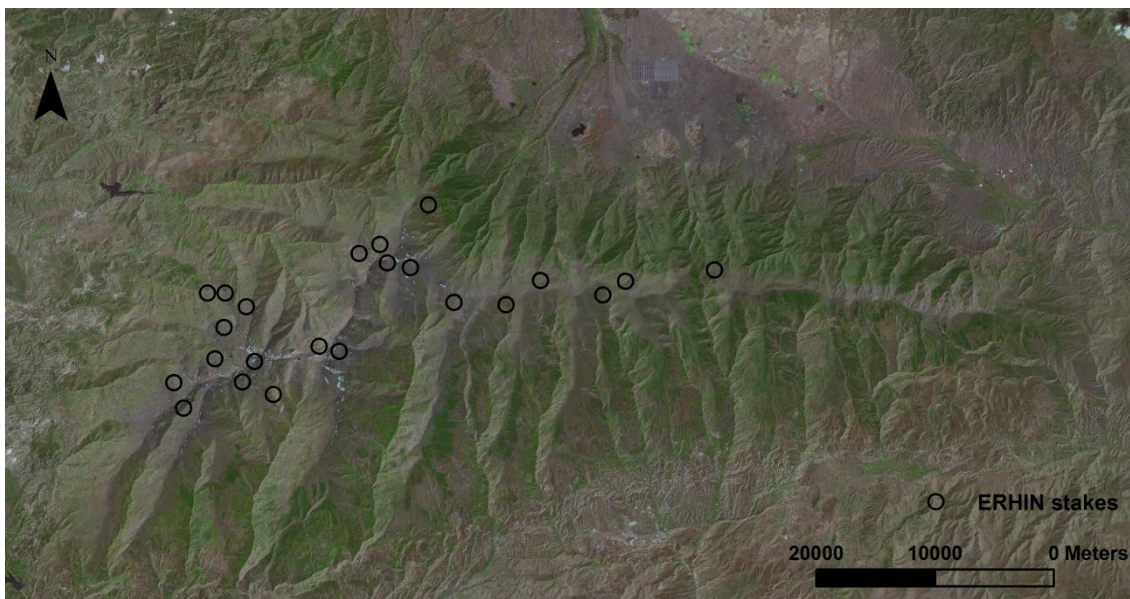


1. LOCATION OF THE STUDY AREA AND DATA

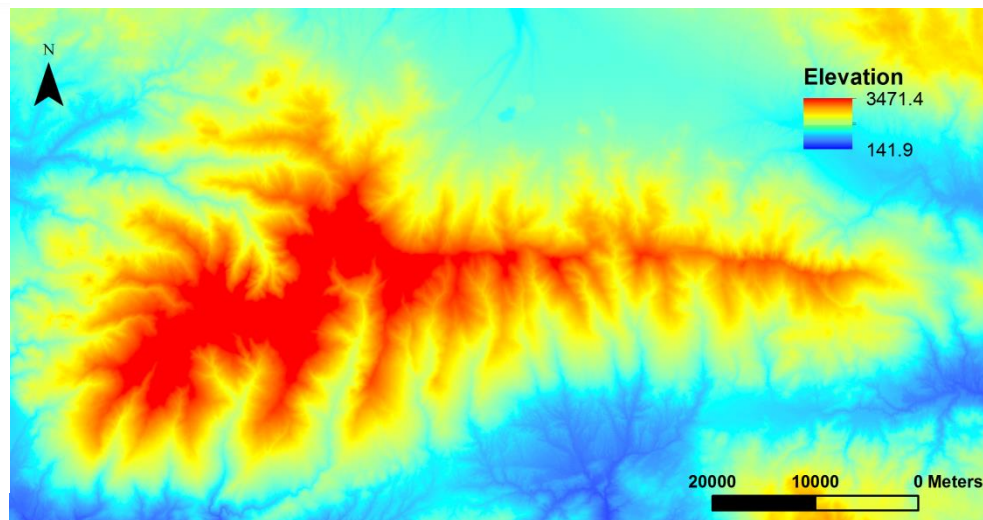
- Snow pack: 23 stakes in 11 campaigns from ERHIN program
- SCA from MODIS
- Digital terrain model

Explanatory variables

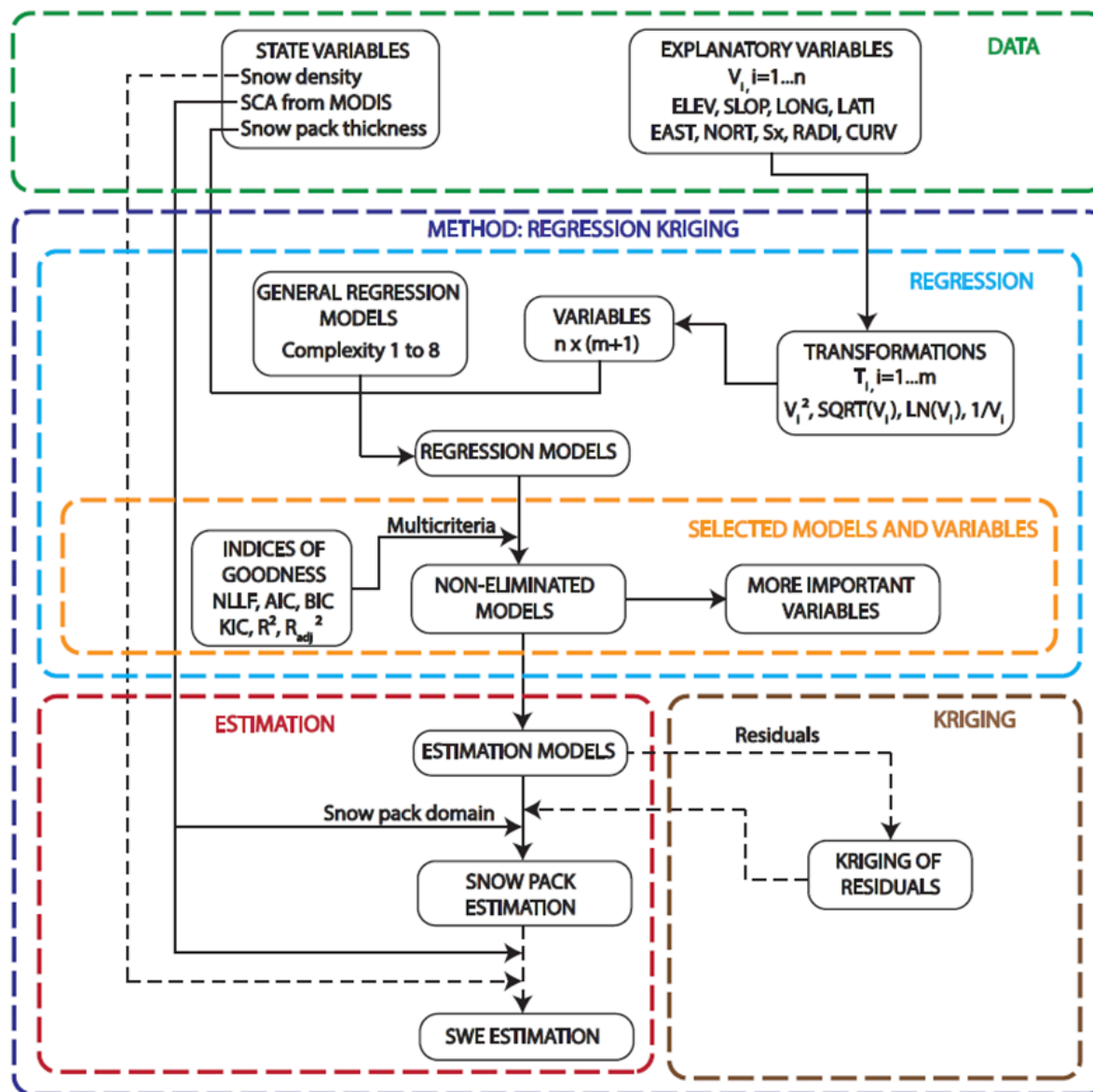
ELEVATION, SLOPE,
LONGITUDE, LATITUDE,
EASTNESS, NORTHNESS,
MAXIMUM UPWIND SLOPE,
RADIATION, CURVATURE



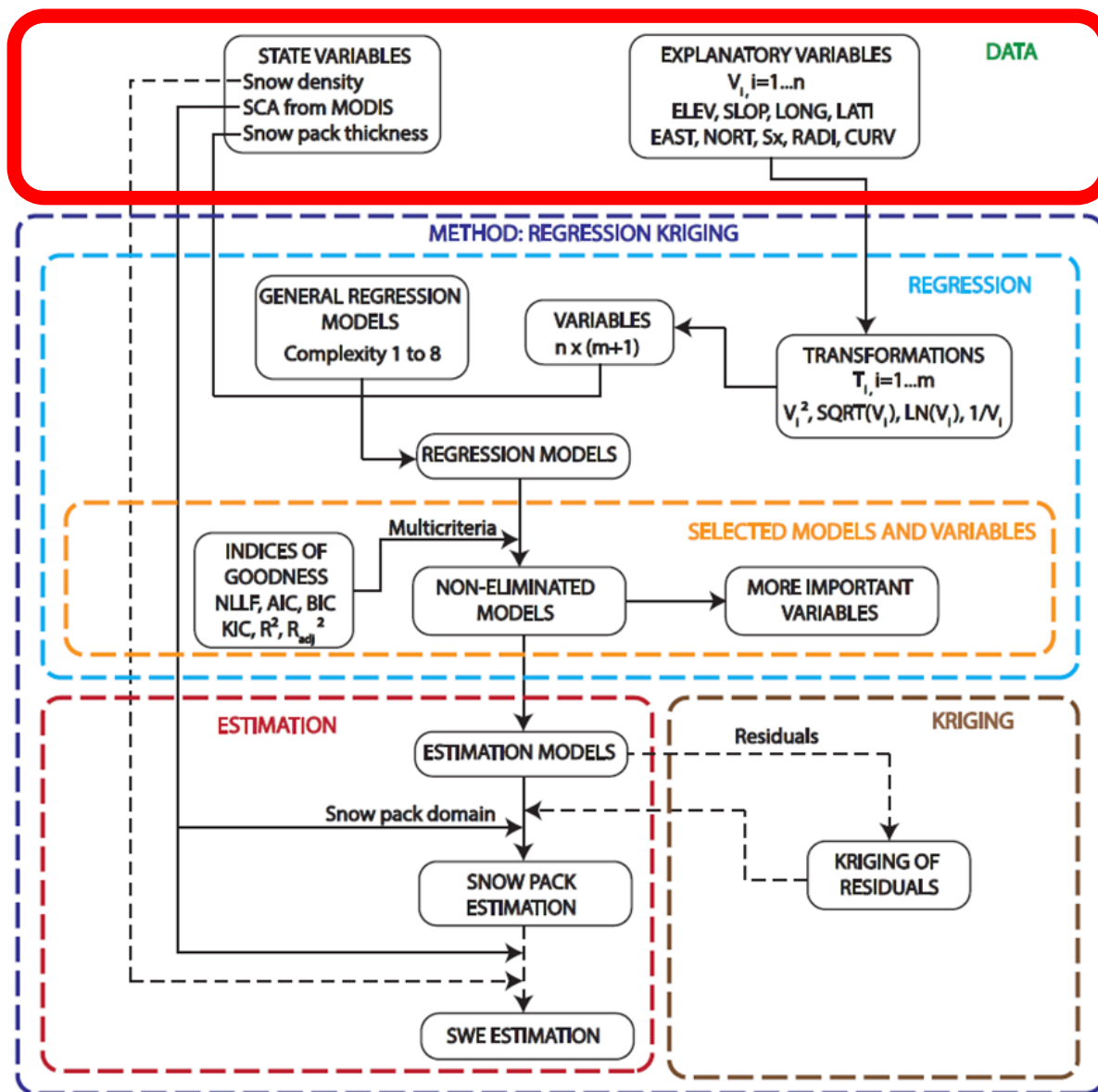
Snowline is above 1837 m in 90% of the days with snow



