Reconstruction of LGM ice extents in Europe indicates a cold and dry climate with precipitation patterns similar to present day

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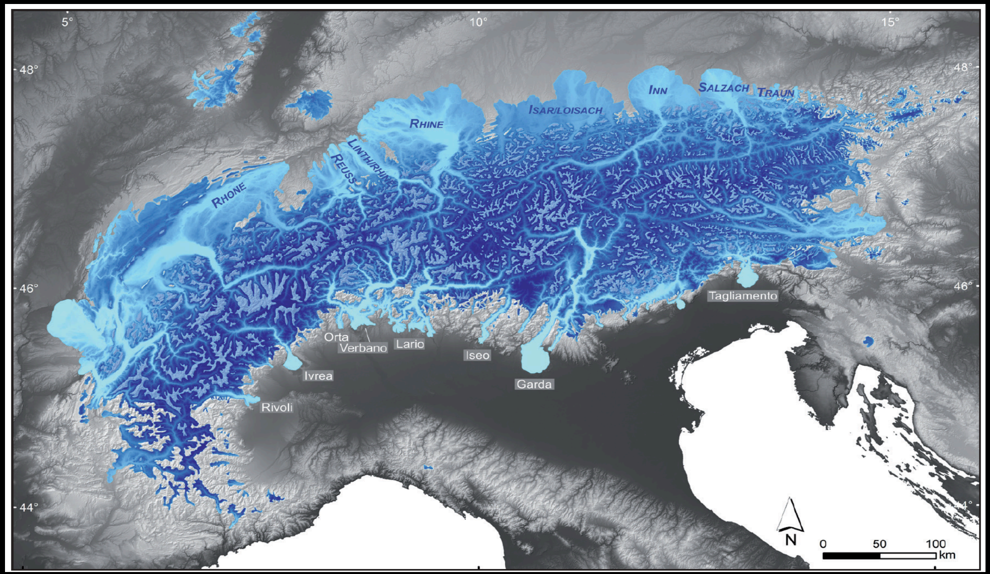
Objectives

1. Use an ice flow model to gain information on mass balance in the past and how it varies in space
2. Invert the ice extent data to constrain past climate patterns over the Alps and the Pyrenees
3. Constrain temperature and precipitation change over the Alps and the Pyrenees since the LGM



(Alps LGM reconstruction, Ivy-Ochs, 2015)

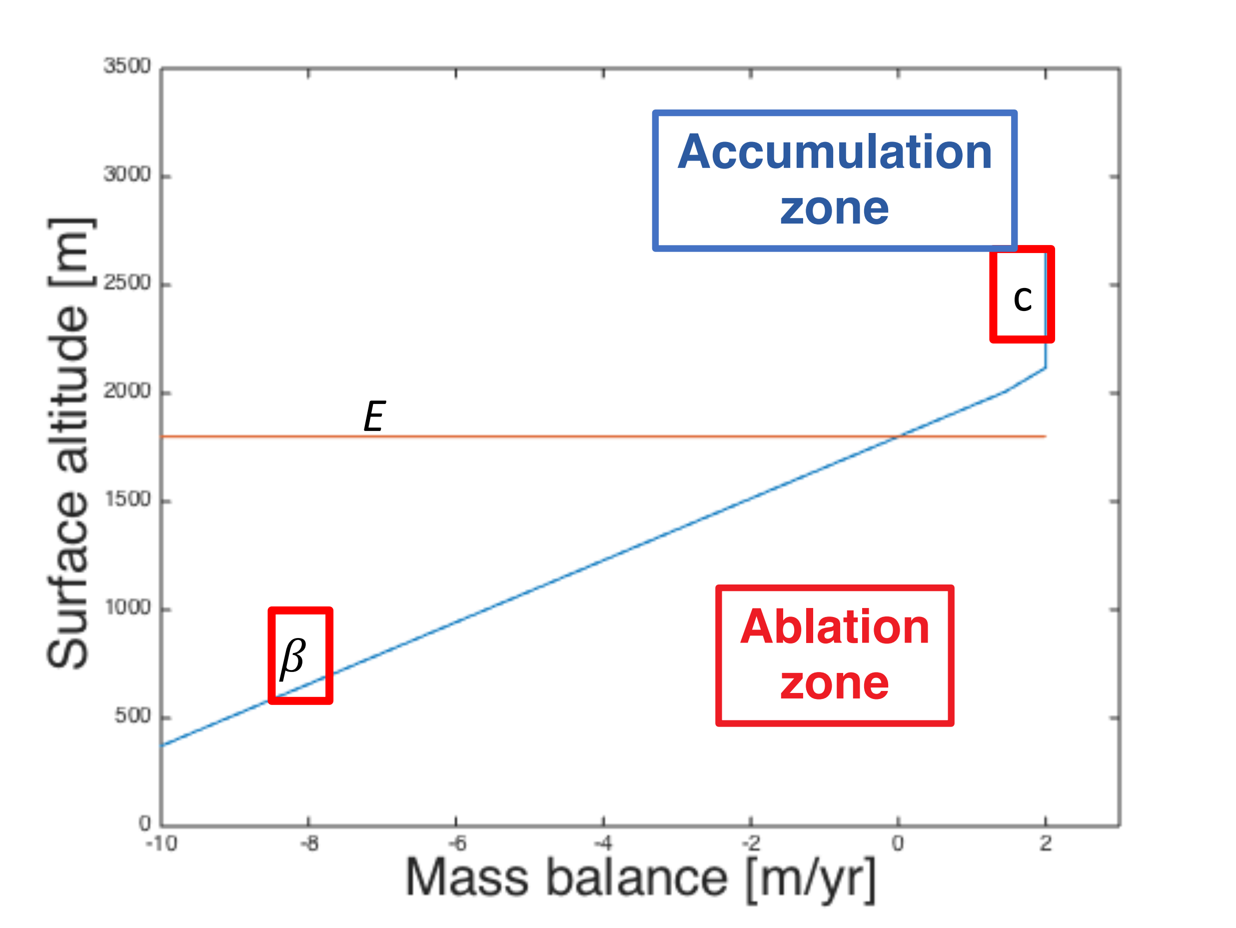
Mass balance rate

$$\dot{m} = \min\left(\boxed{\beta} \cdot (S(x,y) - E(x,y)), \boxed{c}\right)$$

- Mass conservation equation:

$$\frac{dH}{dt} = -\nabla \cdot q + \boxed{\dot{m}}$$

- $\dot{m}$ – mass balance rate
- β – mass balance gradient
- *S(x,y)* – Surface topography
- *c* – maximum accumulation
- *E(x,y)* – equilibrium line altitude (ELA)
- ELA reflects temperature and precipitation
- Examining the reconstructed ELA spatial pattern we try to better understand regional climate conditions



