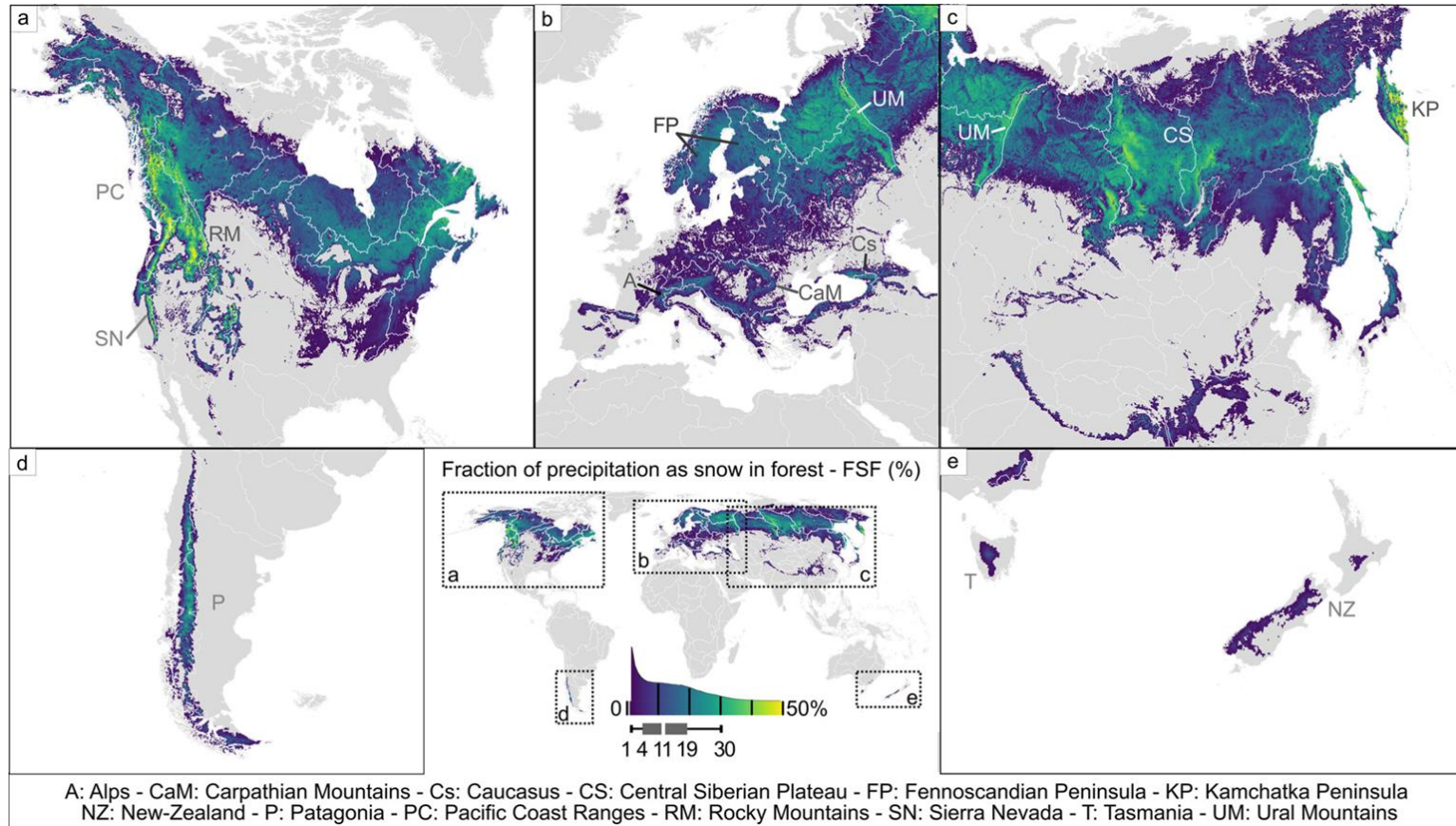


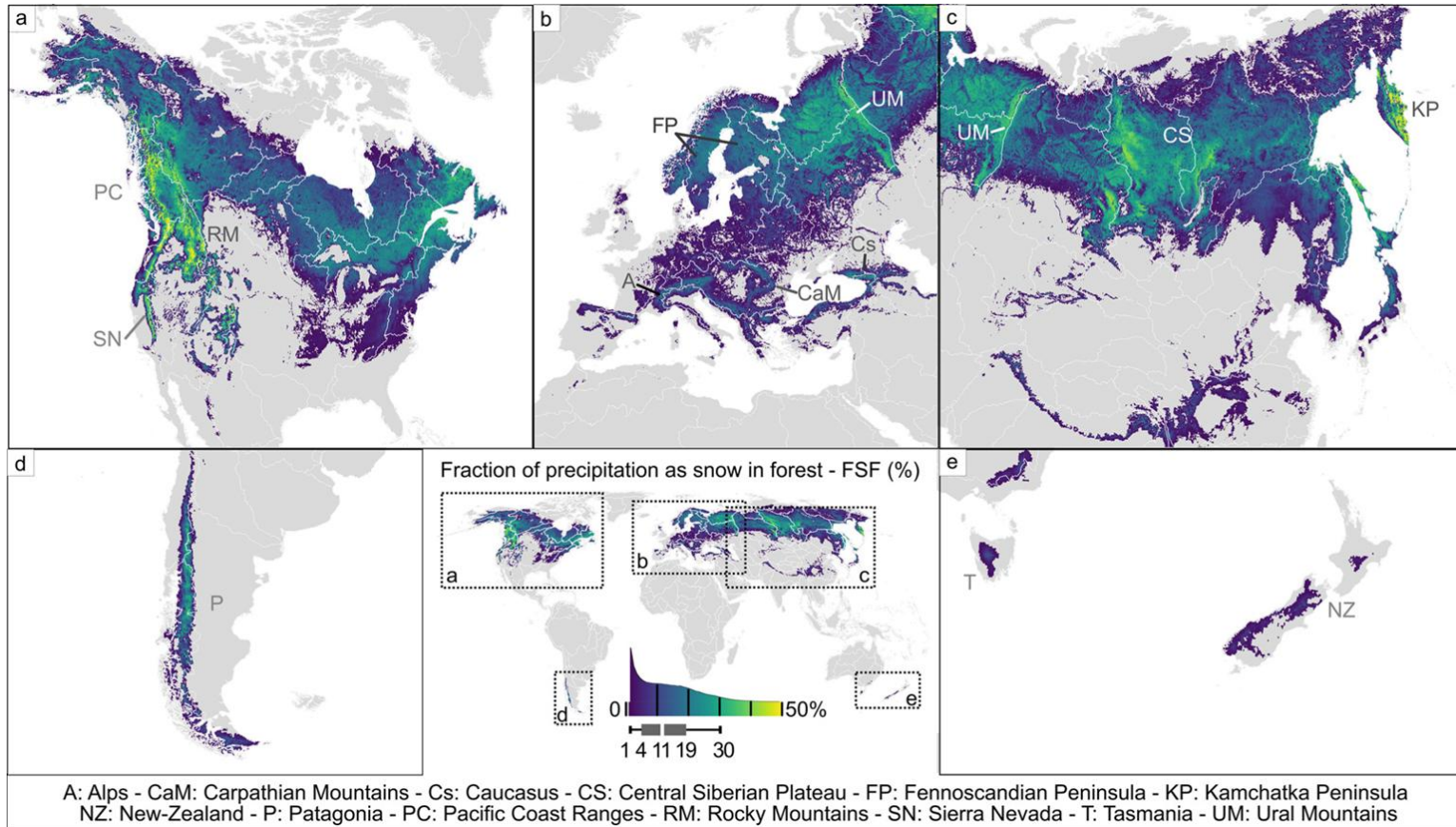
Recent advances in snow data assimilation in forests

Esteban Alonso-Gonzalez
Instituto Pirenaico de Ecología - CSIC

23% of the land mass experiences snowfall in forested areas (Deschamps-Berger et al., 2025)