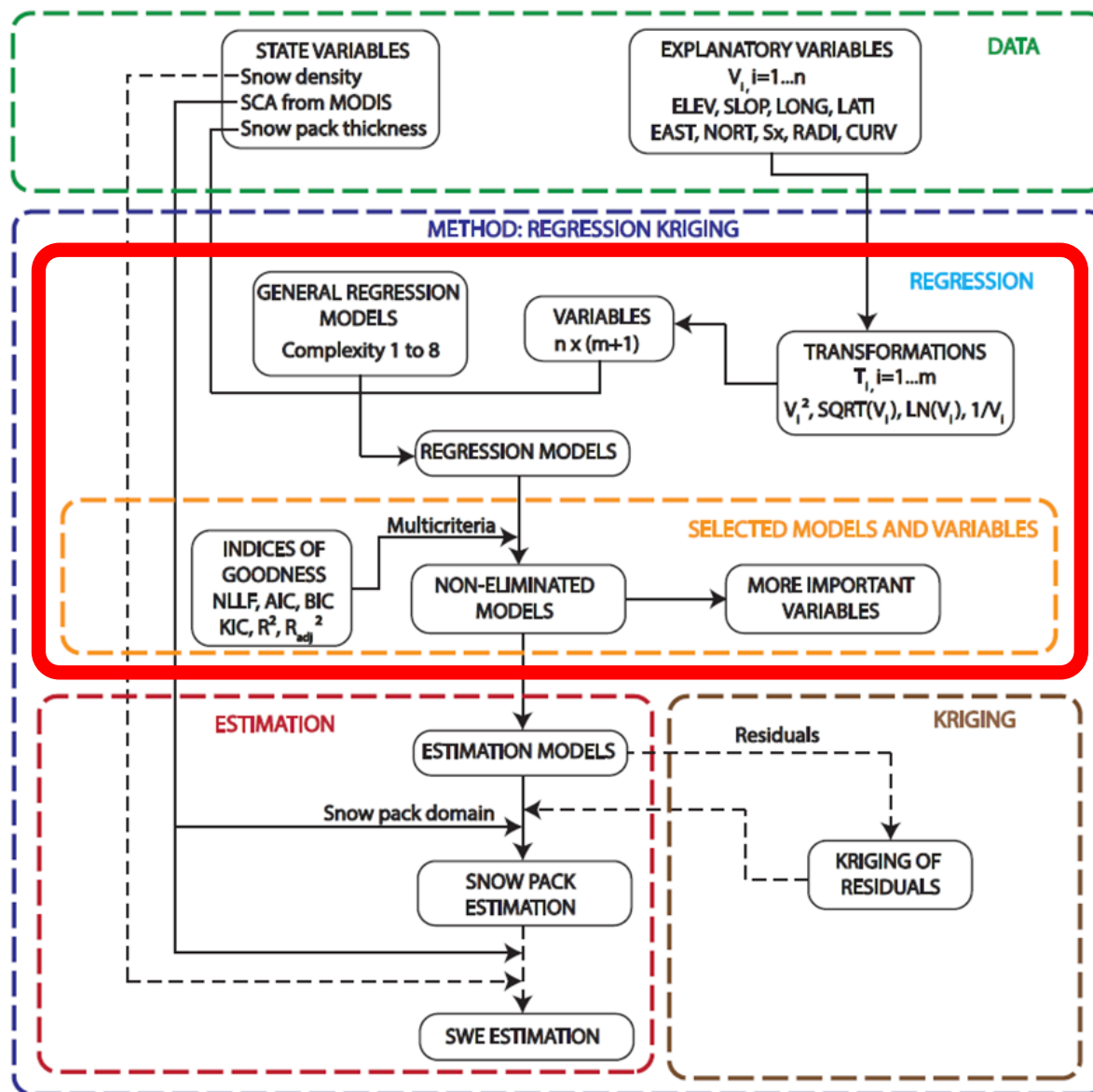
2. ESTIMATION METHOD



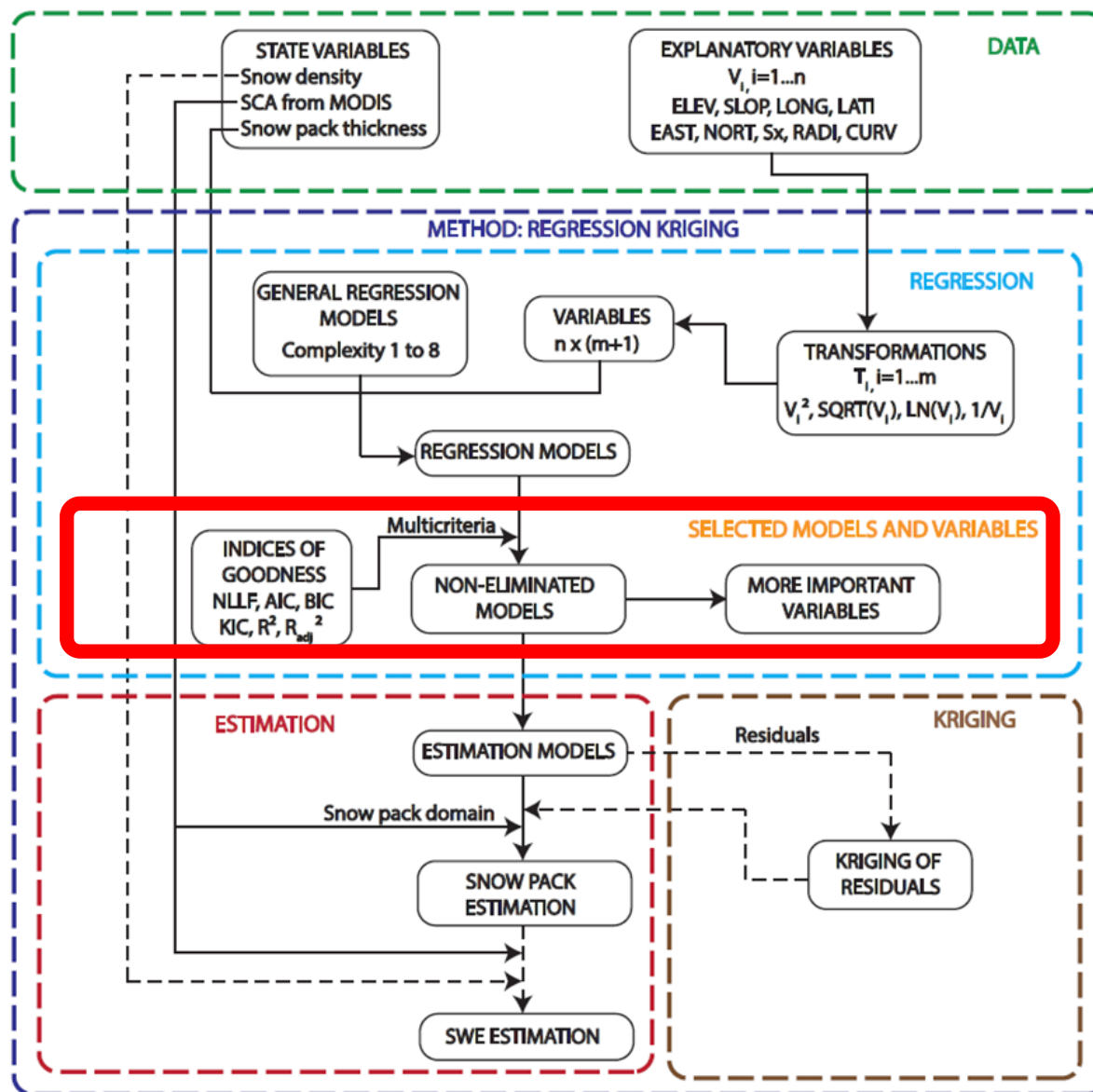
2. ESTIMATION METHOD



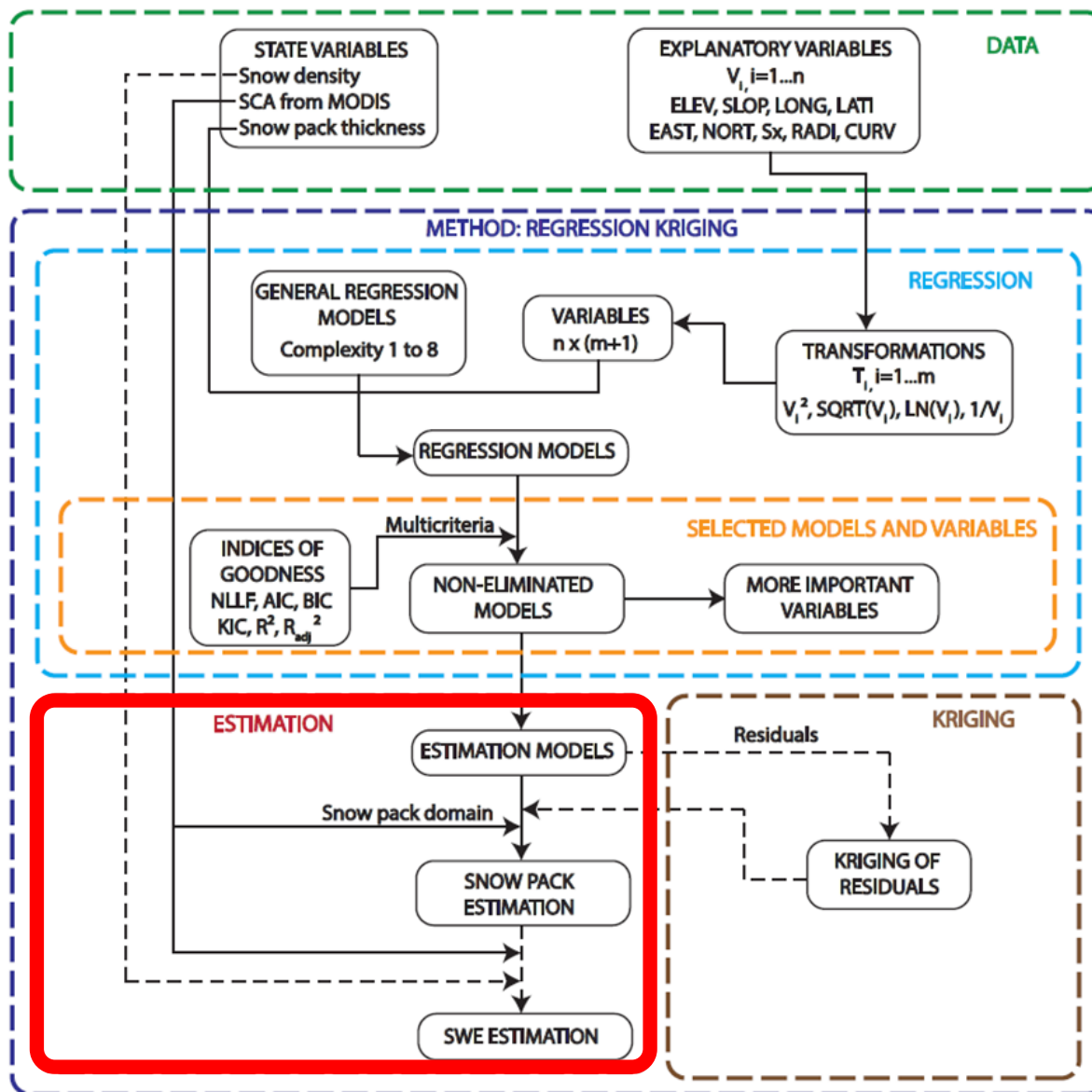
2. ESTIMATION METHOD



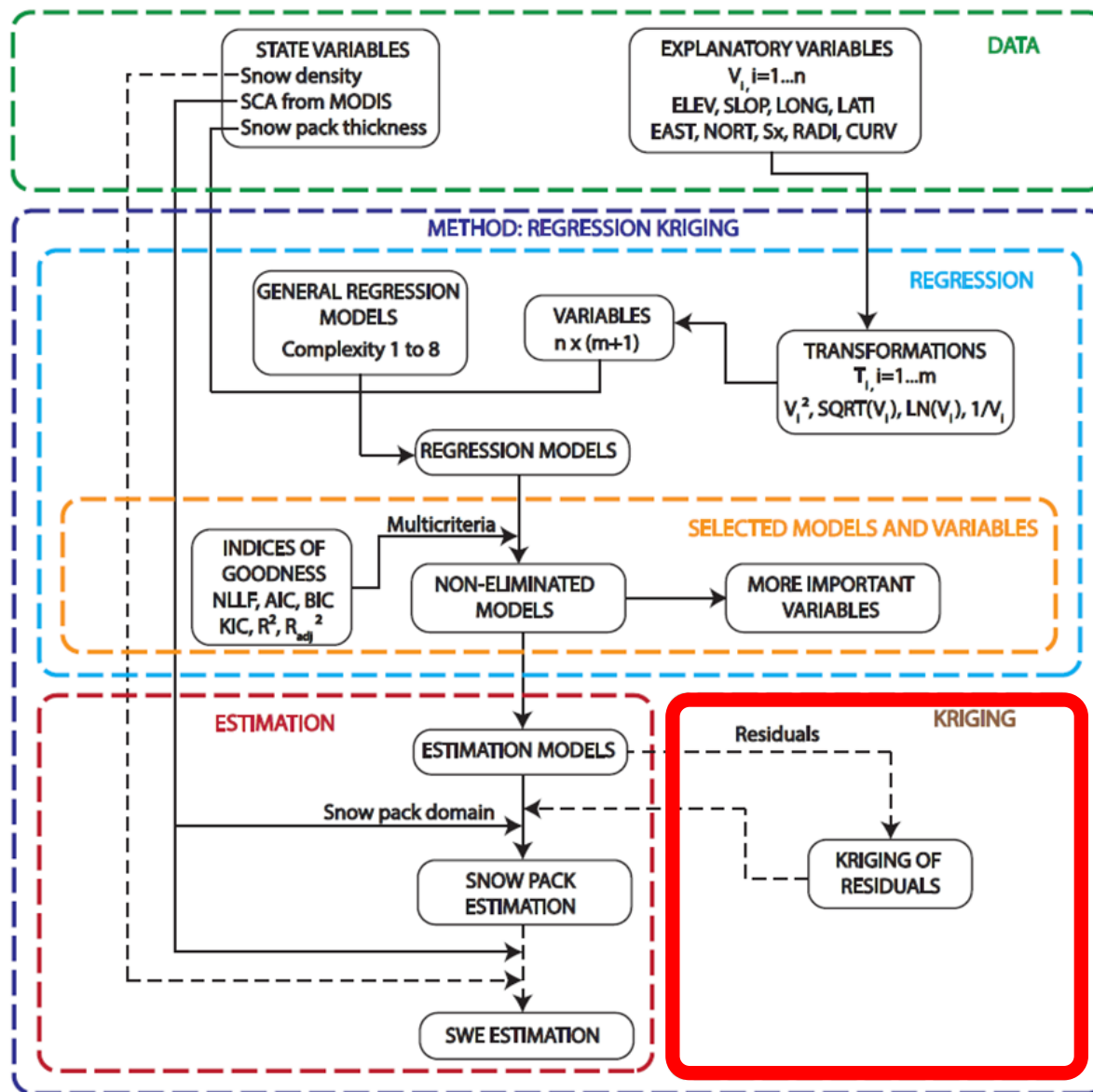
2. ESTIMATION METHOD



2. ESTIMATION METHOD



2. ESTIMATION METHOD



2. ESTIMATION METHOD / 2.1 SELECTED MODELS

REGRESSION

Best model to estimate



$$Y_1 = \beta_0 + \beta_1 x_i$$

$$Y_2 = \beta_0 + \beta_1 x_i x_j$$

$$Y_3 = \beta_0 + \beta_1 x_i + \beta_2 x_j$$

$$Y_4 = \beta_0 + \beta_1 x_i + \beta_2 x_j x_\ell$$

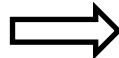
$$Y_5 = \beta_0 + \beta_1 x_i x_k + \beta_2 x_j x_\ell$$

$$Y_6 = \beta_0 + \beta_1 x_i + \beta_2 x_j + \beta_3 x_\ell$$

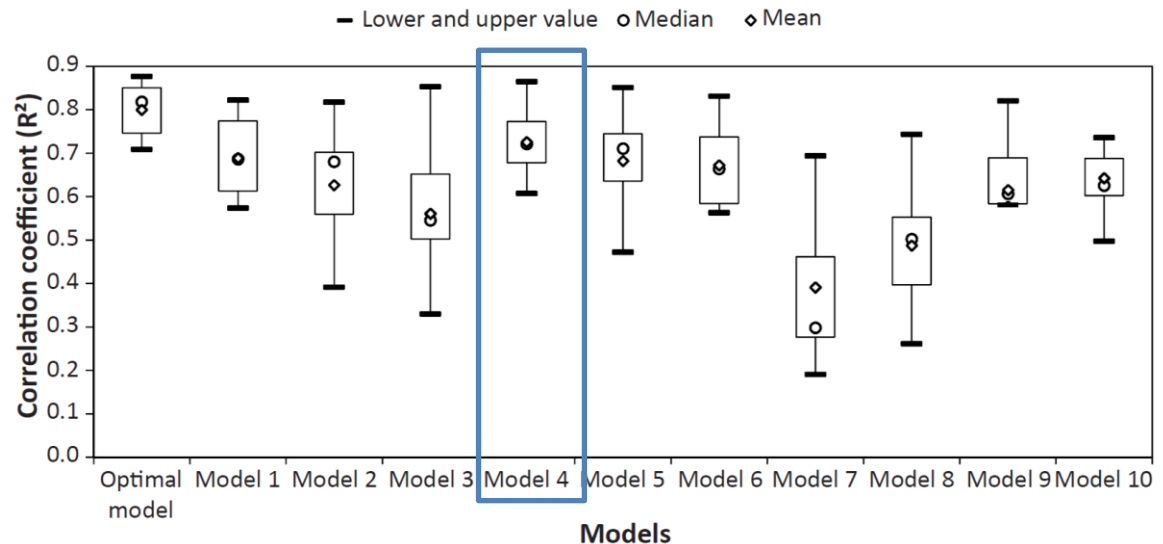
$$Y_7 = \beta_0 + \beta_1 x_i + \beta_2 x_j + \beta_3 x_\ell x_k$$

$$Y_8 = \beta_0 + \beta_1 x_i + \beta_2 x_j + \beta_3 x_\ell + \beta_4 x_k$$