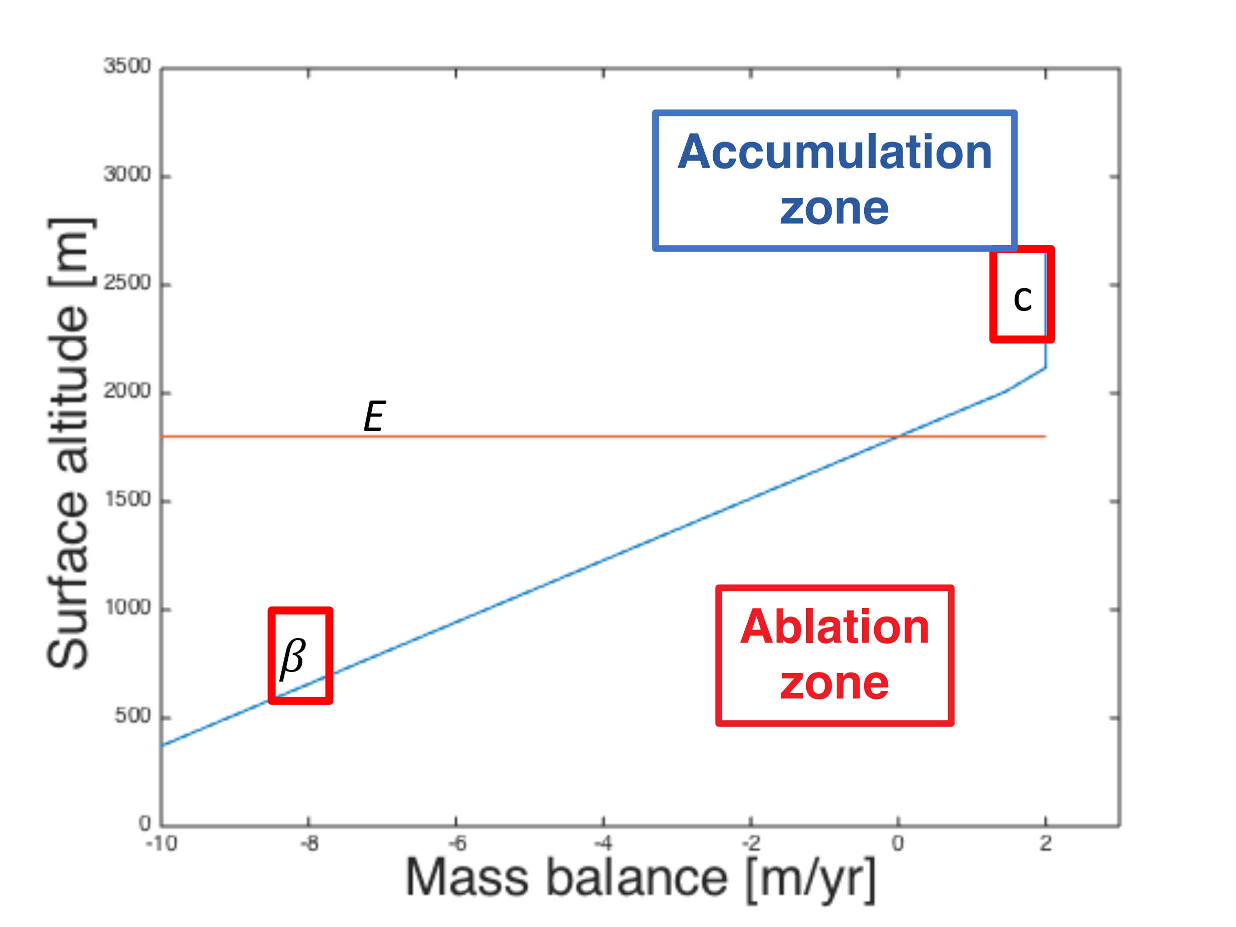
Forward model

- Mass conservation equation:

$$\frac{dH}{dt} = -\nabla \cdot q + \boxed{\dot{m}}$$

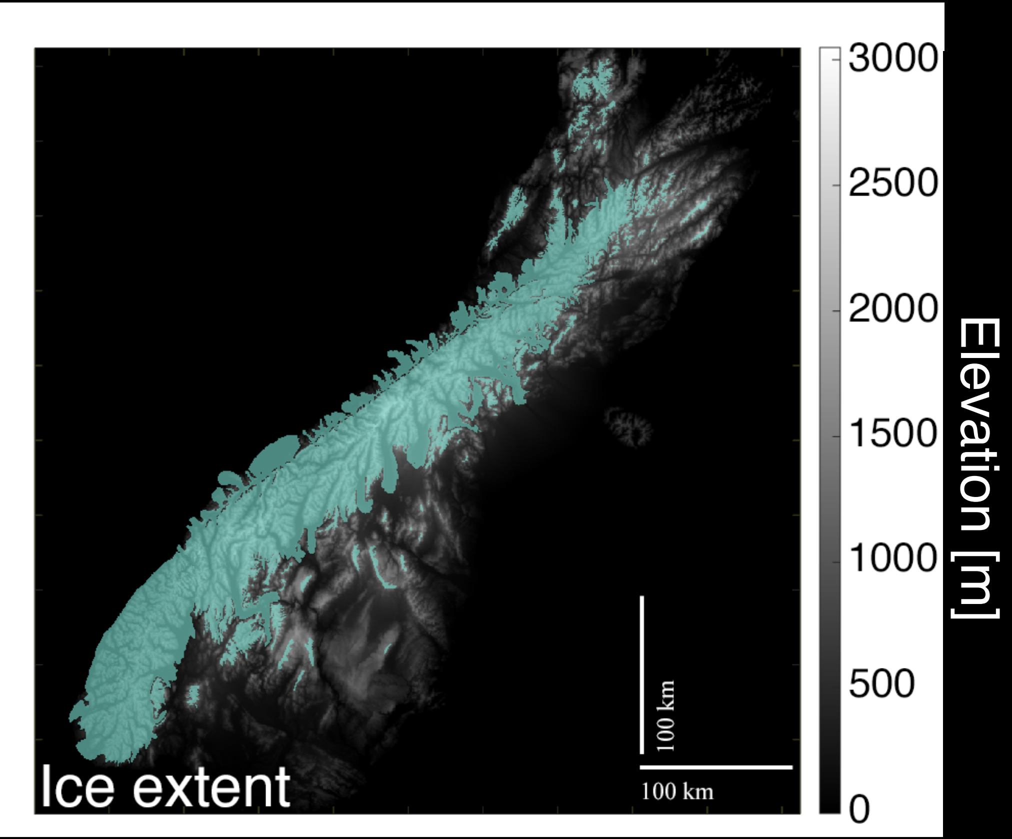
- Shallow Ice approximation (SIA)
- Explicit finite difference
- Staggered grid
- GPU implemented (CUDA C)
- Added flux limiter, constriction factor, flexure
- Steady state solution
- Each inversion consists of 1000 forward model runs

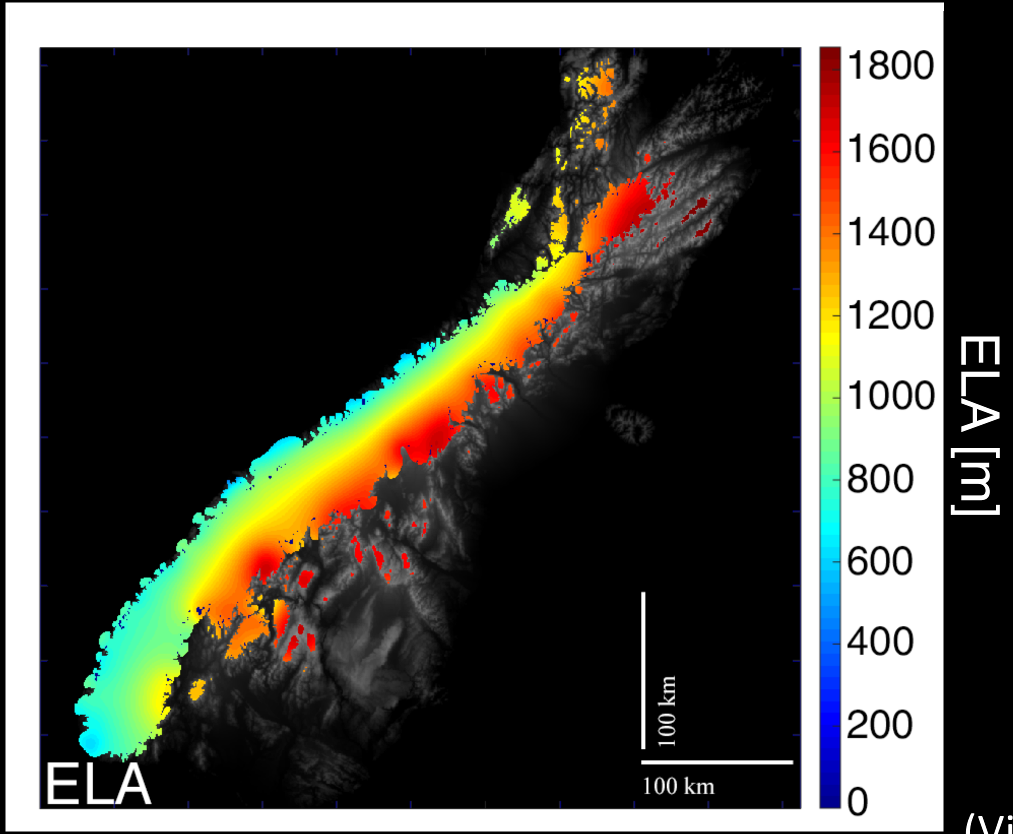
$$\dot{m} = \min\left(\boxed{\beta} \cdot (S(x,y) - E(x,y)), \boxed{c}\right)$$



(see Visnjevic et al., 2018 for details)