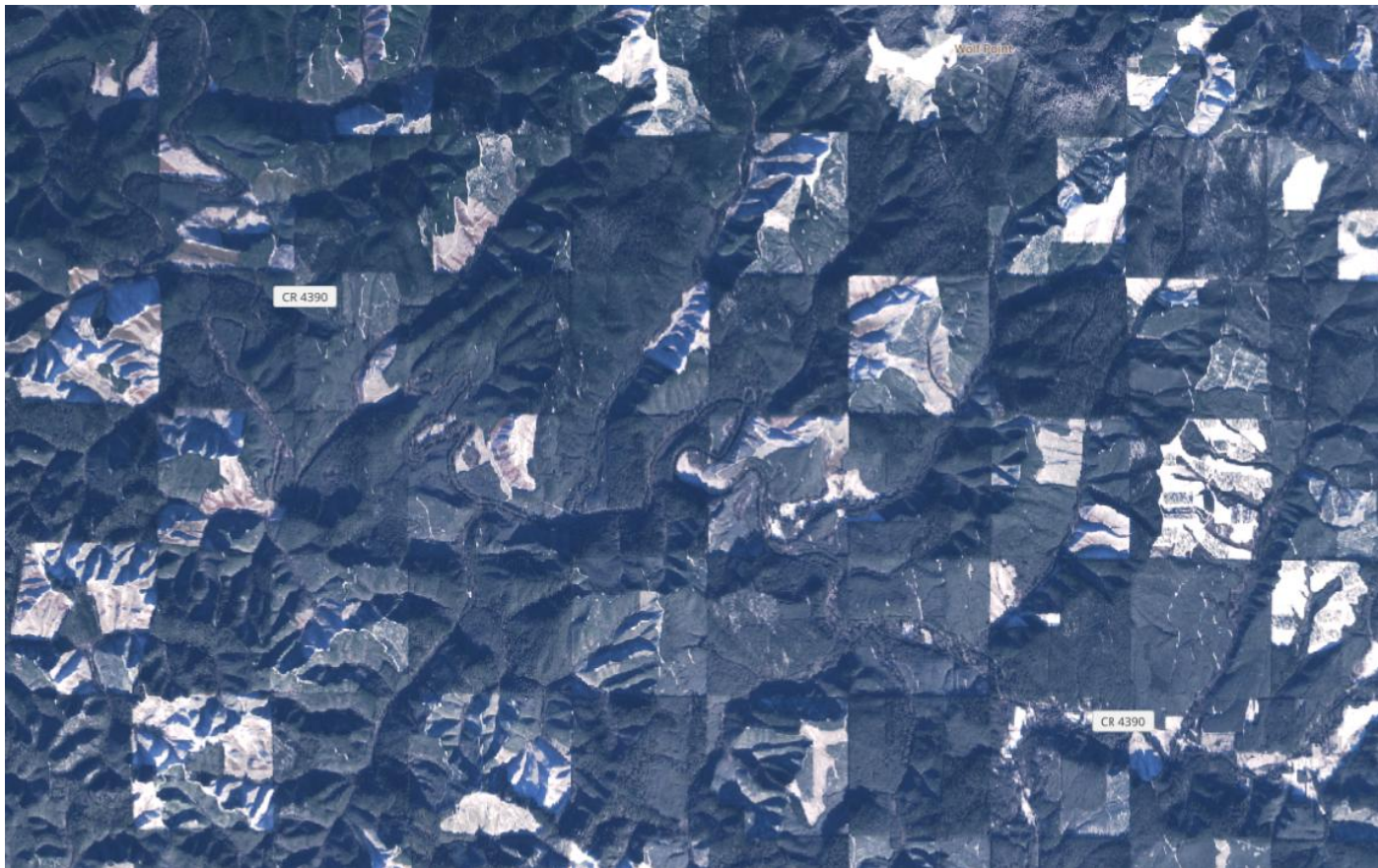
The occlusion of the ground below the forest canopy limits the retrieval of snowpack information from remote sensing tools. If there is no data, is there no data assimilation (?)



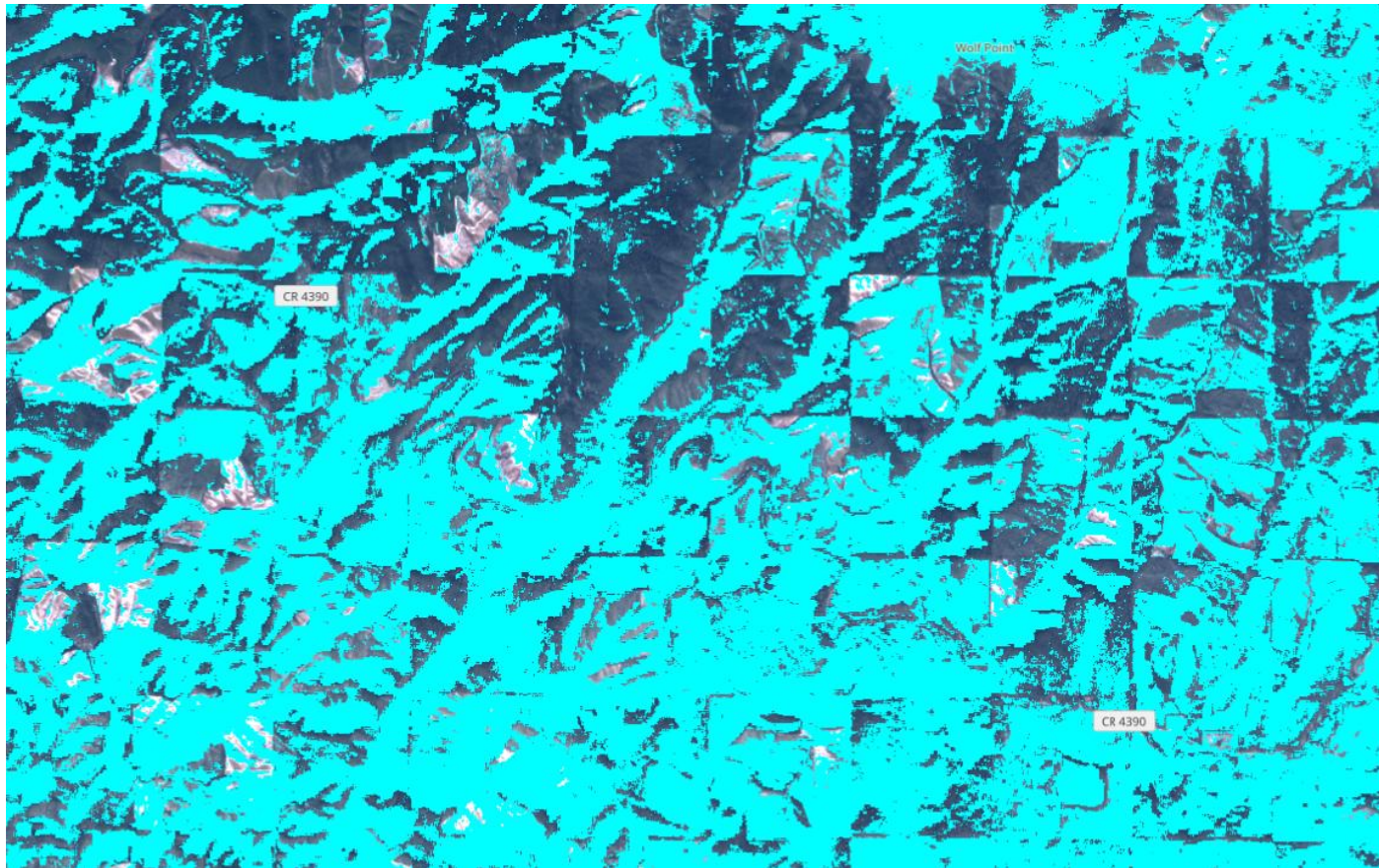


Spanish Pyrenees 2026 (E. Izaguirre)

- Many forests sustaining deep snowpacks are found in boreal and alpine areas, where **forests are sparse**
- It is **possible to retrieve information** of the snowpack in forest gaps
- The key is to **propagate the information** from forest gaps towards beneath the canopy (no observations)



Real (RGB) satellite image of a presumably constant snow cover (white area) in a checkerboard forest in Oregon (USA) from Sentinel-2 L1C (2017/01/06, S.Gascoin)