Best general model
for the 11 campaigns



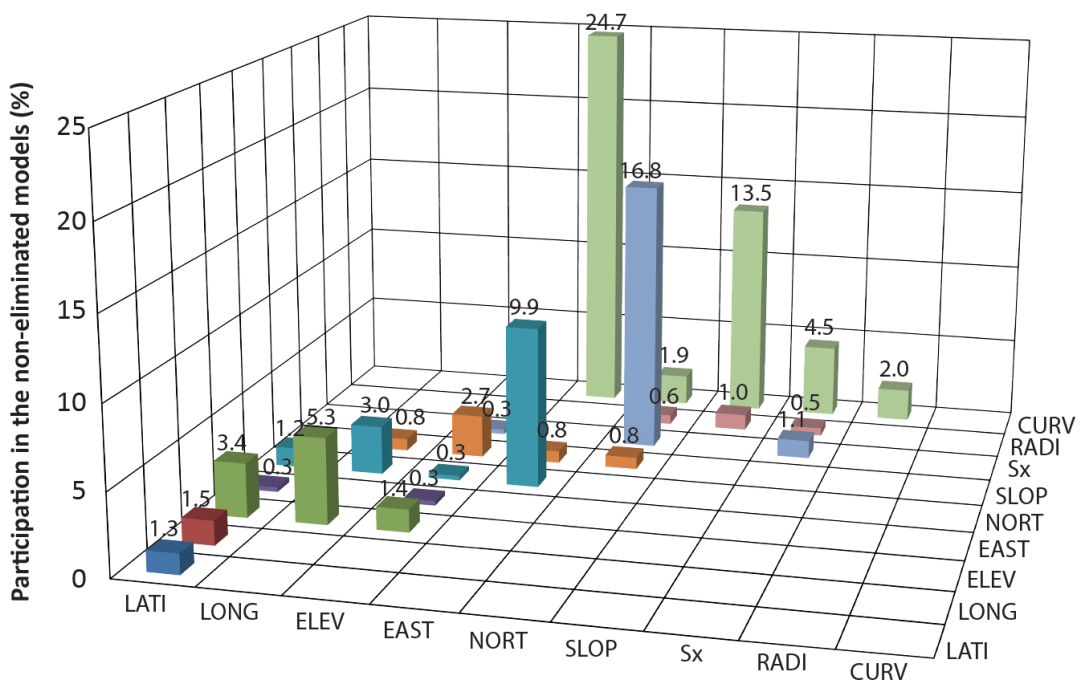
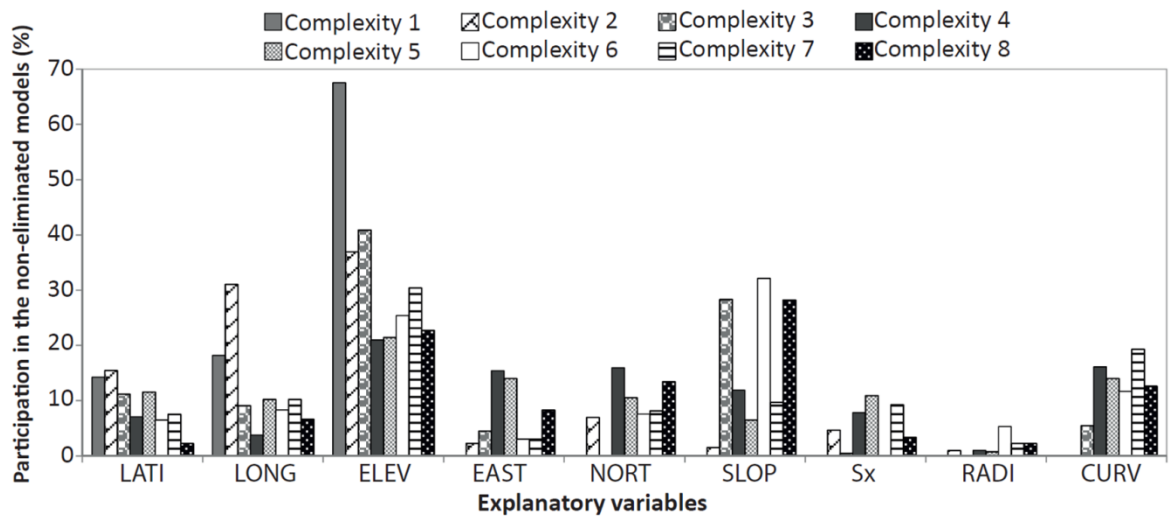
Model	x_i	x_j	x_ℓ	x_k	Optimal for:
1	(ELEV)	(ELEV) ²	(MUWS) ²	(CURV) ²	16/03/2000
2	1/(LATI)	1/(ELEV)	(NORT) ²	(MUWS) ²	05/04/2001, 05/04/2003
3	LN(NORT)	1/(ELEV)	SQRT(LONG)	SQRT(NORT)	21/04/2003
4	(ELEV)	(SLOP) ²	(EAST) ²	(CURV) ²	13/01/2004
5	1/(SLOP)	(ELEV) ²	(SLOP) ²	SQRT(CURV)	26/04/2004
6	LN(CURV)	(ELEV) ²	(EAST) ²	(CURV) ²	24/03/2005
7	LN(CURV)	(LONG) ²	(MUWS) ²	(CURV) ²	27/02/2006
8	(LONG) ²	(SLOP) ²	(EAST) ²	(CURV) ²	13/02/2009
9	(ELEV)	(EAST)	LN(NORT)	1/(EAST)	08/05/2013
10	LN(ELEV)	1/(ELEV)	(SLOP)**2	(CURV) ²	21/03/2014



+

KRIGING OF RESIDUALS

2. ESTIMATION METHOD / 2.1 SELECTED VARIABLES



Most important variables

- The elevation is the most frequently variable.
- For the more complex models other variables appear with a high frequency.