Method example: LGM New Zealand, South Island

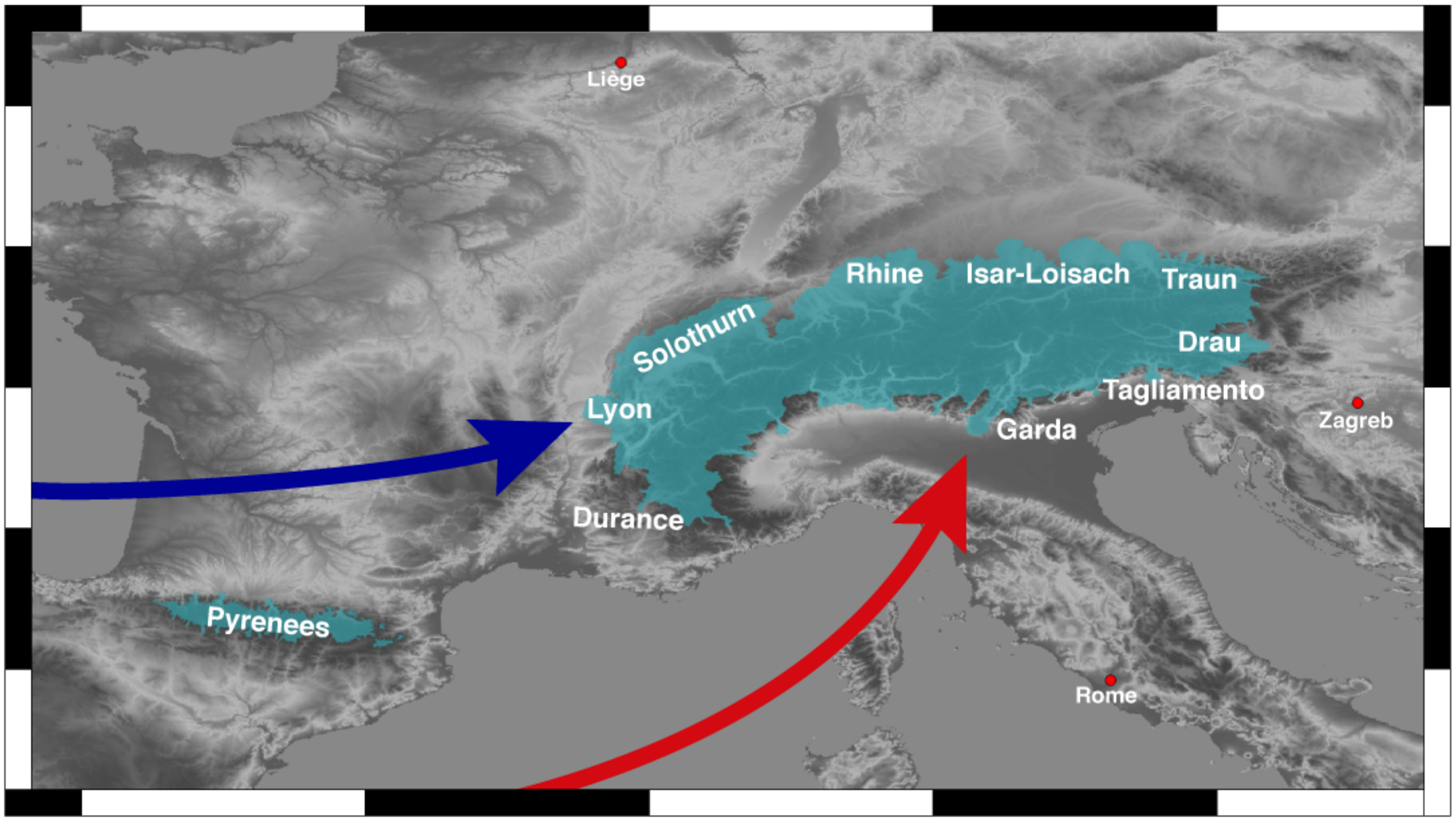




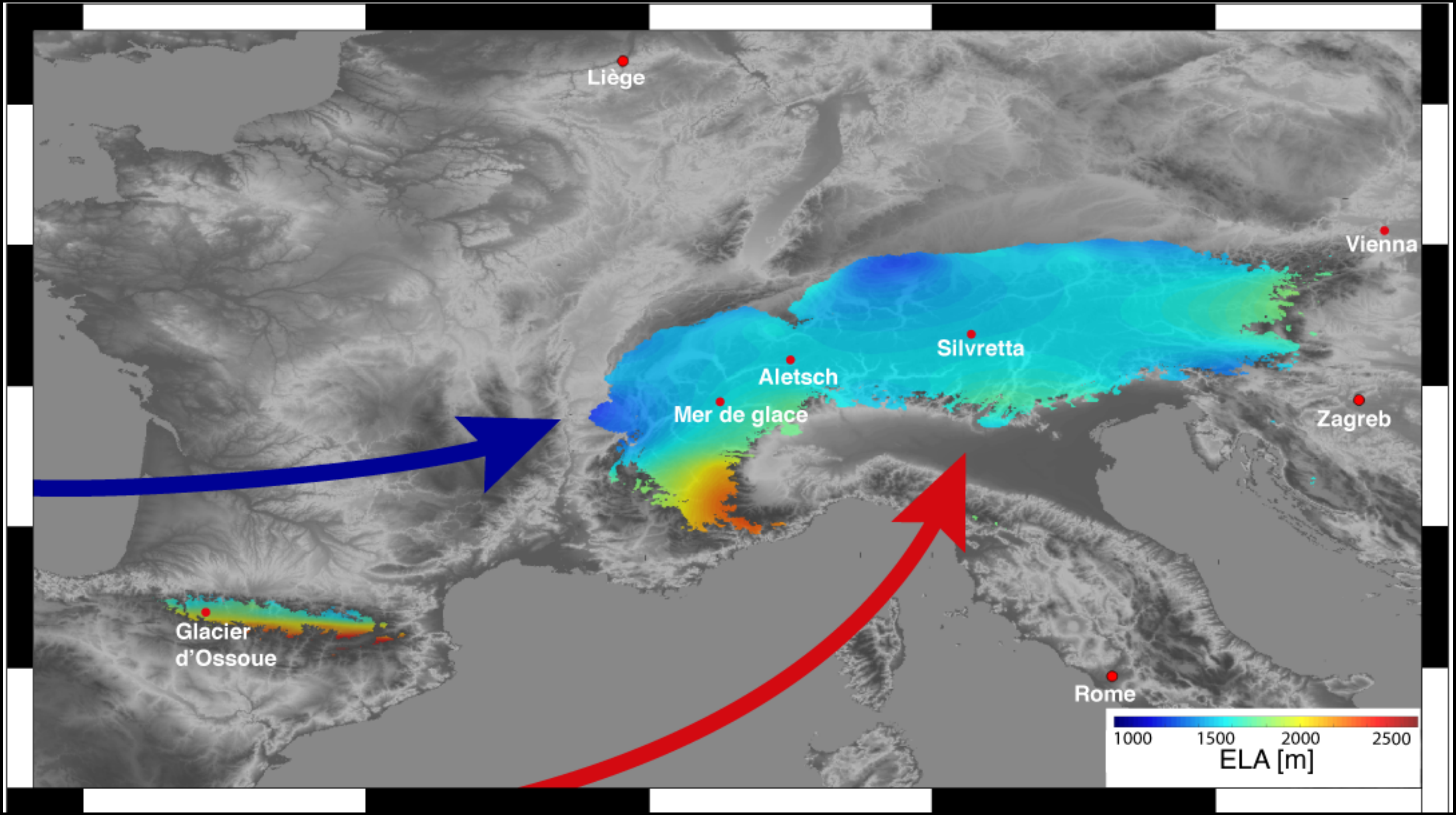
(Visnjevic et al., 2018)