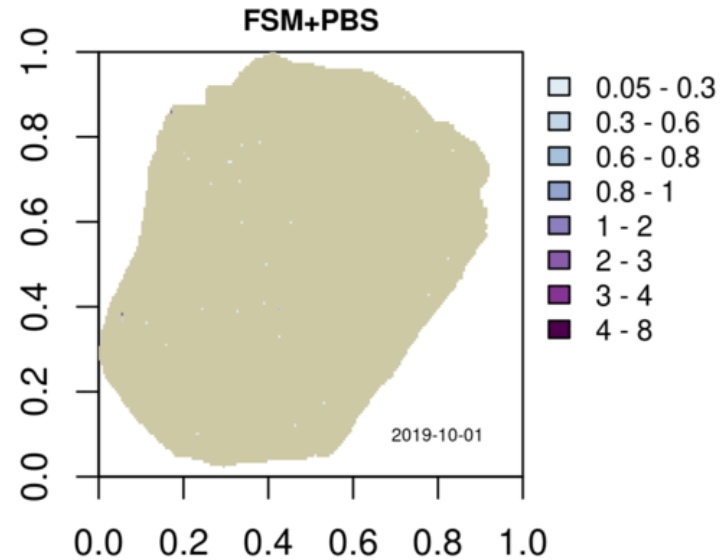
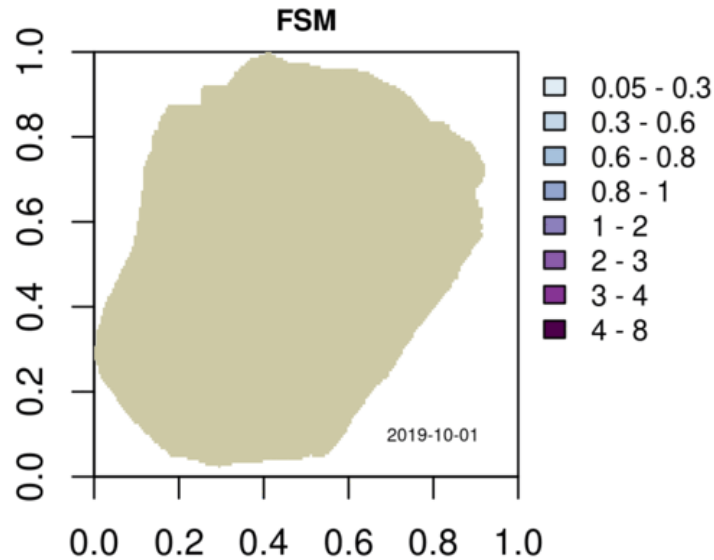


Real (**NDSI**) satellite image of a presumably constant snow cover (blue) in a checkerboard forest in Oregon (USA) from Sentinel-2 L1C (2017/01/06)

How to spread the information obtained in forest clearings beneath canopy?

- Snow under trees behaves differently than in clearings
- Not all methods are compatible with the spatial propagation of information (spatiotemporal DA)

MuSA: The Multiple Snow Data Assimilation System



The Multiple Snow Data Assimilation System (MuSA v1.0)

Esteban Alonso-González^{1,★}, Kristoffer Aalstad^{2,★}, Mohamed Wassim Baba³, Jesús Revuelto⁴,
Juan Ignacio López-Moreno⁴, Joel Fiddes⁵, Richard Essery⁶, and Simon Gascoin¹

Geoscientific
Model Development

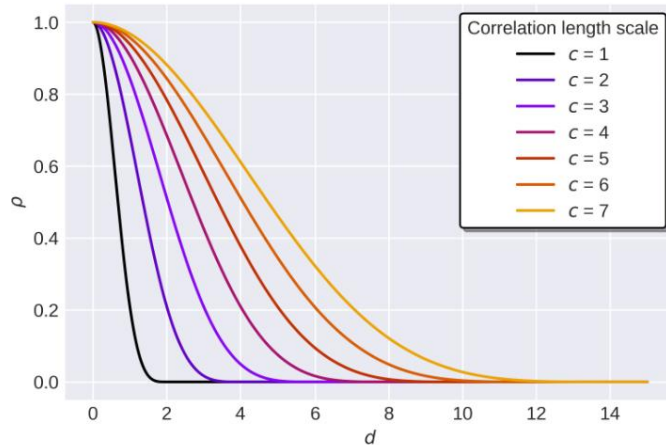
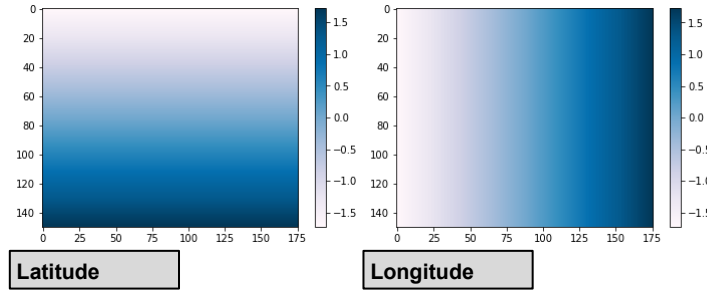
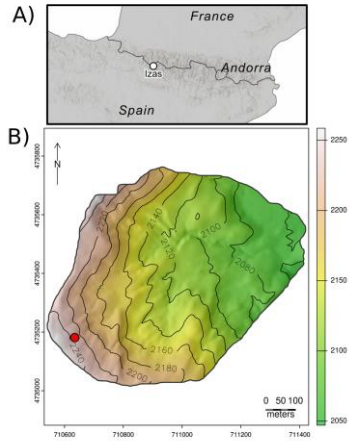


MuSA:

- Distributed runs
- 5m resolution snow depth from Drones.

Spatial propagation:

- Generate correlated prior parameters considering distances between cells
- Some hyperparameters to configure (correlation length scale)



Generate correlated parameters

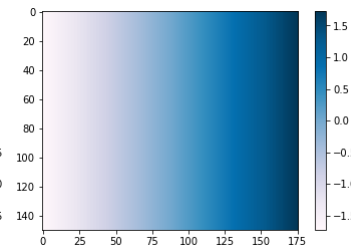
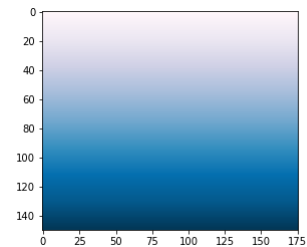
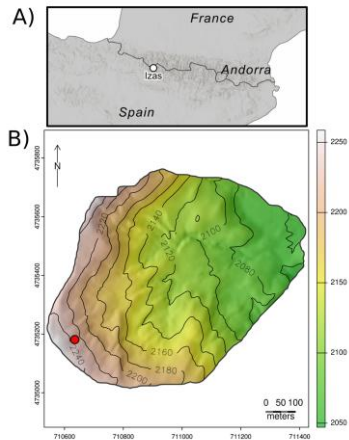
- Gaspari and Cohn Function -> Typical in NWP community
- Correlation length scale -> Important hyperparameter
- How to choose this hyperparameter and the impact of other localization functions has to be investigated

Spatio-temporal information propagation using sparse observations in hyper-resolution ensemble-based snow data assimilation

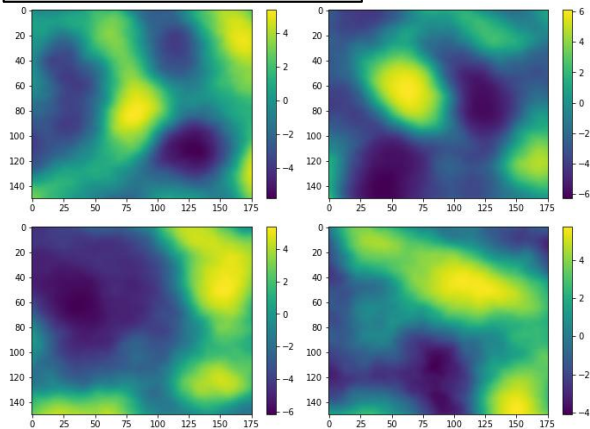
Esteban Alonso-González¹, Kristoffer Aalstad², Norbert Pirk², Marco Mazzolini², Désirée Treichler², Paul Leclercq², Sebastian Westermann², Juan Ignacio López-Moreno³, and Simon Gascoin¹

Spatial propagation:

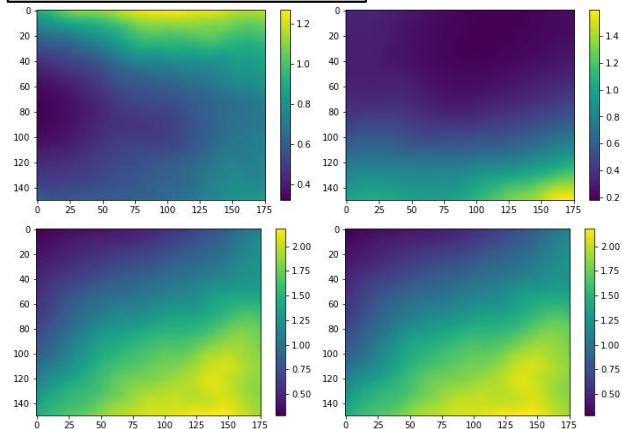
- Generate correlated prior parameters considering euclidean distances between cells
- Some hyperparameters to configure (correlation length scale)
- Example of 4 member ensemble



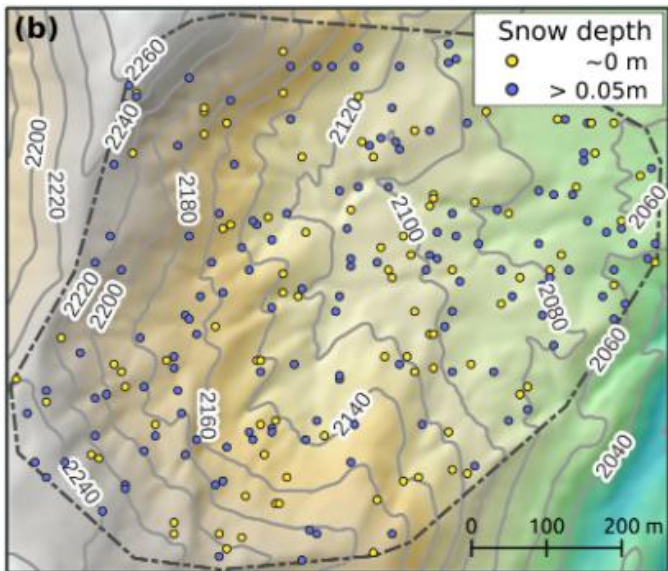
Small correlation length scale



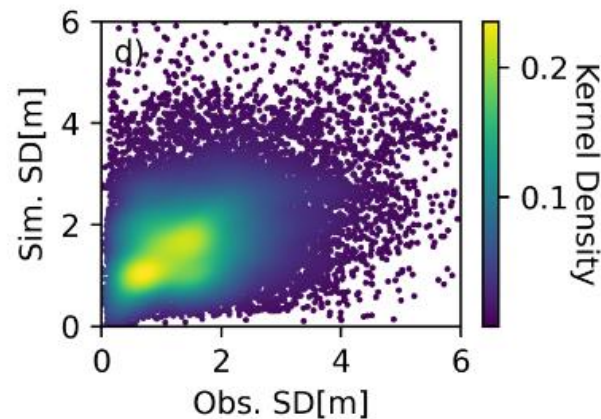
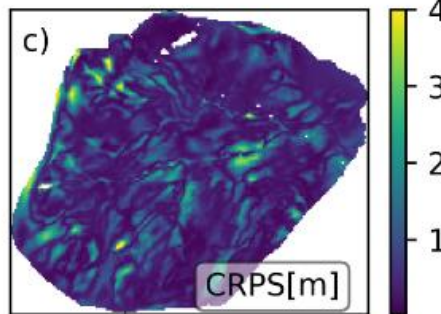
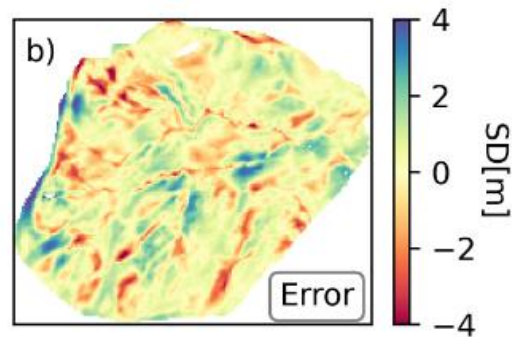
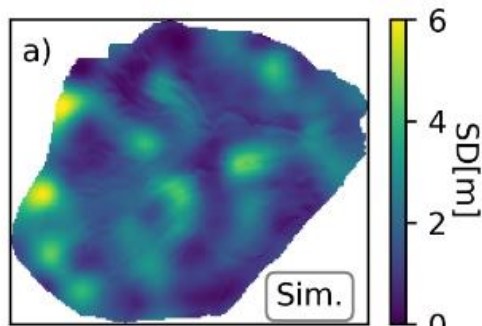
Big correlation length scale

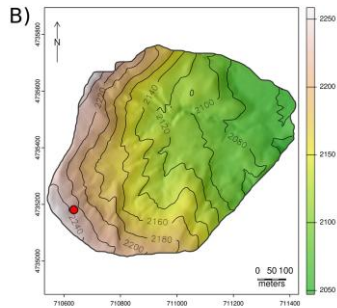


MuSA: The Multiscale Snow Data Assimilation System



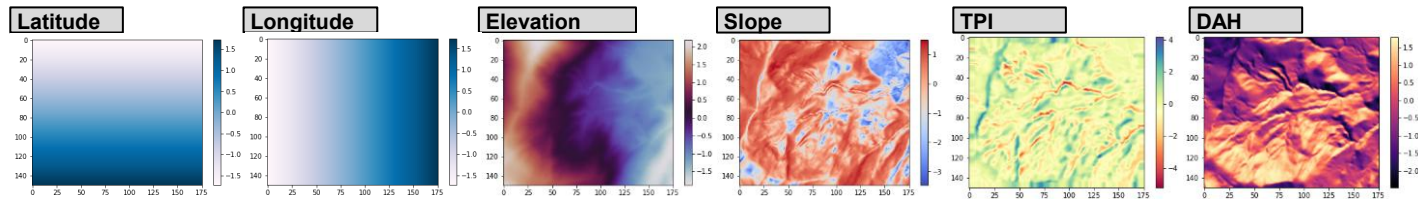
Using northing & easting to map similarities





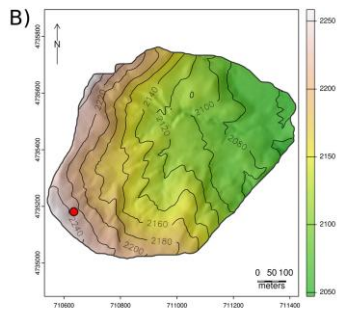
Spatial propagation:

- Generate prior parameters considering ~~Euclidean~~ Mahalanobis! distances between cells
- Some hyperparameters to configure (correlation length scale)



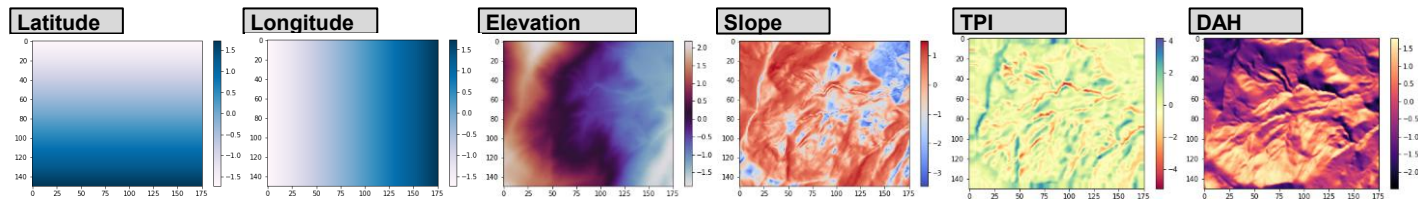
“Small” correlation length scale

“Big” correlation length scale

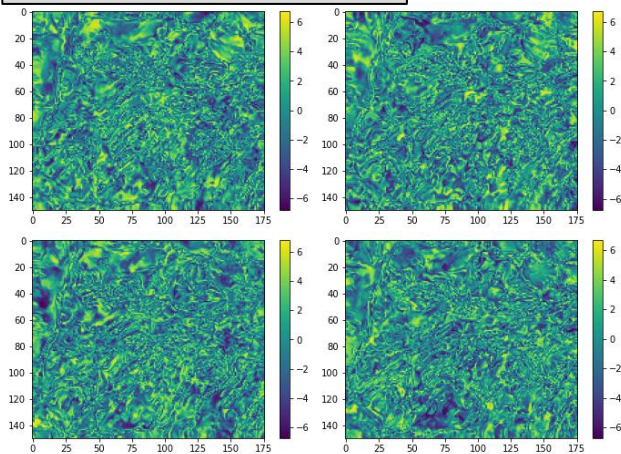


Spatial propagation:

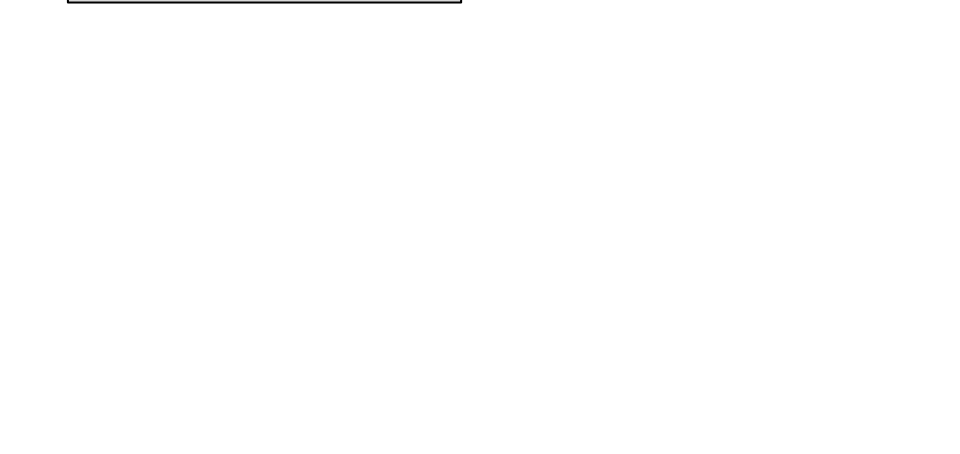
- Generate prior parameters considering ~~Euclidean~~ Mahalanobis! distances between cells
- Some hyperparameters to configure (correlation length scale)

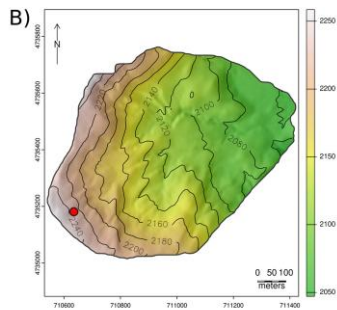


“Small” correlation length scale



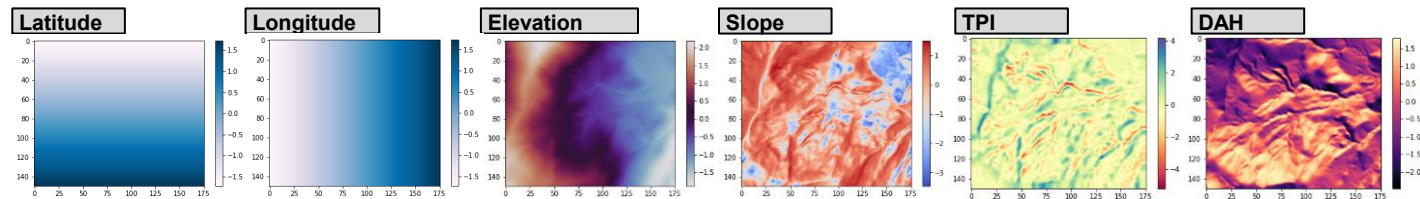
“Big” correlation length scale



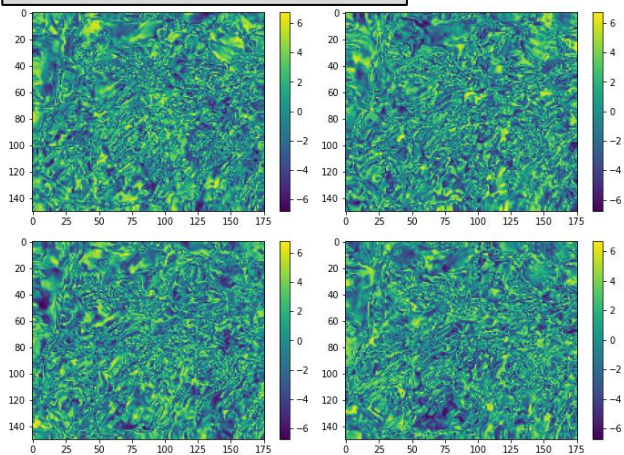


Spatial propagation:

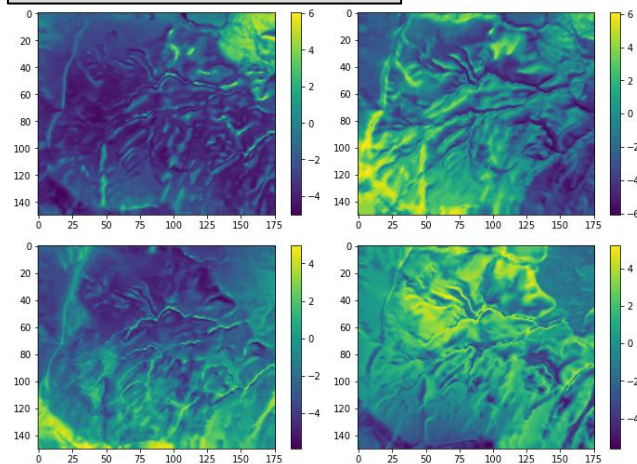
- Generate prior parameters considering ~~Euclidean~~ Mahalanobis! distances between cells
- Some hyperparameters to configure (correlation length scale)



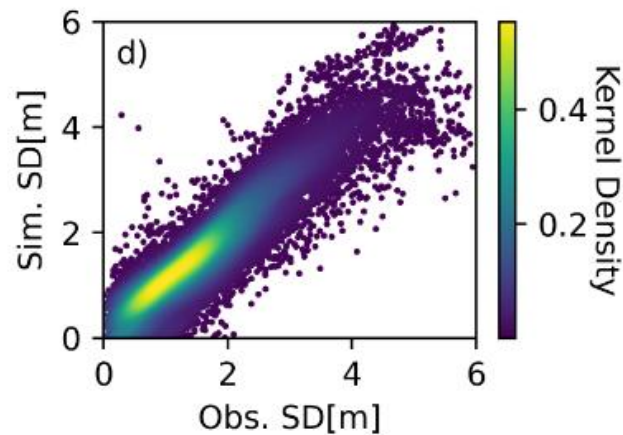
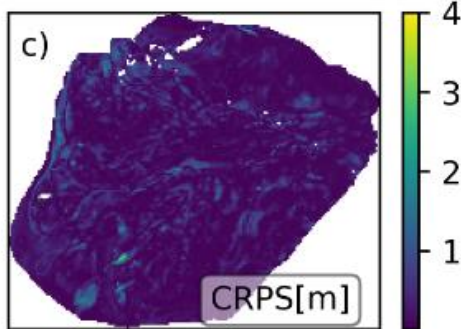
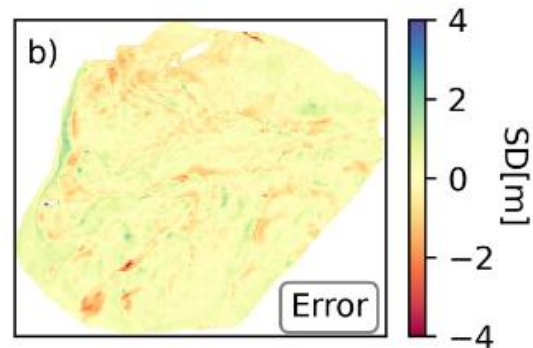
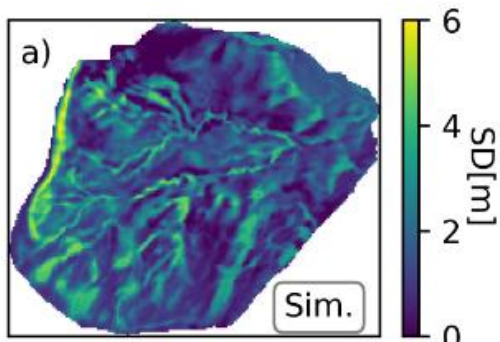
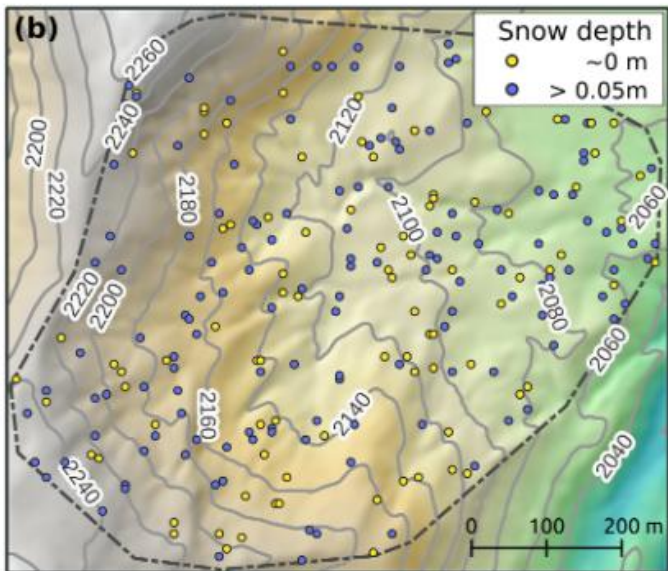
“Small” correlation length scale