Multicriteria analysis



Most important products of variables

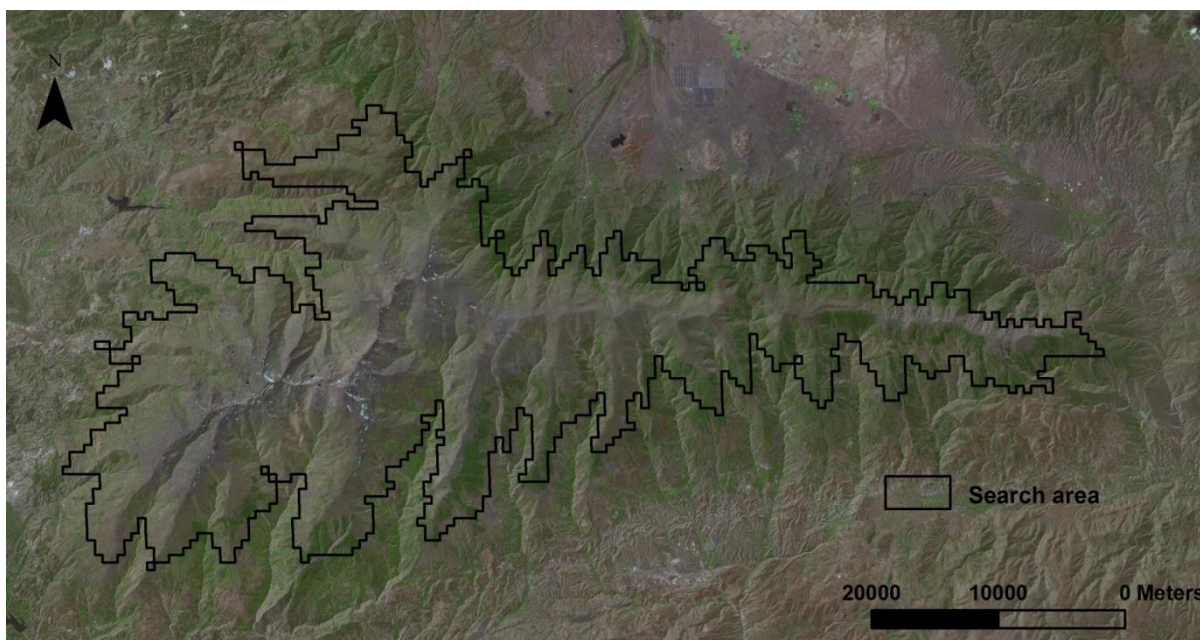
- Curvature-Eastness
- Sx-Northness
- Curvature-Slope
- Northness-Eastness

3. OPTIMIZATION METHOD

We search a location within the “search area” that minimize total standard deviation in the “search area”

Search area: >1837 m (735 km²)

Snowline is above 1837 m in 90% of the days with snow



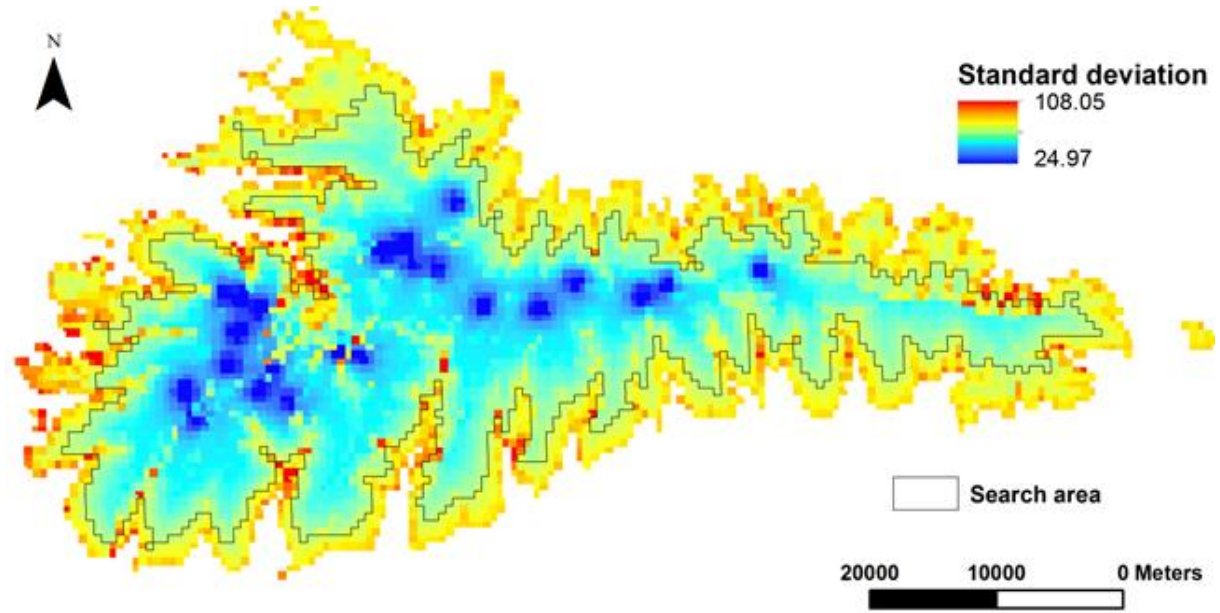
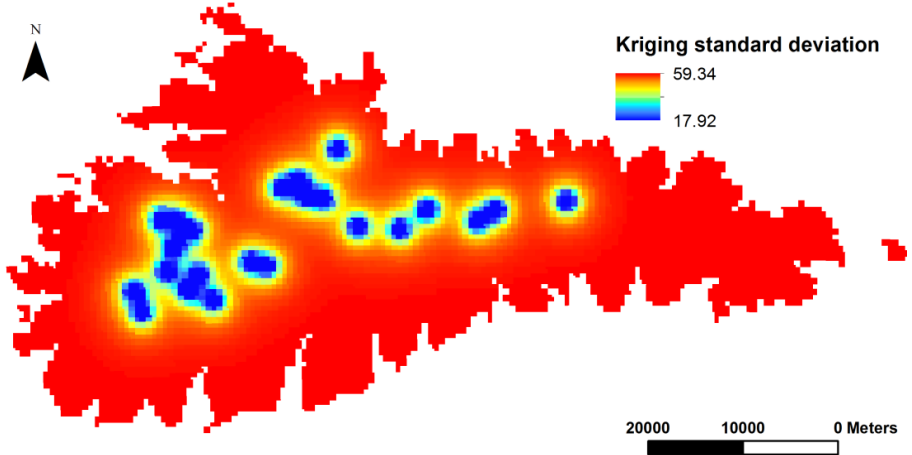
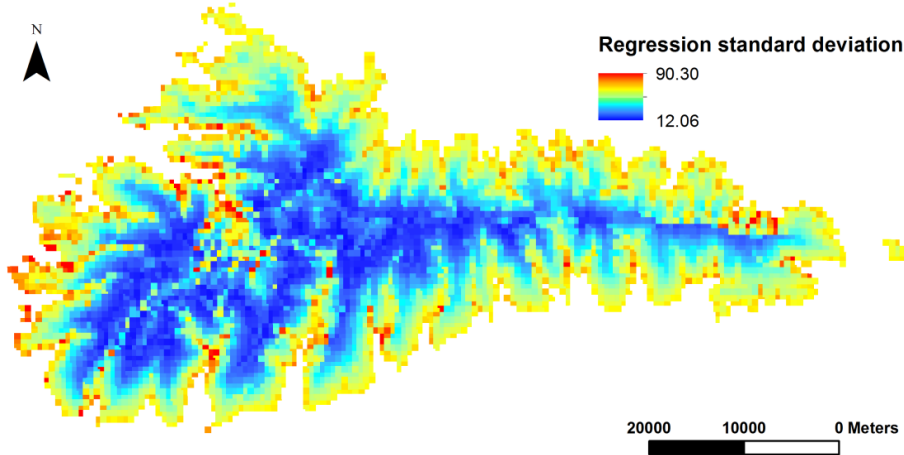
Cases:

- 1. Augmentation and Reduction one by one from 23 stakes**
- 2. Reduction one by one from 23 to 4 stakes and augmentation one by one until 23 stakes**
- 3. Reduction by pairs from 23 stakes**
- 4. Augmentation considering the MODIS “zeros” in kriging**

3. OPTIMIZATION METHOD

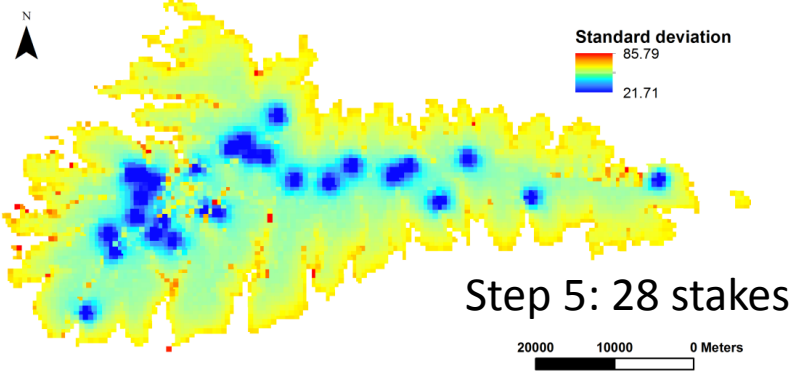
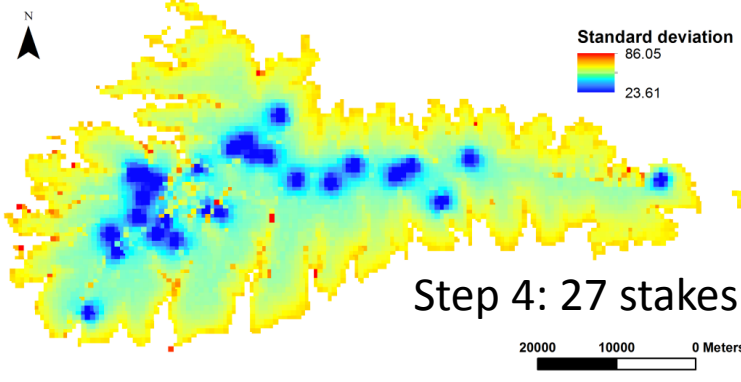
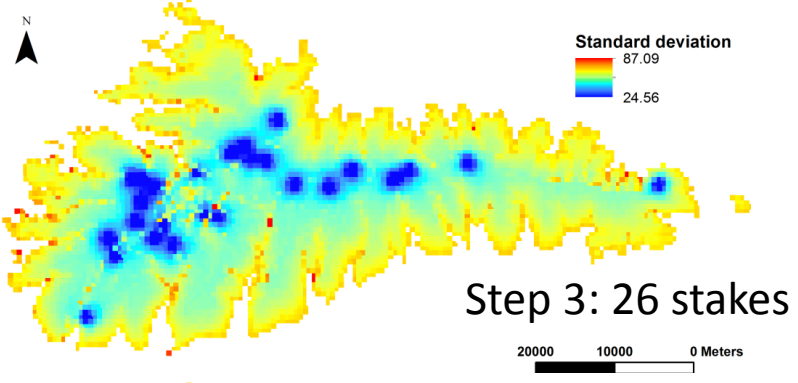
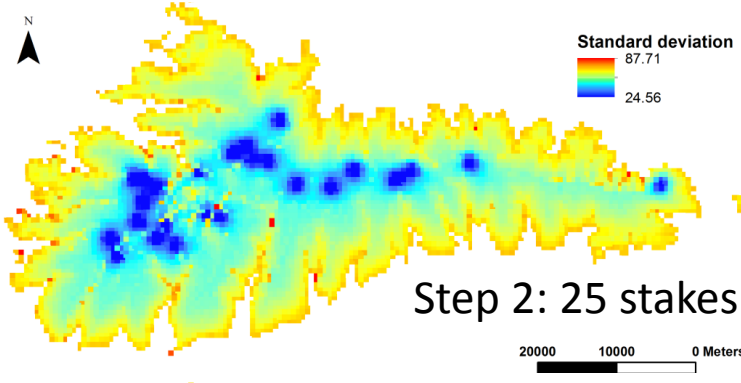
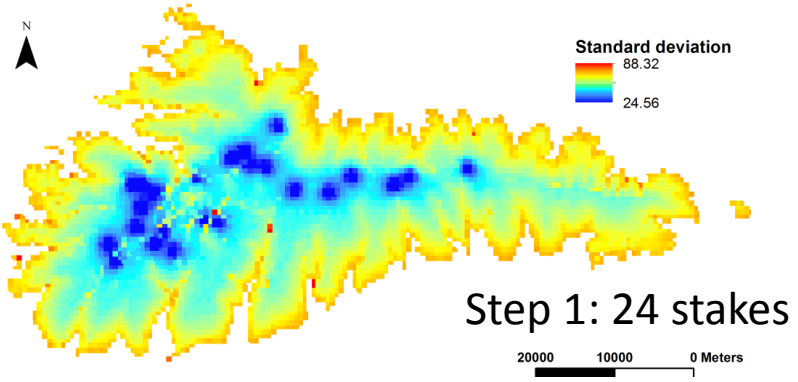
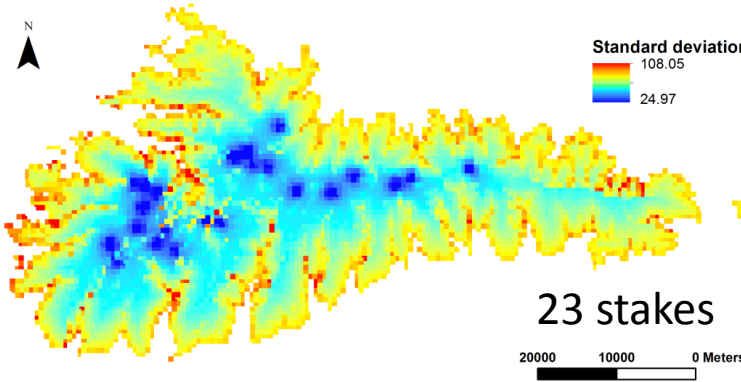
STANDARD DEVIATION OF ESTIMATION IN THE INITIAL SITUATION (23 STAKES)