- We invert the mapped ice extent (left) to get a spatially variable ELA field (right)
- In the case of New Zealand the retrieved ELA is dominated by two gradients: N-S gradient – due to latitude change (temperature), and W-E gradient – due to Westerly winds (precipitation)

Proposed climate scenarios for the LGM - can we see evidence of the shift of the Westerlies in our ELA results?

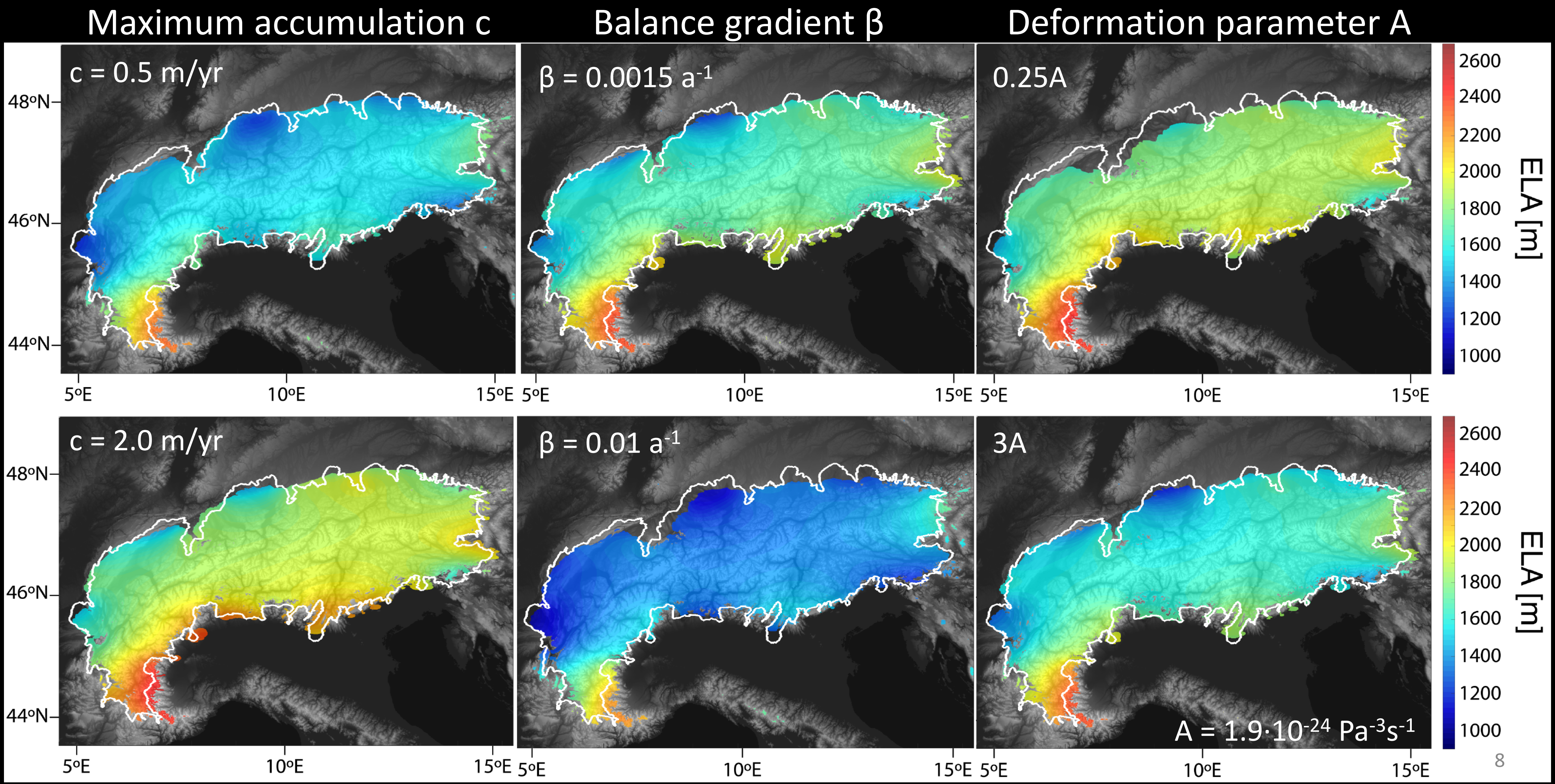


Reconstructed ELA – presenting one of the scenario results



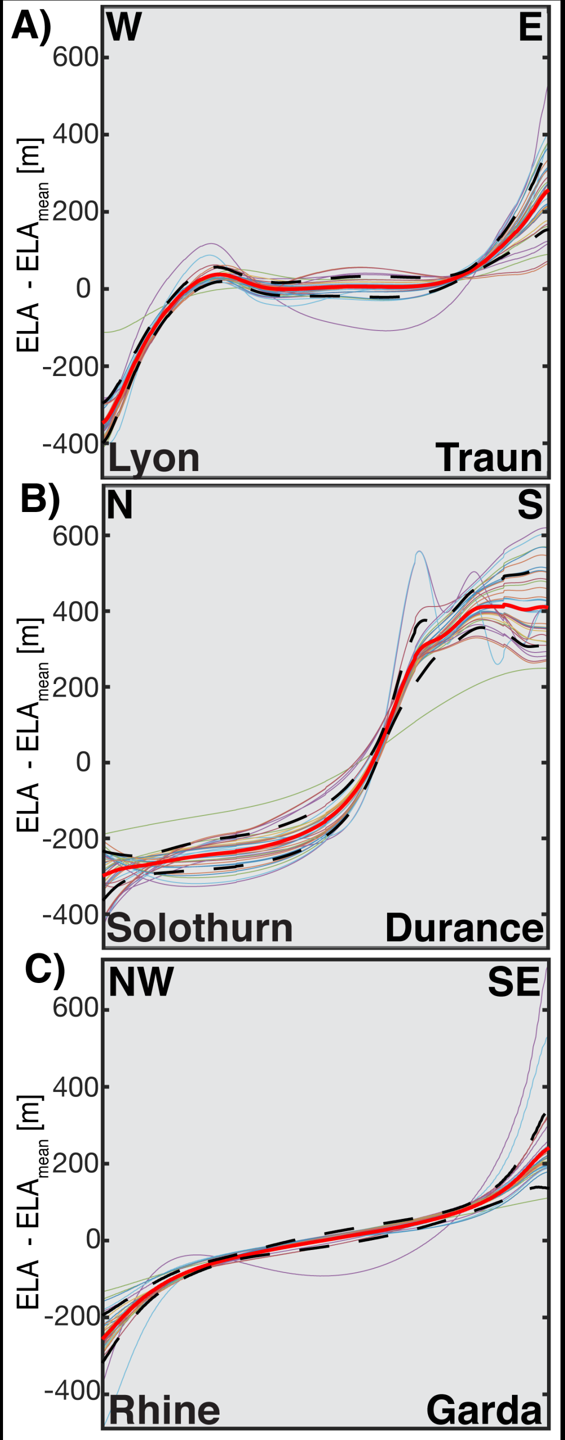
(Visnjevic et al., in review)