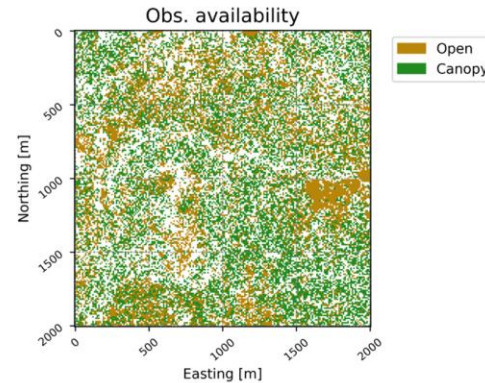
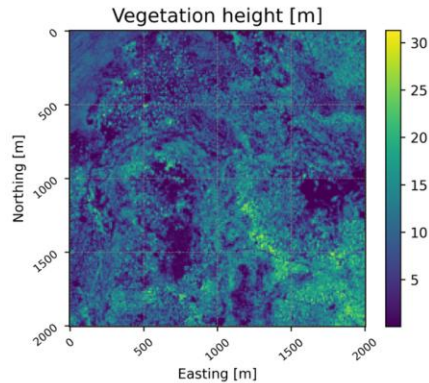
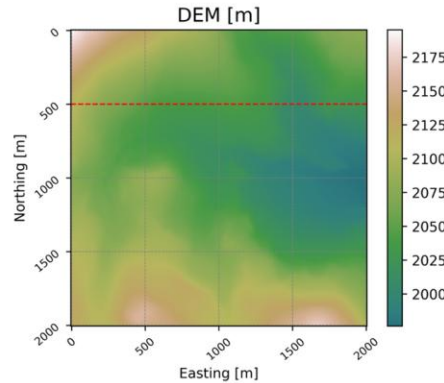


“Big” correlation length scale



MuSA: The Multiscale Snow Data Assimilation System





Experimental setup:

- Sageshen Creek forest
- DA lidar based snow depth (10m)
- Obs in clearings are assimilated
- Obs beneath the canopy are used for validation

MuSA improvements:

- Sparse linear algebra
- Kd-tree distance mapping
- Activate canopy module in FSM2

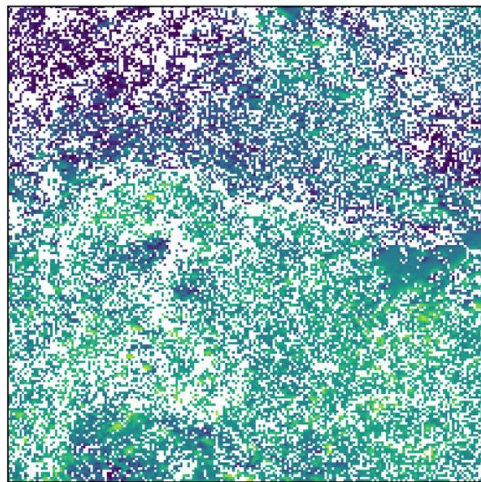
Ensemble-based data assimilation improves hyperresolution snowpack simulations in forests

Esteban Alonso-González¹, Adrian Harpold², Jessica D. Lundquist³, Cara Piske^{2,4}, Laura Sourp^{5,6}, Kristoffer Aalstad⁷, and Simon Gascoin⁵

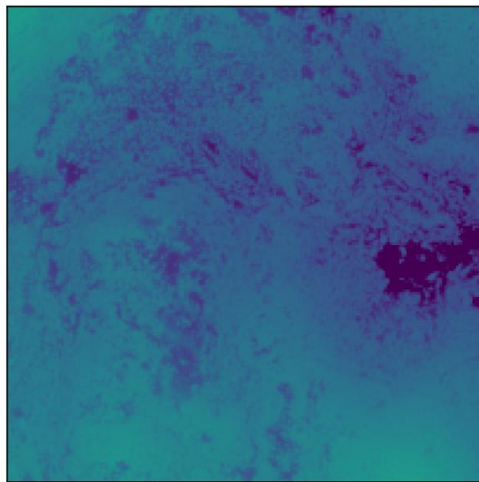
The Cryosphere



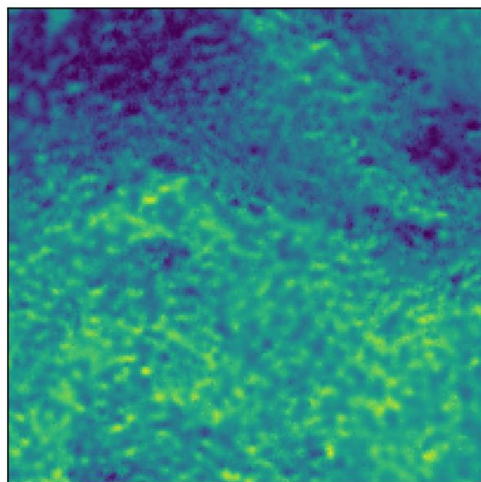
All Obs.



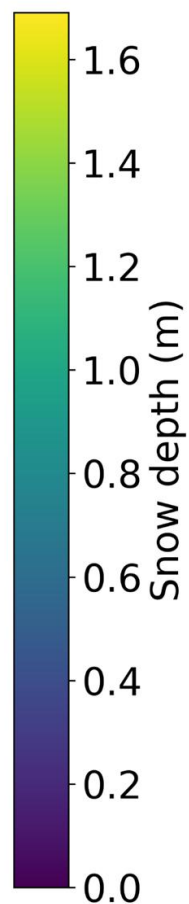
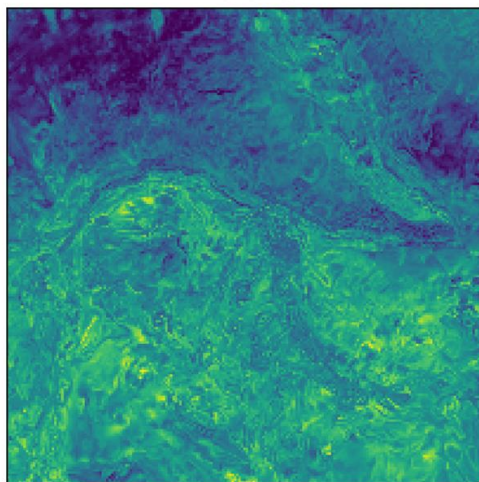
Reference