$$\sigma_{RK}^2 = \sigma_R^2 + \sigma_K^2$$



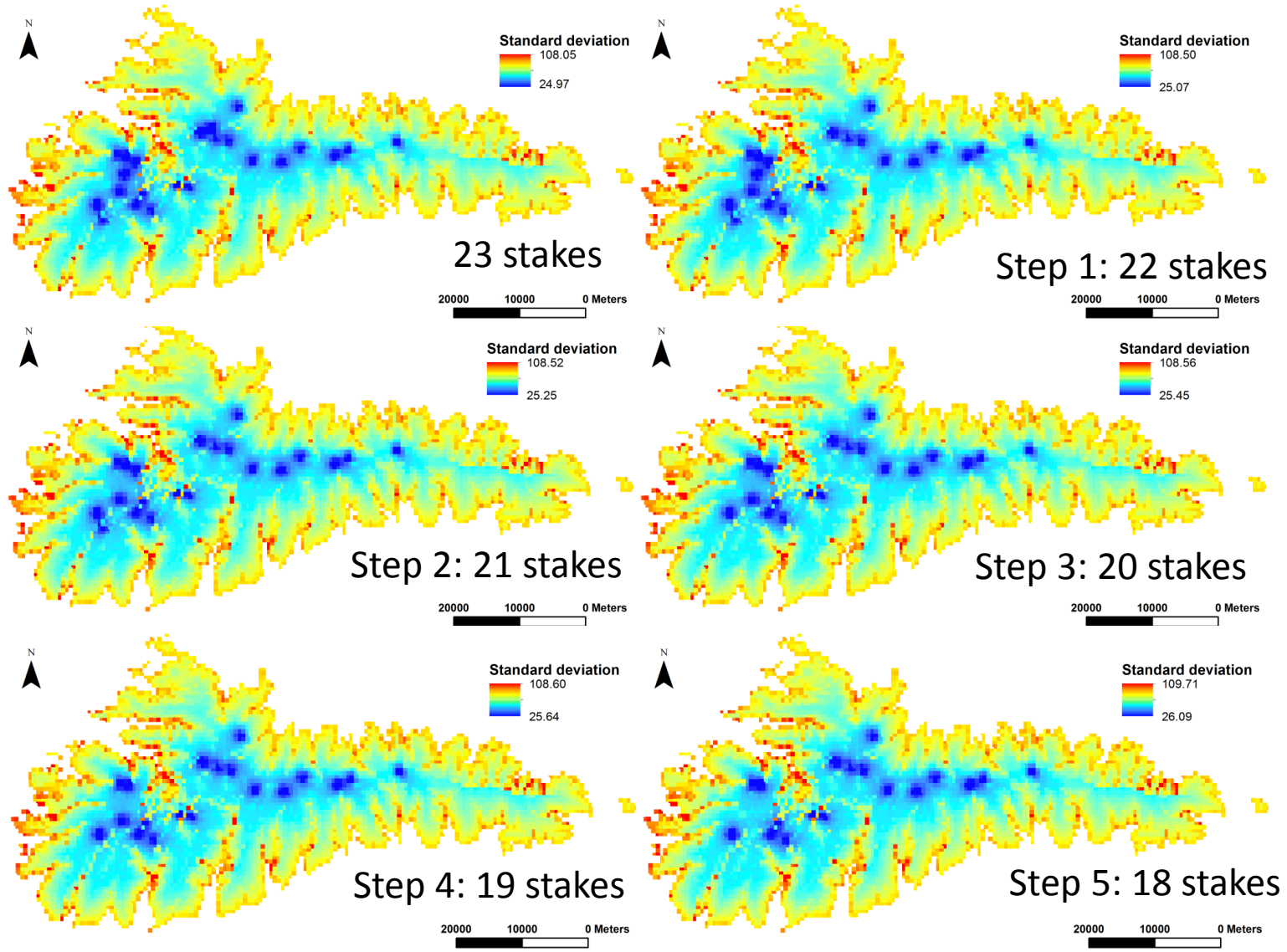
4. RESULTS / 4.1 AUGMENTATION AND REDUCTION ONE BY ONE

AUGMENTATION ONE BY ONE

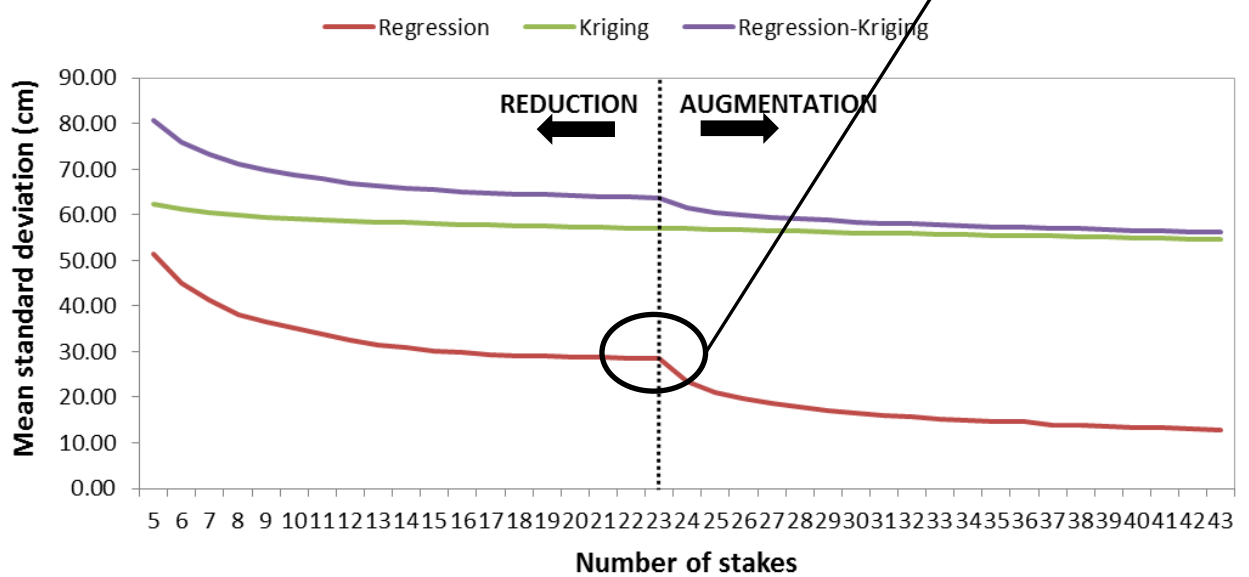
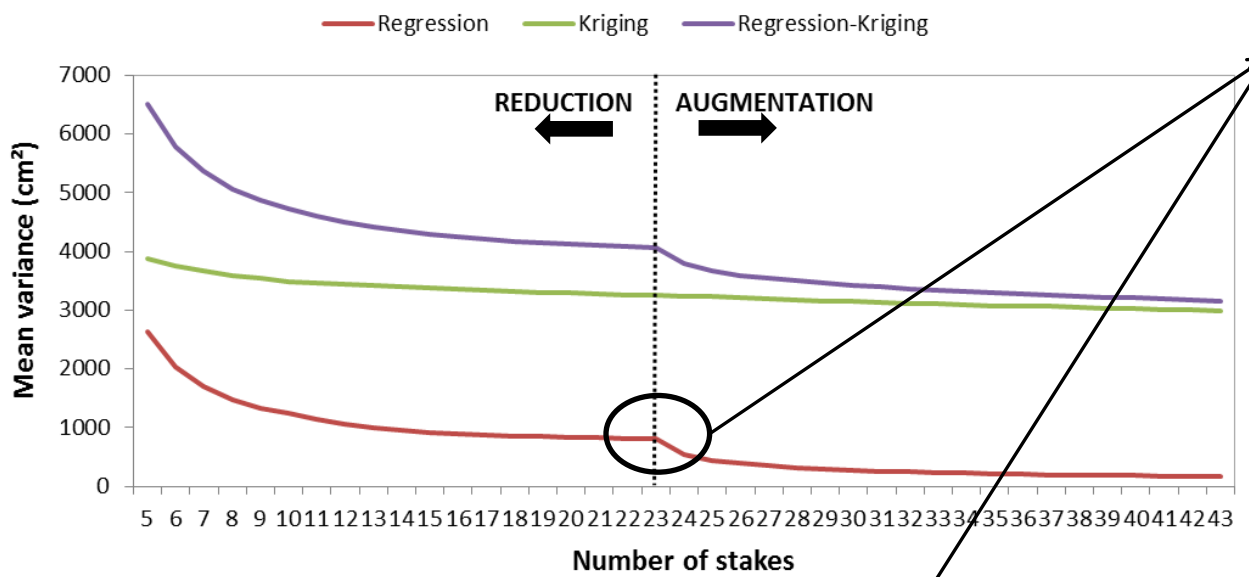


4. RESULTS / 4.1 AUGMENTATION AND REDUCTION ONE BY ONE

REDUCTION ONE BY ONE



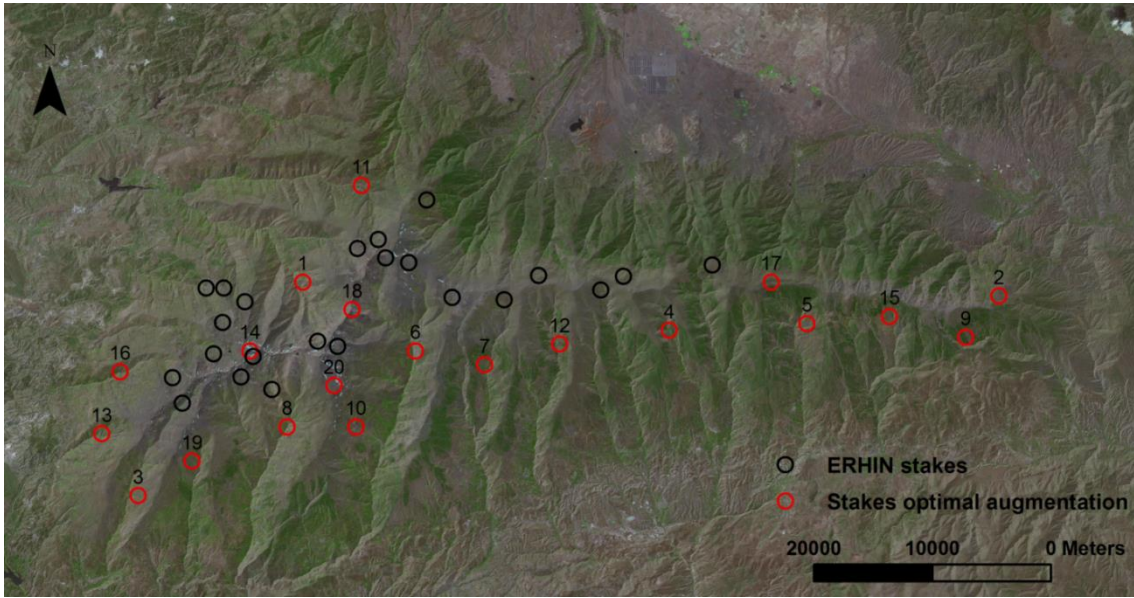
4. RESULTS / 4.1 AUGMENTATION AND REDUCTION ONE BY ONE



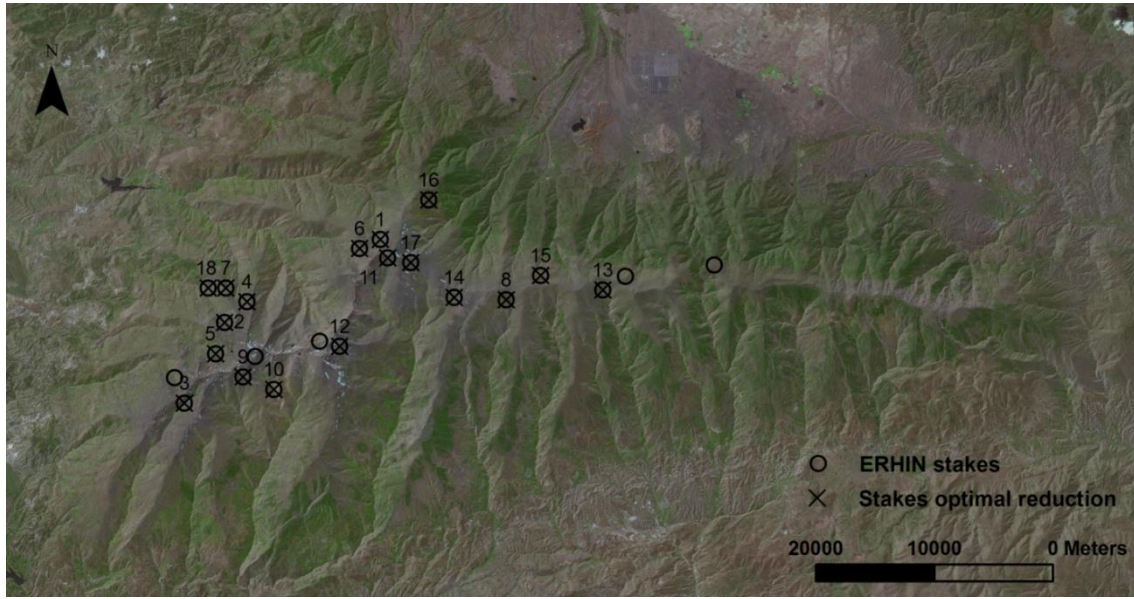
High change in slope
 ↓
 Not optimal location of the 23 initial stakes?
 ↓
 Possibility of reduction until 4 stakes + augmentation until 23?
 ↓
 A smaller σ^2 and the same cost