Inversion results: Alps sensitivity test

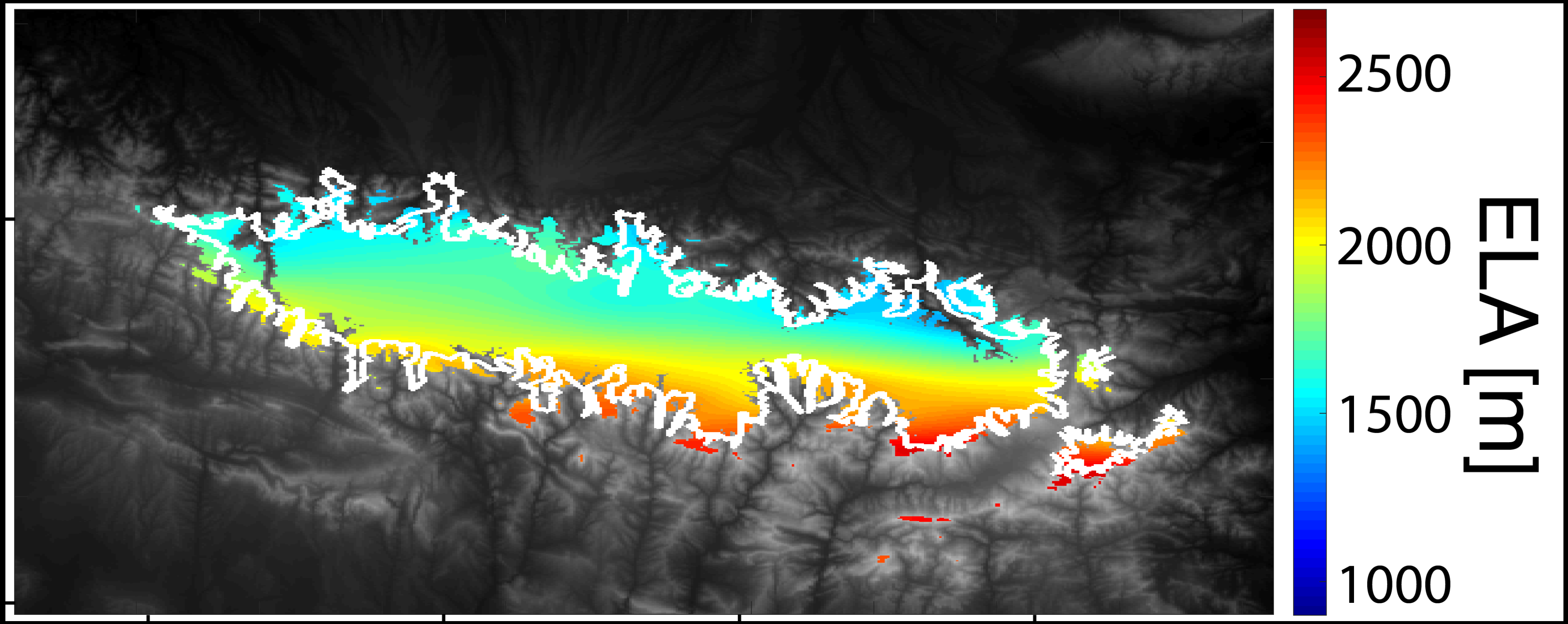


Inversion results: Alps sensitivity test

- 36 inversion scenarios, varying mass balance, ice flow and inversion model parameters
- Observed ice extent can be reproduced for a range of scenarios, each with different ELA values
- All scenarios show a W-E change in the ELA, increasing from west to east
- All scenarios show a N-S change in the ELA in the west and central Alps
- Profiles of modeled ELA with removed mean (right fig) for all the scenarios.