Eu50

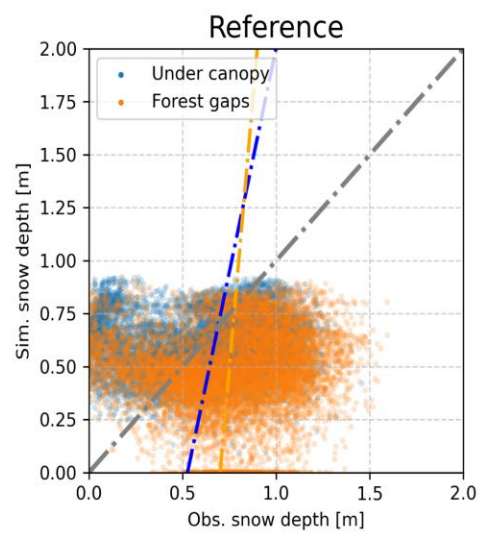


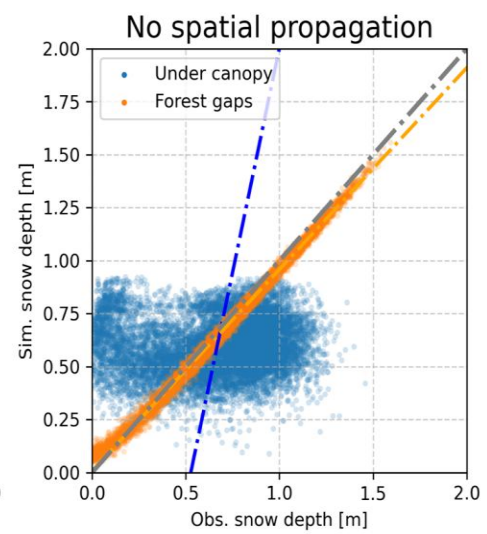
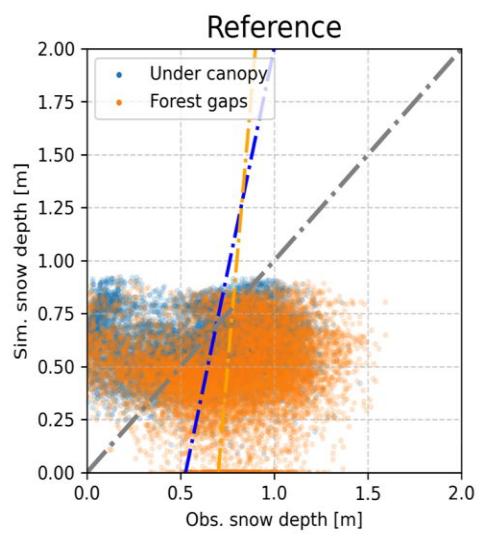
Ma0.5

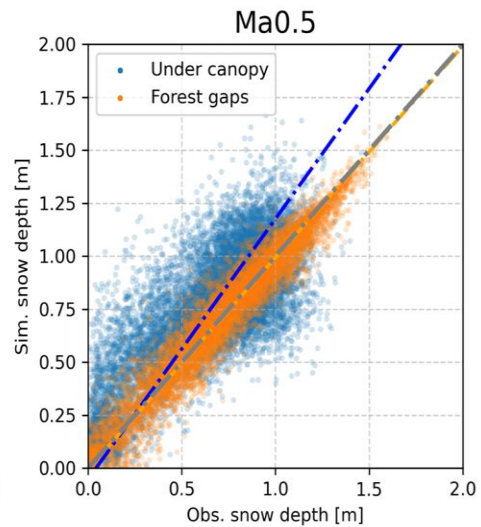
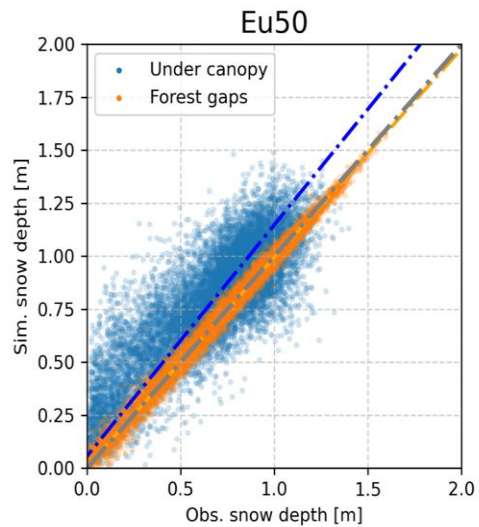
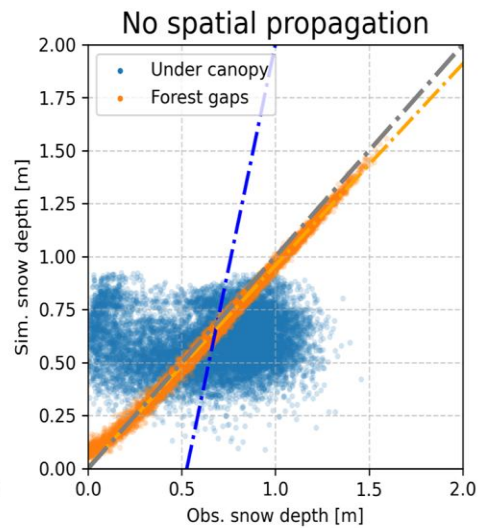
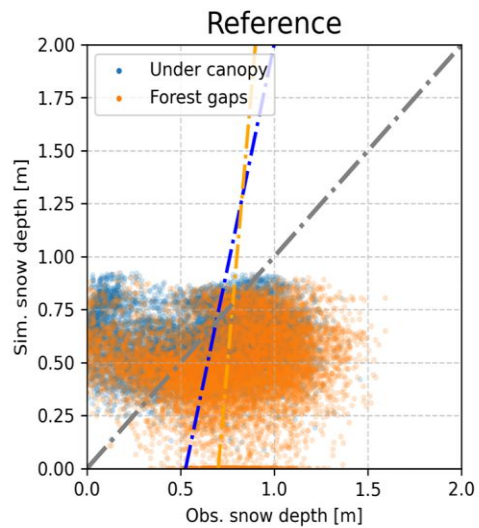


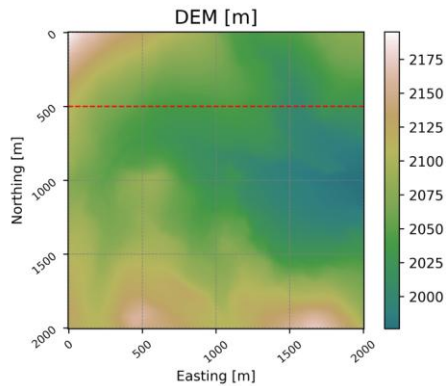
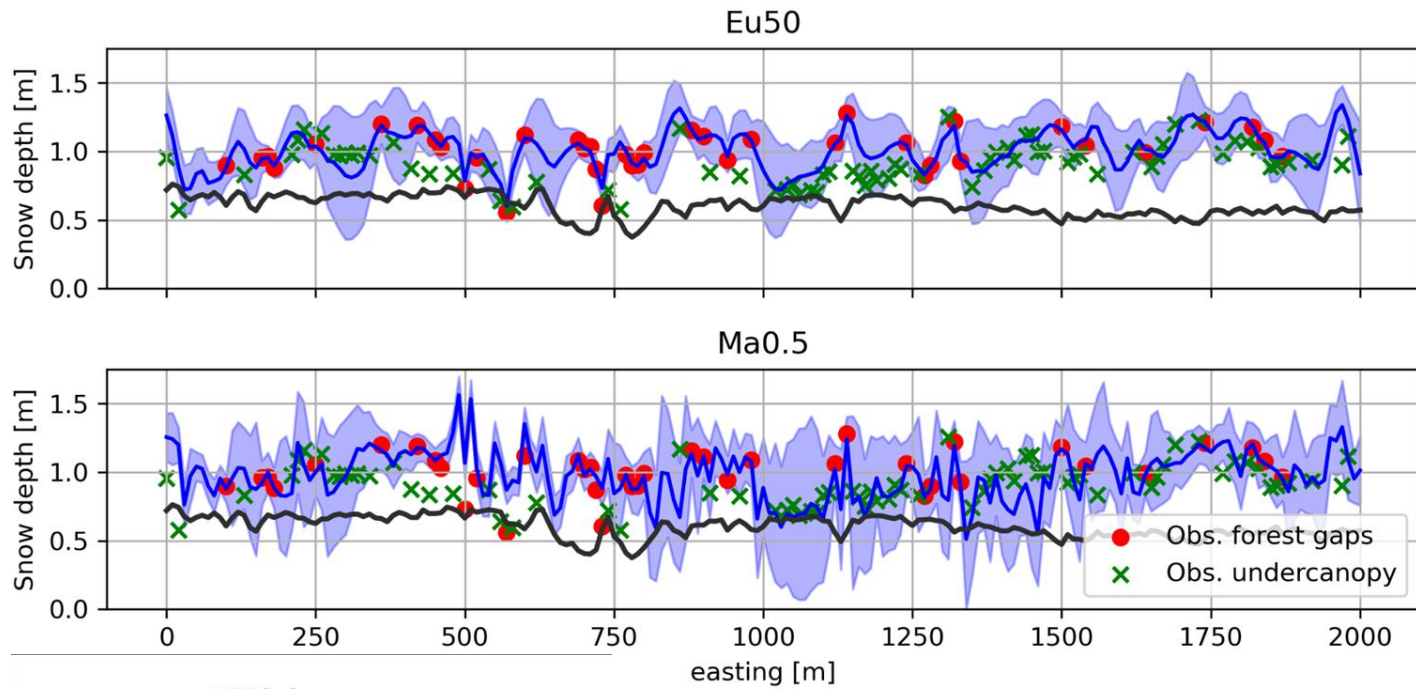
MuSA improvements:

- Spatially complete simulations based on incomplete observations





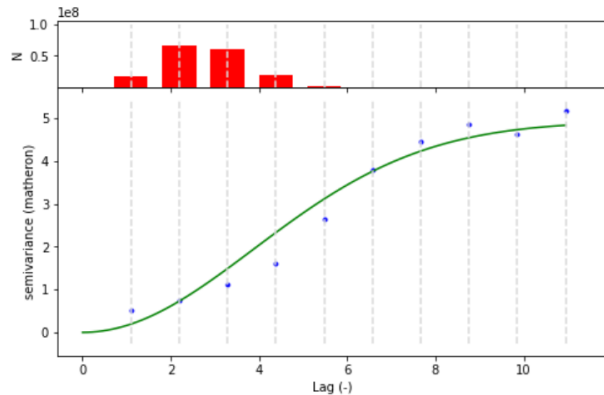




- East- West snow depth profile of posterior mean and standard deviation

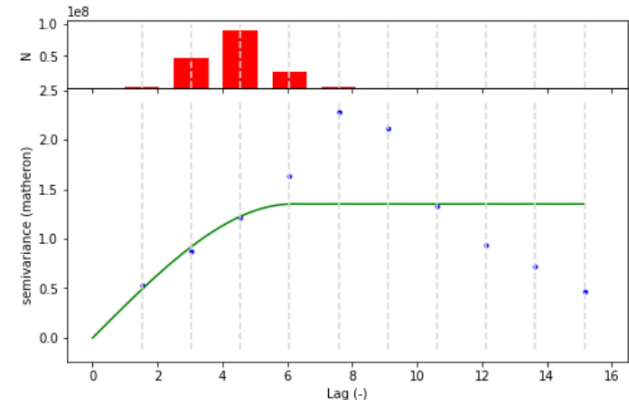
What remains to be done

- Propagate information from forest gaps under canopy
 - In which space? -> Define/find “better” dimensions
 - Which localization function? -> Explore new kernels
 - Which parameters to update? -> Where does the uncertainty come from?
 - Effect of mixed pixel -> Use the vegetation as a new dimension
 - Adapting the (hyper!)space -> ML, Automatic Relevance Determination (ARD)
 - Improve error models
- **We need data to test all our new hypothesis**
 - LiDAR data to obtain snow depth under the canopy for validation



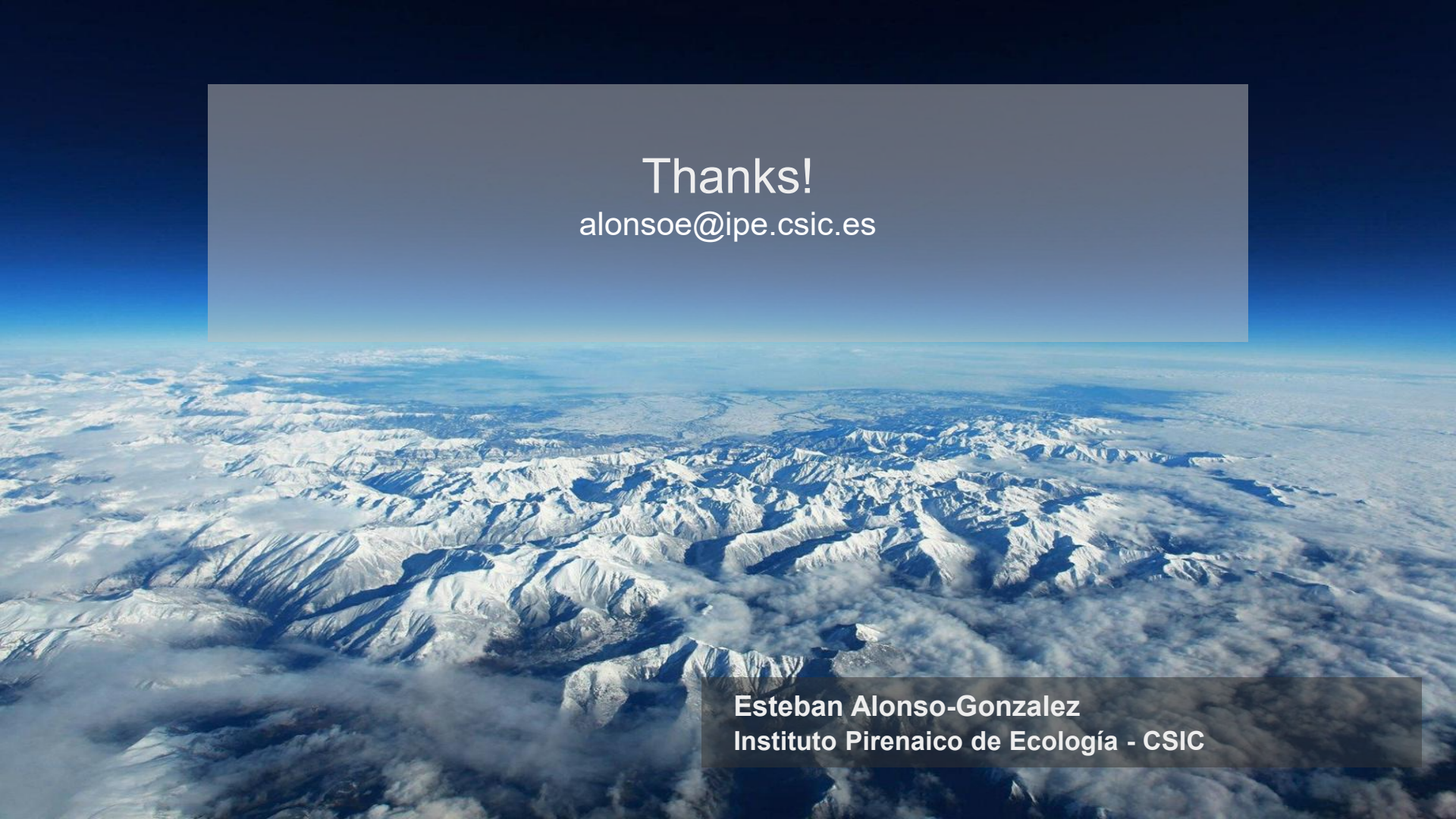
-> **Euclidean distance**
in a (2D) PCA space

Mahalanobis distance <-
in a (6D) Topographical
space



The Roadmap: Towards a generalisable assimilation strategy

- Building an international network
 - Snow / forests interactions changes with the climate
 - Create a representative dataset under different climates
 - Pyrenees, Spain
 - Alps, Switzerland
 - Hokkaido, Japan
 - Finse, Norway
- Improve understanding of (under-canopy) snow dynamics
 - Exploring snow variability in forested areas across multiple dimensions
 - Create tailored covariance functions (Kernes)
- Improve the spread of the information
 - Combine DA and ML
 - Explore different spaces where the information could be propagated
- Run new experiments
 - Conducting experiments in different areas
 - Extend to orbital based remote sensing (S2, ICESat-2....)
 - Release a new MuSA version with the improvements



Thanks!
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