4. RESULTS / 4.1 AUGMENTATION AND REDUCTION ONE BY ONE

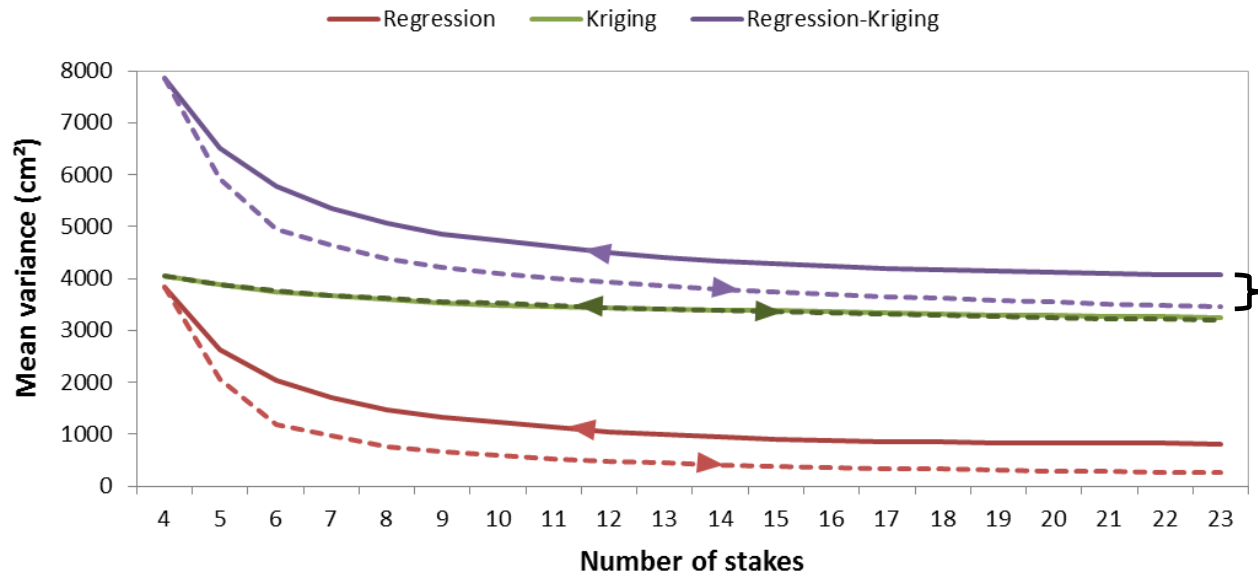
AUGMENTATION CASE



REDUCTION CASE

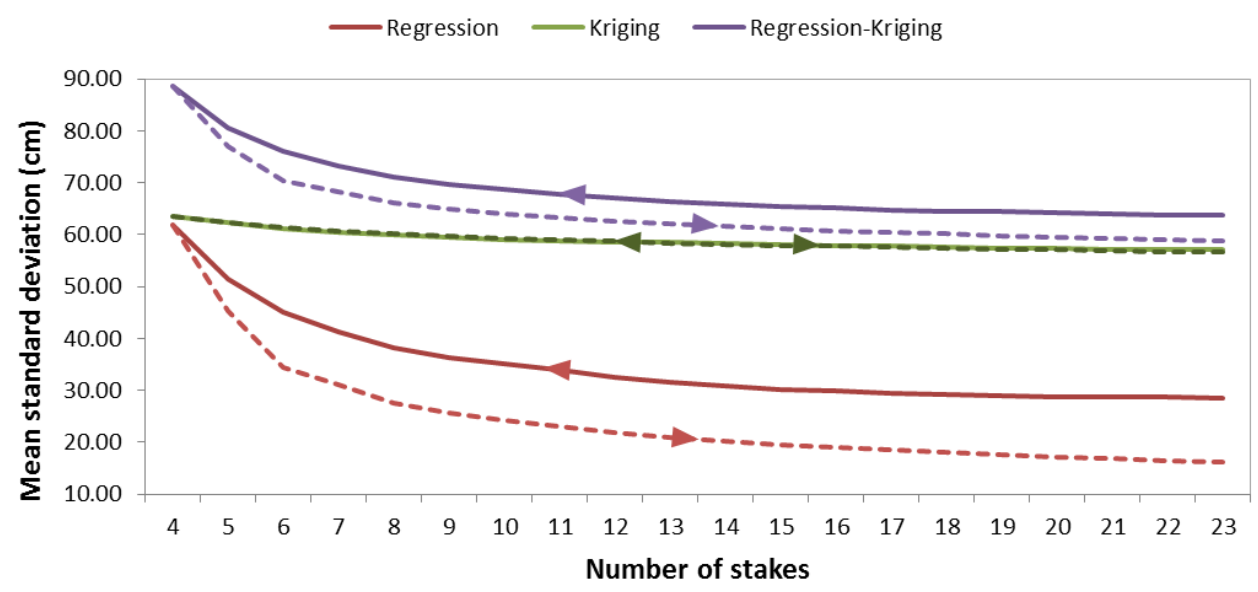


4. RESULTS / 4.2 COMBINATION OF REDUCTION AND AUGMENTATION



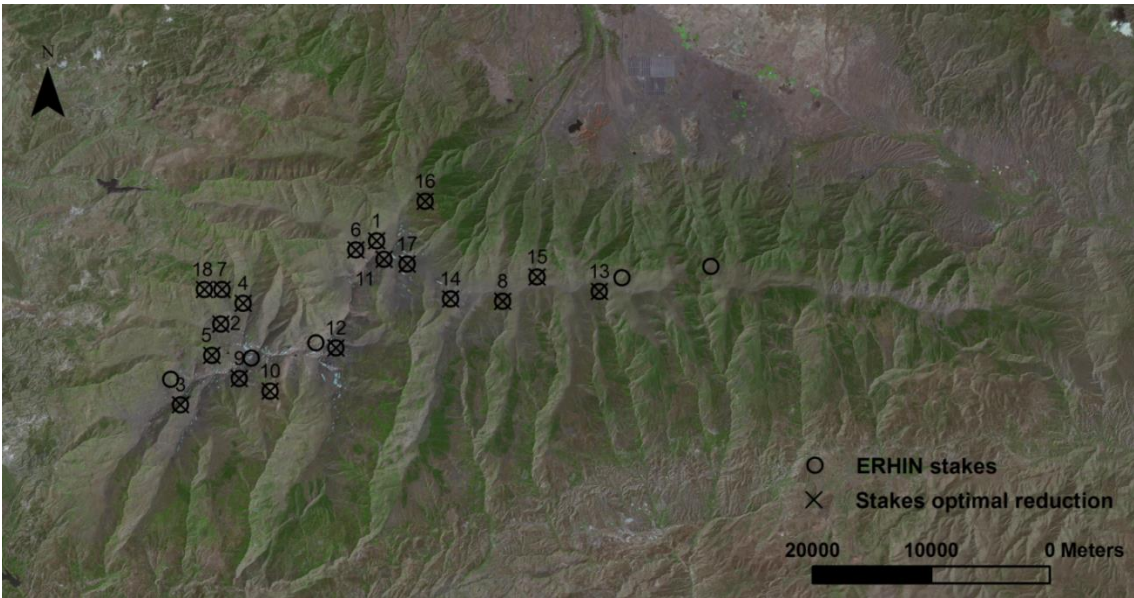
$\Delta\sigma^2 = -607 \text{ cm}^2$

The same number of stakes and a smaller σ^2



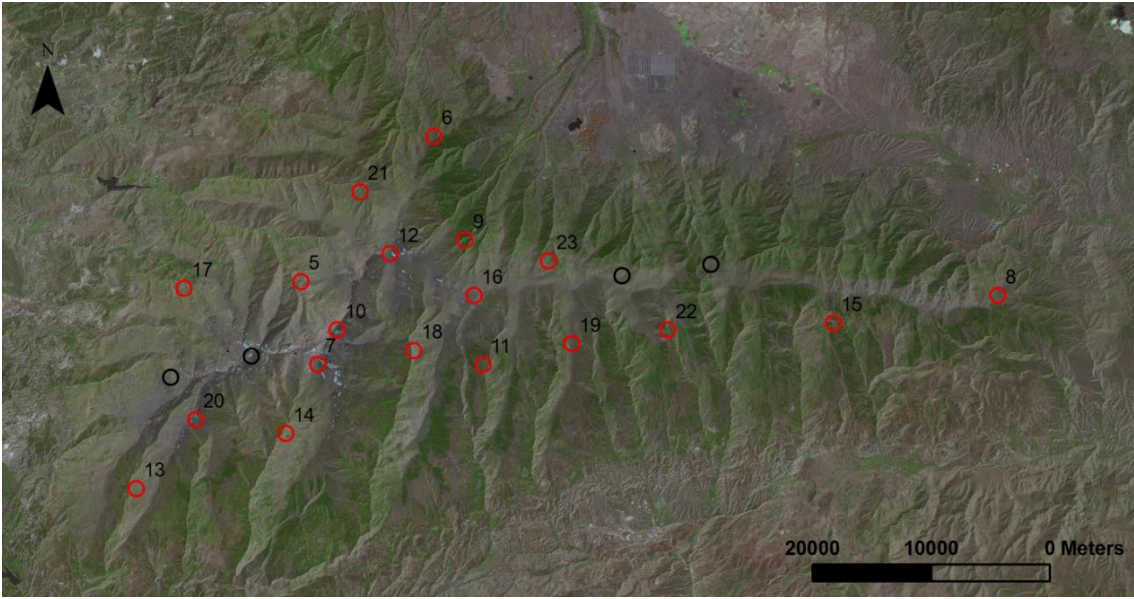
4. RESULTS / 4.2 COMBINATION OF REDUCTION AND AUGMENTATION

REDUCTION PHASE

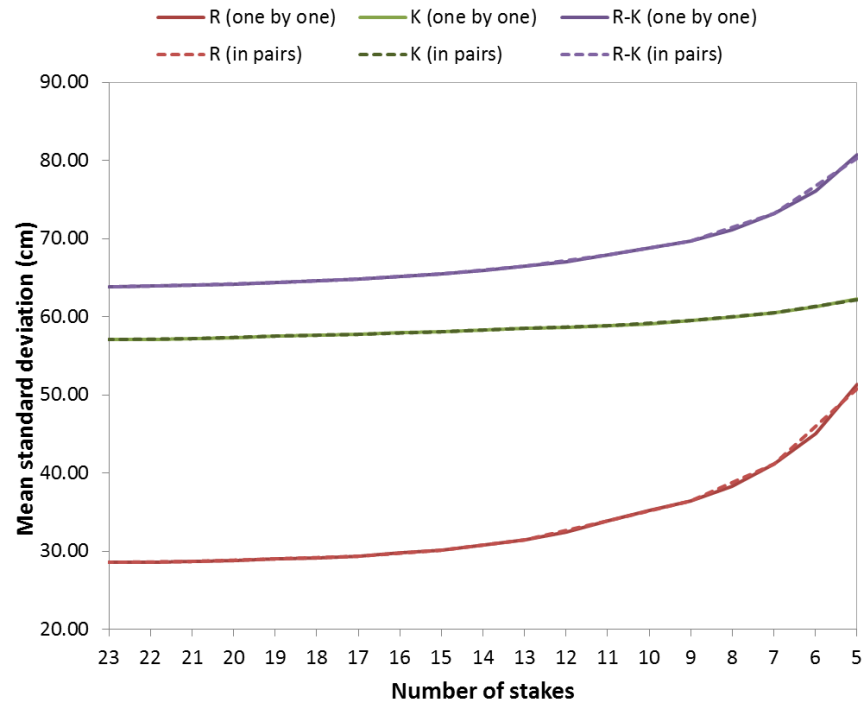
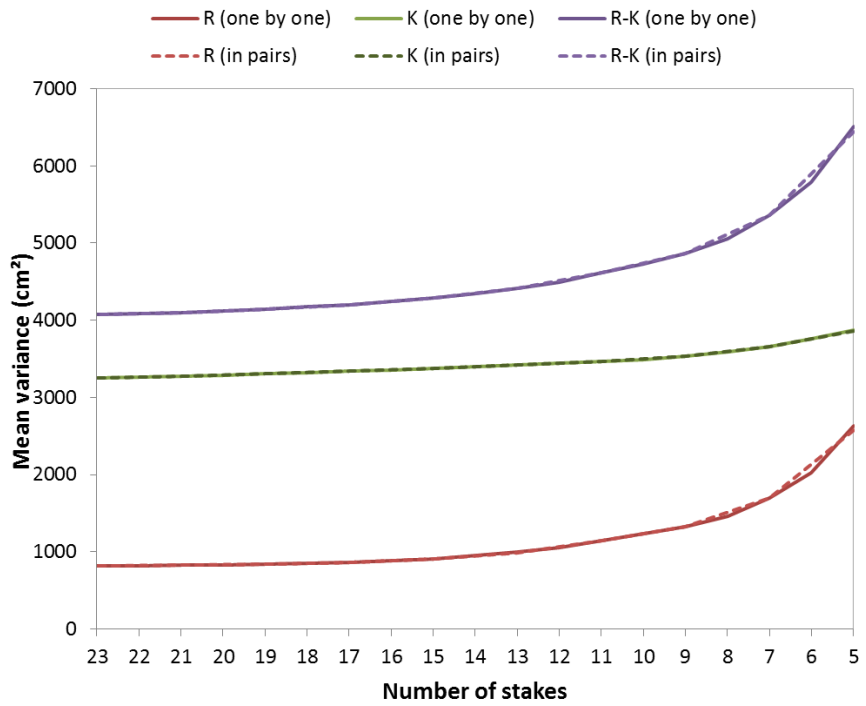


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AUGMENTATION PHASE