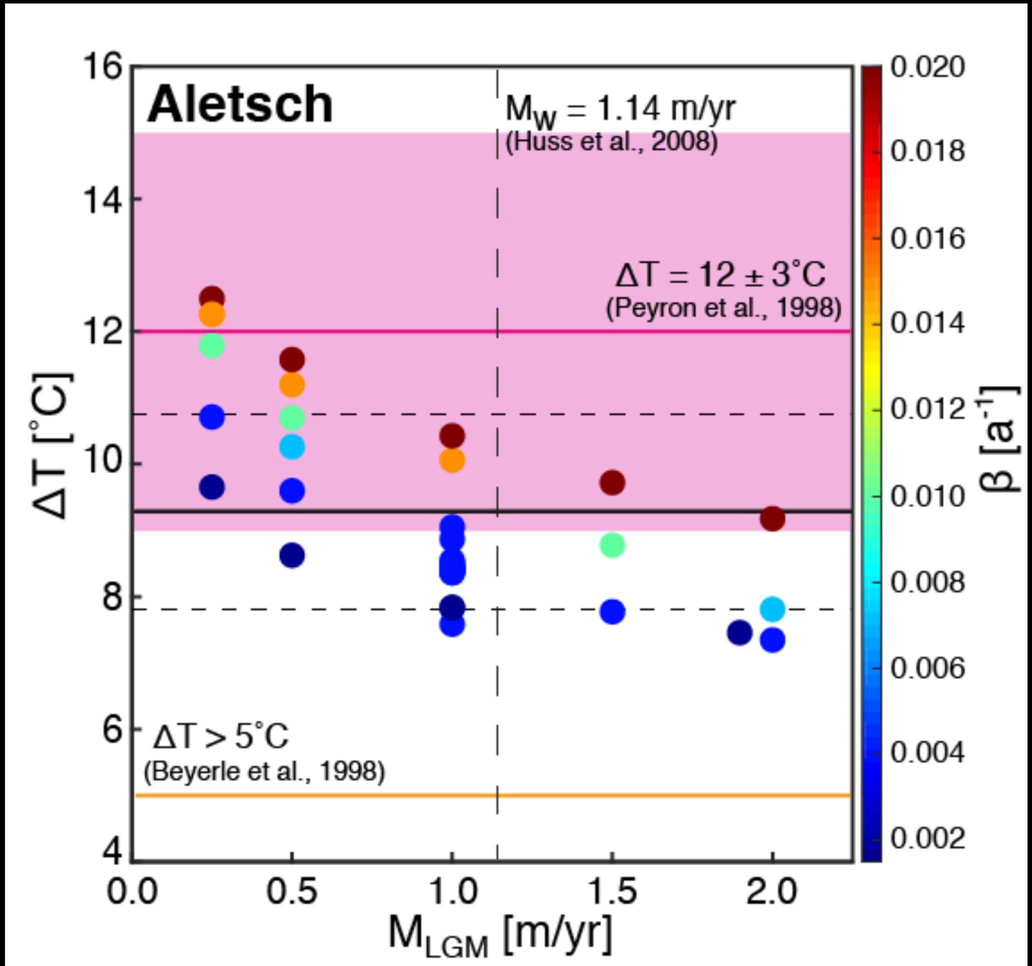
Inversion results: Pyrenees



(Visnjevic et al., in review, b)

- 27 tested scenarios
- Dominating N-S gradient in all of the results, higher ELA in the south, lower in the north