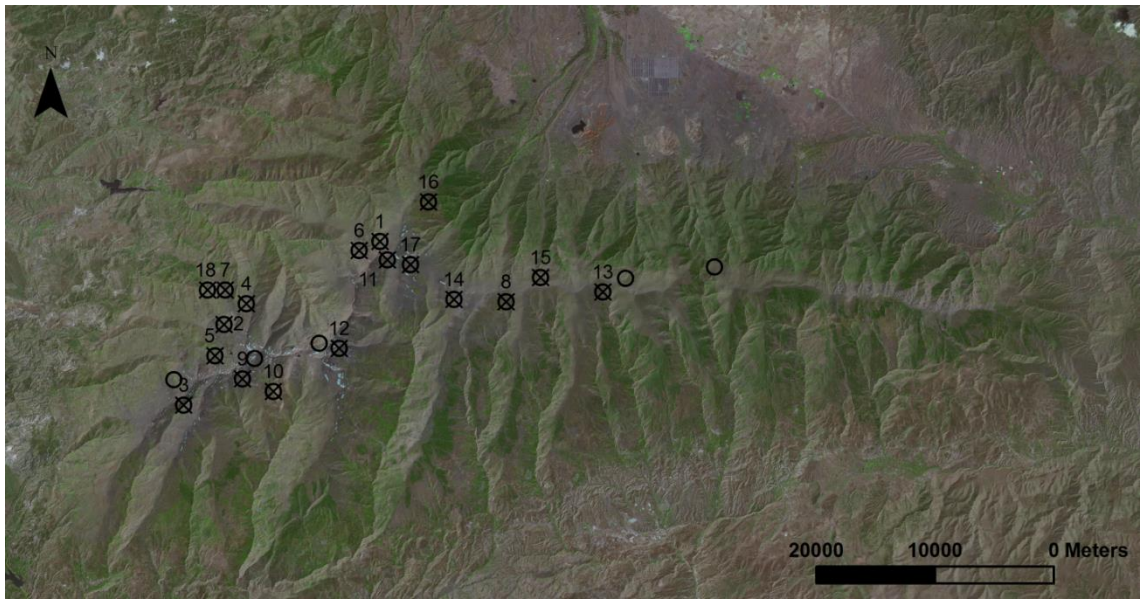
4. RESULTS / 4.3 REDUCTION ONE BY ONE VS REDUCTION BY PAIRS



- Small difference between the two cases: Similar variance change
- The reduction order of the stakes is a bit different

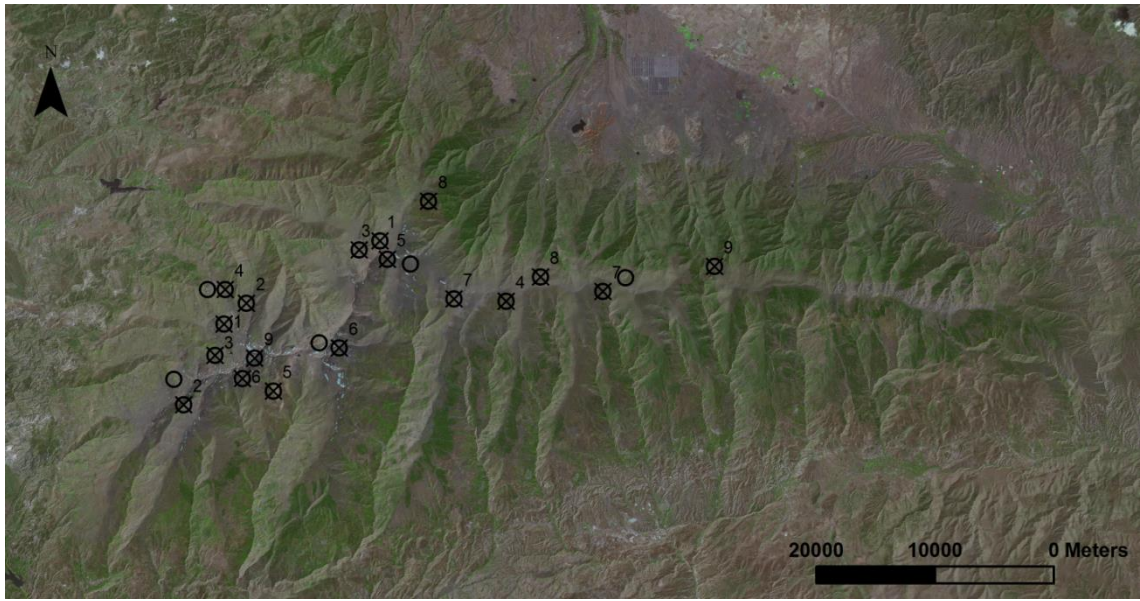
4. RESULTS / 4.3 REDUCTION ONE BY ONE VS REDUCTION BY PAIRS

REDUCTION ONE BY ONE



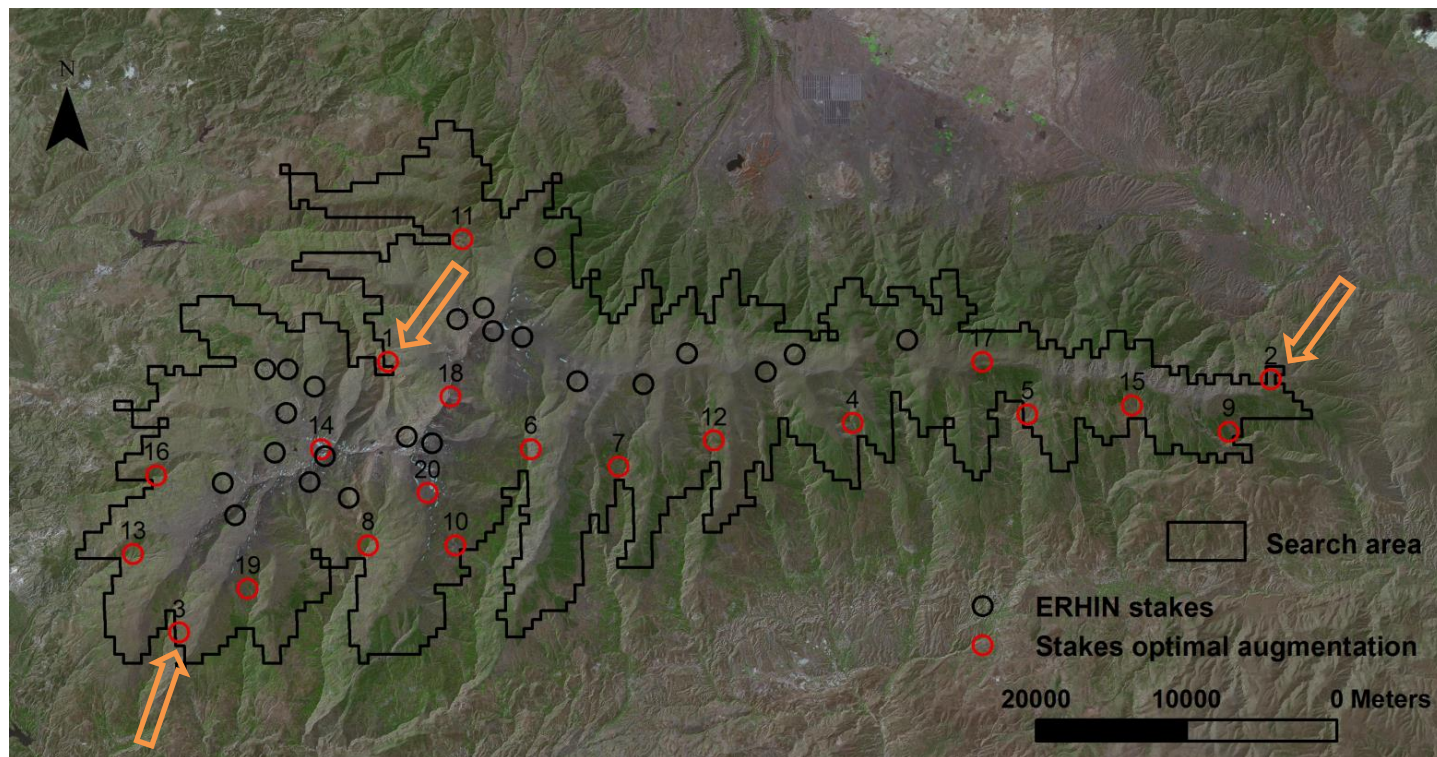
VS

REDUCTION BY PAIRS



4. RESULTS / 4.4 AUGMENTATION CONSIDERING THE MODIS ZEROS

Optimal locations
without MODIS
zeros as data

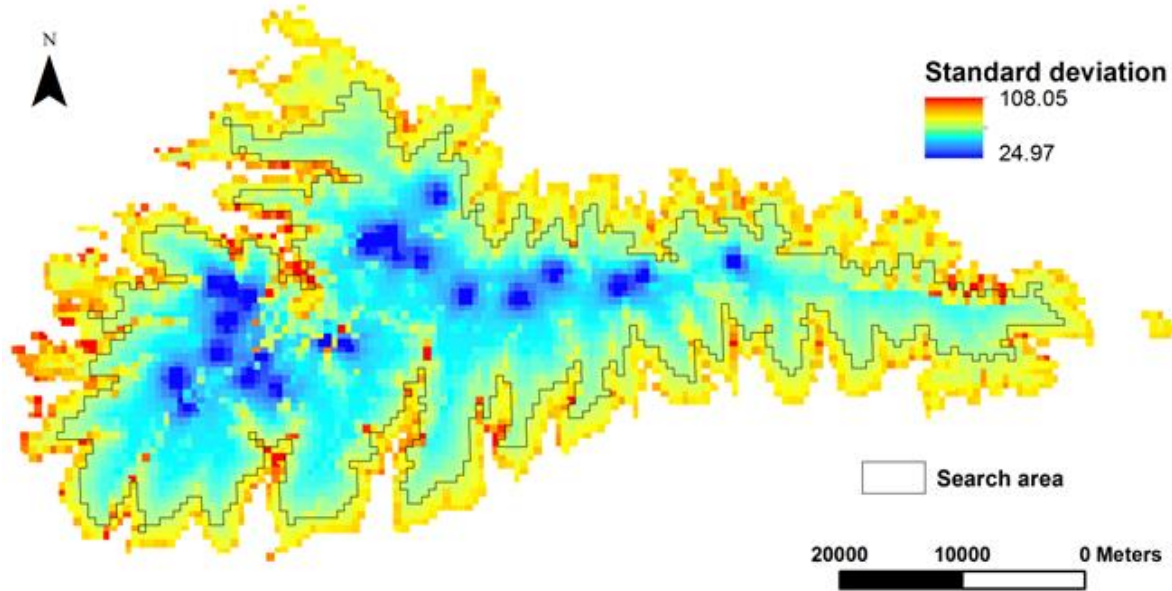


A lot of optimal location are situated next to the search area border.

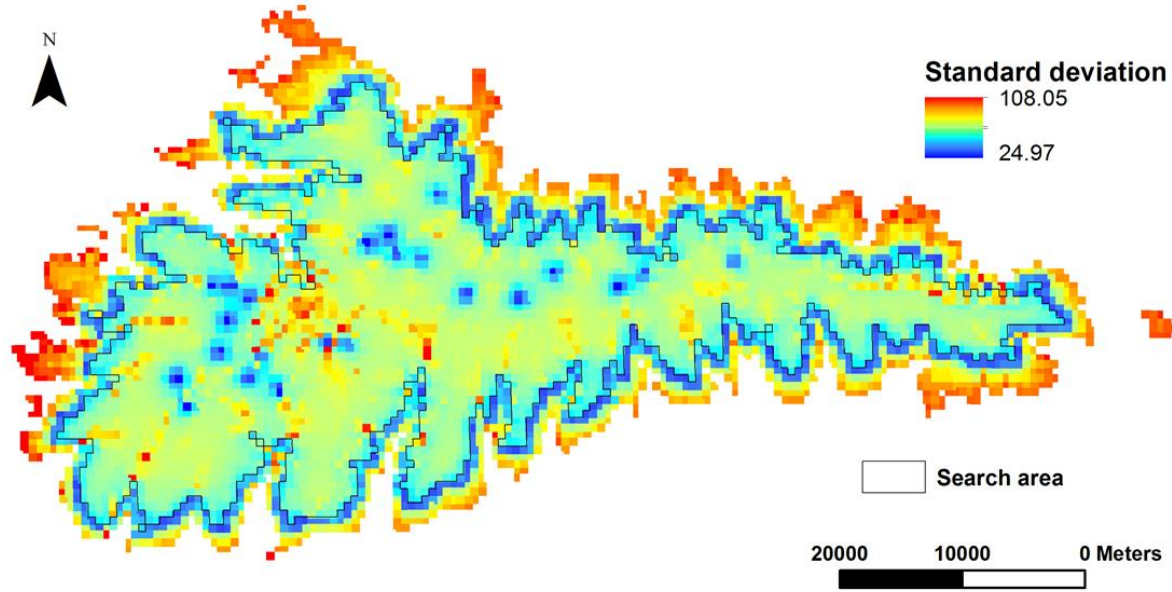
If we include the zeros in Kriging the optimal locations change?

4. RESULTS / 4.4 AUGMENTATION CONSIDERING THE MODIS ZEROS

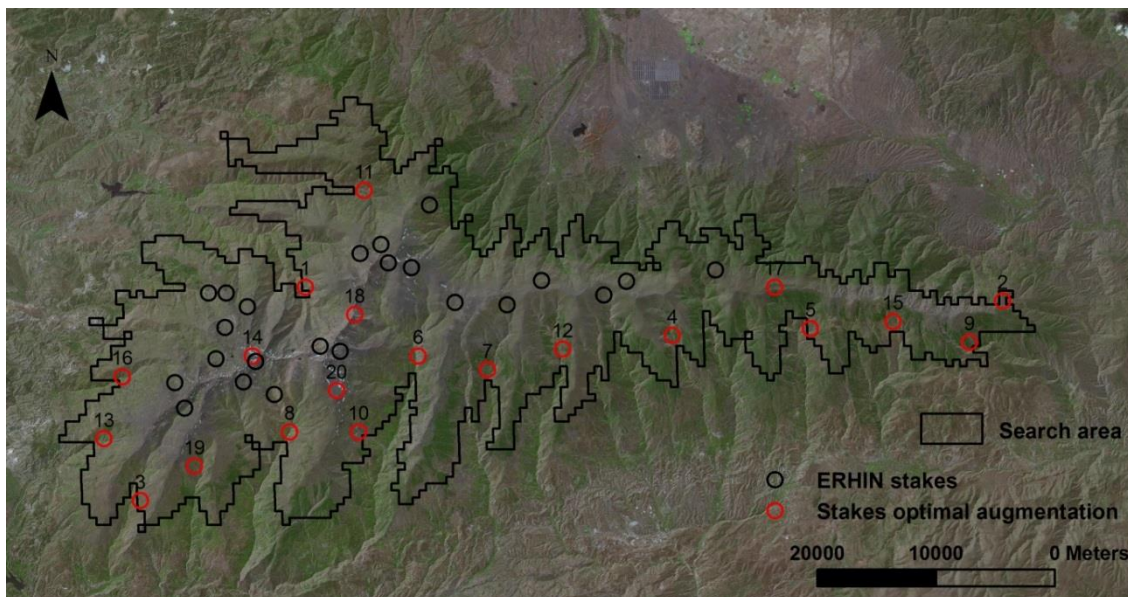
σ WITHOUT MODIS ZEROS AS DATA



σ WITH MODIS ZEROS AS DATA



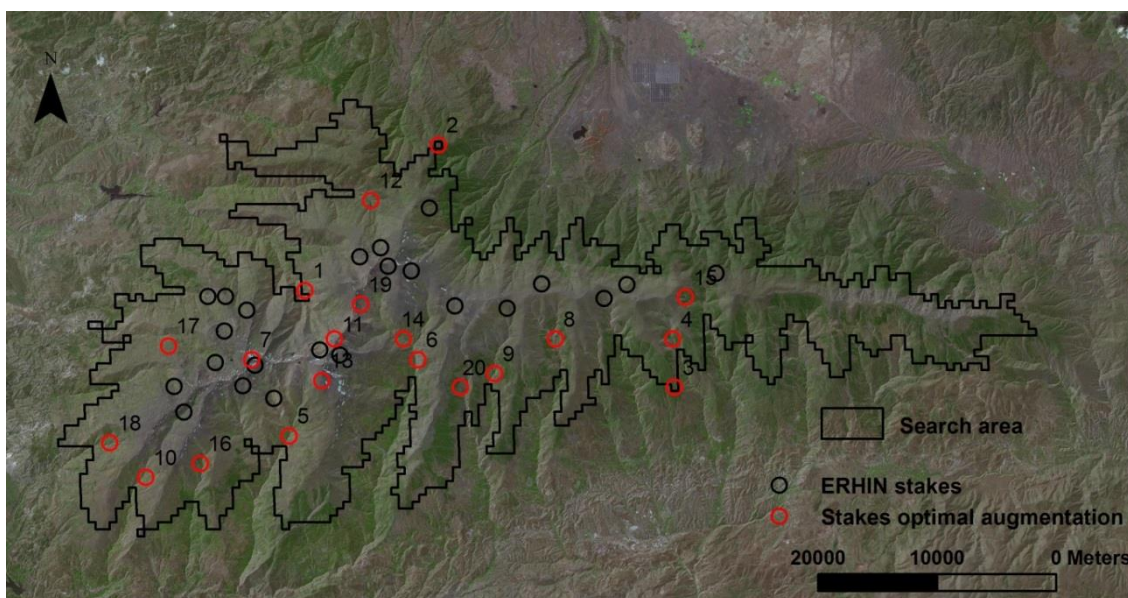
4. RESULTS / 4.4 AUGMENTATION CONSIDERING THE MODIS ZEROS



Optimal locations without MODIS zeros as data

13 of 20 new stakes are located < 1.2 Km to the border

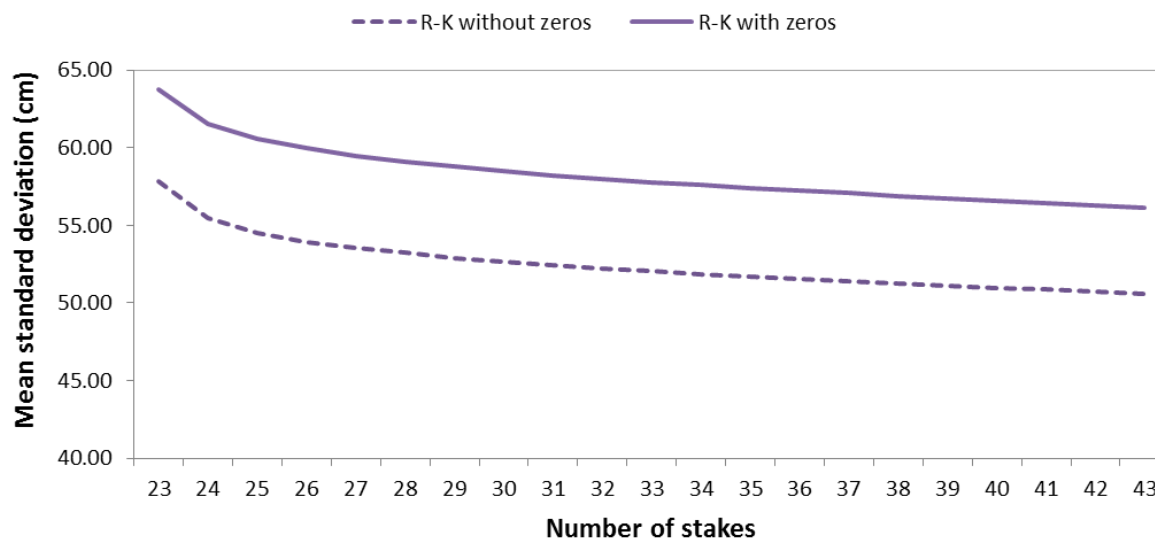
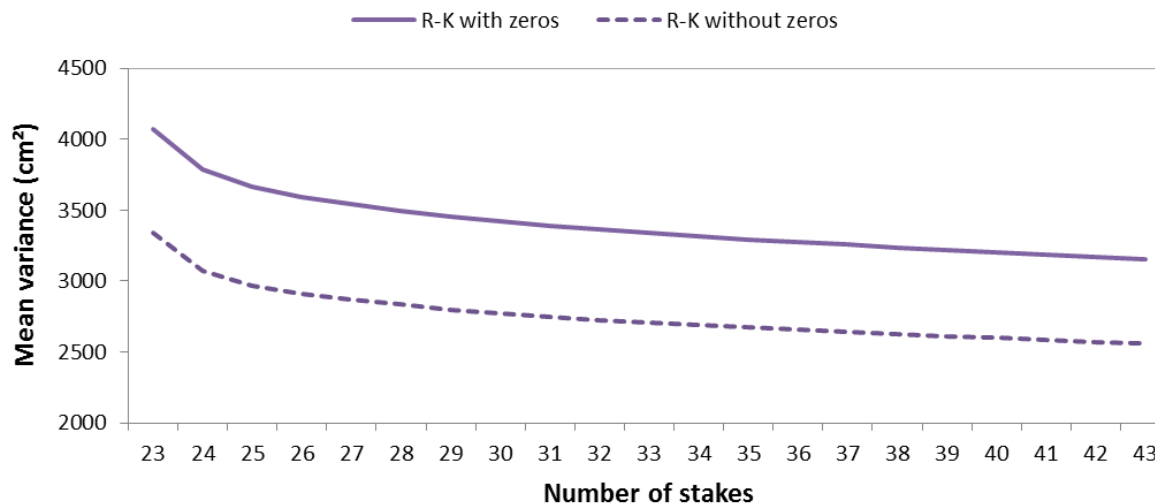
Range of variogram = 1200 m



Optimal location with MODIS zeros as data

6 of 20 new stakes are located < 1.2 Km to the border

4. RESULTS / 4.4 AUGMENTATION CONSIDERING THE MODIS ZEROS



Considering zeros the total variance in the search area is lower but the slope of the augmentation line is similar

4. CONCLUSIONS

- This method allows to design of an optimal snow observation network to estimate snowpack thickness matching ground data, digital terrain models and satellite observation.
- We can combine the reduction and augmentation case to obtain a network with the same number of stakes and a lower estimation error.
- In the reduction case one by one and by pairs the variation of the error is similar but not the location.
- If we use zeros from MODIS in kriging the new stakes appear further of the border and the total error is lower but the slope in the reduction error is similar

A wide-angle photograph of a snowy mountain landscape. In the foreground, a large evergreen tree is heavily laden with snow, standing on a snow-covered slope. To its right, another smaller snow-covered tree is visible. The middle ground is filled with a dense forest of similar snow-laden evergreen trees. In the background, a winding road or path is visible on a snow-covered mountain slope, leading towards a range of rugged, snow-capped mountains under a clear blue sky.

Thanks for your attention