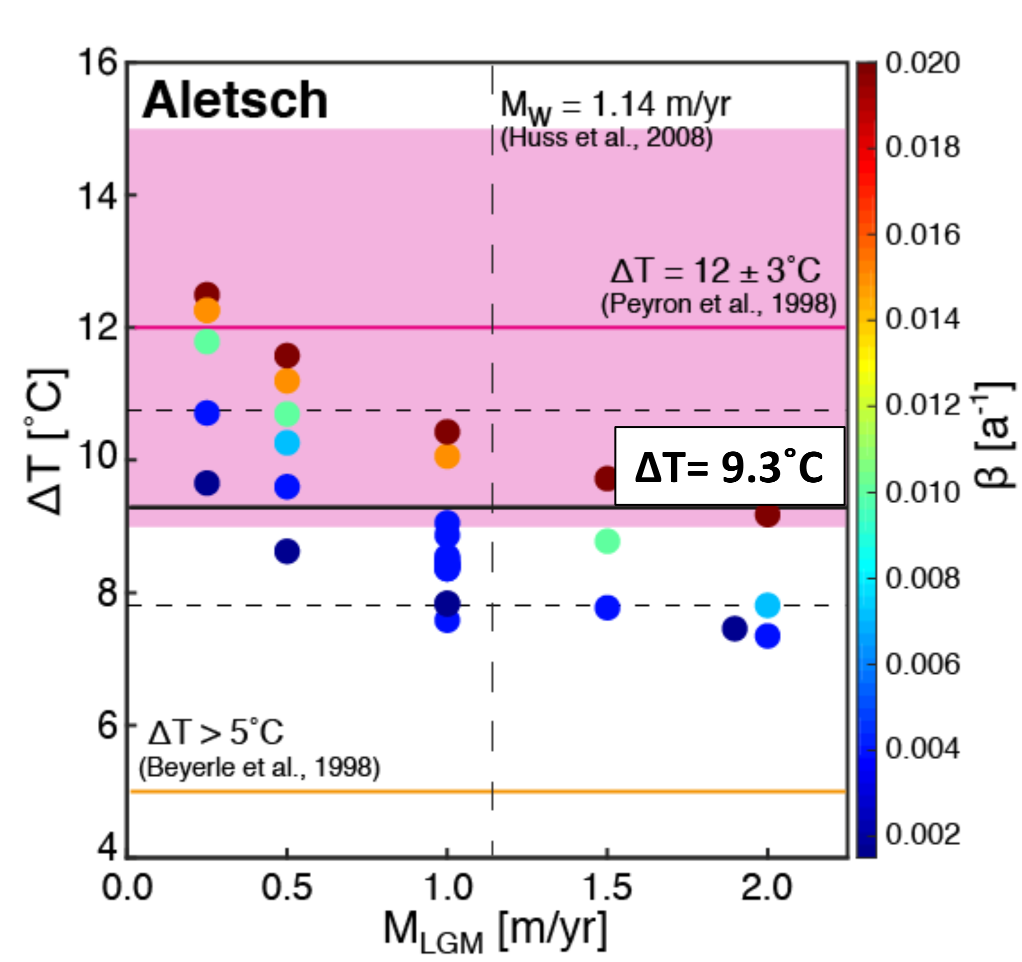
LGM Temperature change

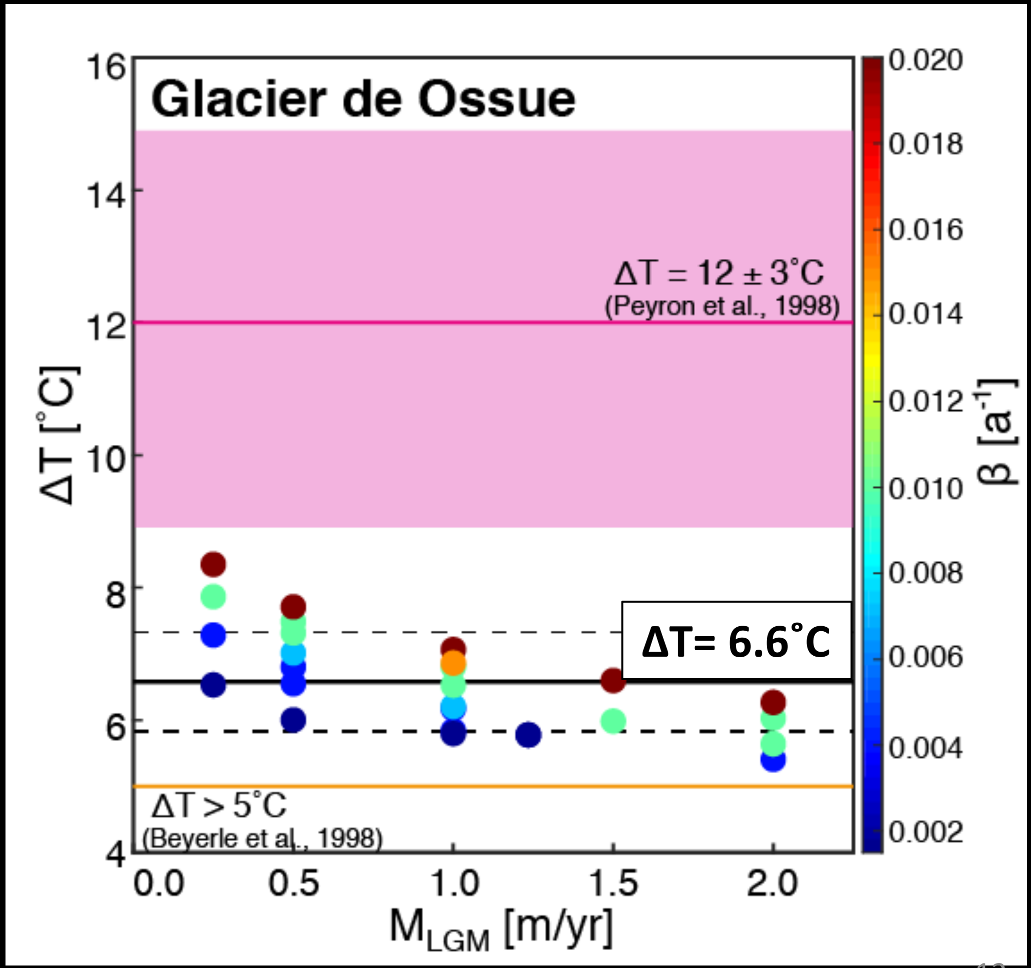


We use a simple relation to translate the difference between present and LGM ELA into temperature change for all of the scenarios

- M_w – present day winter mass balance (Aletsch)
- M_{LGM} – reconstructed mass balance value
- β – mass balance gradient used in the scenario
- ΔT – present day temperature - LGM
- 100 m ΔELA = 0.65˚C (Kuhlemann et al., 2008)
- Lapse rate – 0.65˚C/km

LGM Temperature change





(Visnjevic et al., in review)

Conclusion:

- Mean annual temperature change (ΔMAT) for all scenarios at (2σ):
- Aletsch: 9.3 ± 3˚C
- Mer de Glace: 8.6 ± 3˚C
- Silvretta: 8.0 ± 3˚C
- Glacier de Ossue (Pyrenees): 6.6 ± 1.6˚C
- Independent way of reconstructing paleo temperatures
- Temperature change for a range of different climate scenarios falls within the reported uncertainty of pollen data
- We can reconcile calculated temperature change values with the ones derived by pollen studies (Peyron et al., 1998) if we assume that the precipitation rates during the LGM were around 60% drier than today

Objectives/Conclusion

Objective 1: Use an ice flow model to gain information on the mass balance in the past and how it varies in space

We developed a method to invert the ice extent data to constrain past climate patterns (Visnjevic et al., 2018)

Objective 2: Invert the ice extent data to constrain past climate patterns over the Alps and the Pyrenees

A dominating W-E gradient has been recovered in the Alps and a dominating N-S gradient in the Pyrenees, not supporting the shift of the Westerlies (Visnjevic et al., 2020)

Objective 3: Constrain temperature change over the Alps and the Pyrenees

ΔMAT change Alps: 8 - 9.3 ± 3˚C; Pyrenees: 6.6 ± 1.6˚C (2σ). The error range falls within the uncertainty of pollen data (Visnjevic et al., in review)

Thank you for your attention,
stay safe.

Bonus slide: Implementation of the inverse algorithm

i We start with initial guess for *E*

ii Run the forward model, F(*E*), using the *E* to calculate mass balance rate. Calculate the difference between the mapped ice extent and the modeled one:

$$\gamma = h_{data} - h_{model}$$

iii We update the E field:

$$E = E - \tau_1 \gamma;$$

iv The problem is regularized by applying diffusion to the new *E*

$$E = E + \tau_2 \nabla^2 E \; ;$$

v Repeat step **ii**, until γ is minimized