Towards the First Global Multitemporal Data Set of Glacier Outlines

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Introduction

Glaciers are an essential part of ecological systems and extremely sensitive to climate change

Source: Google Images

- Important indicators to monitor climate change
- Major source of freshwater
- Glacier retreat influences:
  - the local hydrology
  - sea level rise
  - positive albedo feedback
  - ecosystems and their biodiversity
  - risk of hazardous events

Existing GeoData

The only existing global inventory is Global Land Ice Measurements from Space (GLIMS). However, it suffers from several problems:

- Low temporal resolution (e.g., some glaciers are mapped only once)
- Mapping errors (georeferencing, subjectivities for debris-covered ice, …)
- Not consistent as it is made by many different authors
- Poor metadata (errors, not informative)
- Limited automation (e.g., there are no unique IDs for glaciers)

- Regional glacier inventories generally share the same problems (and often are included in GLIMS)

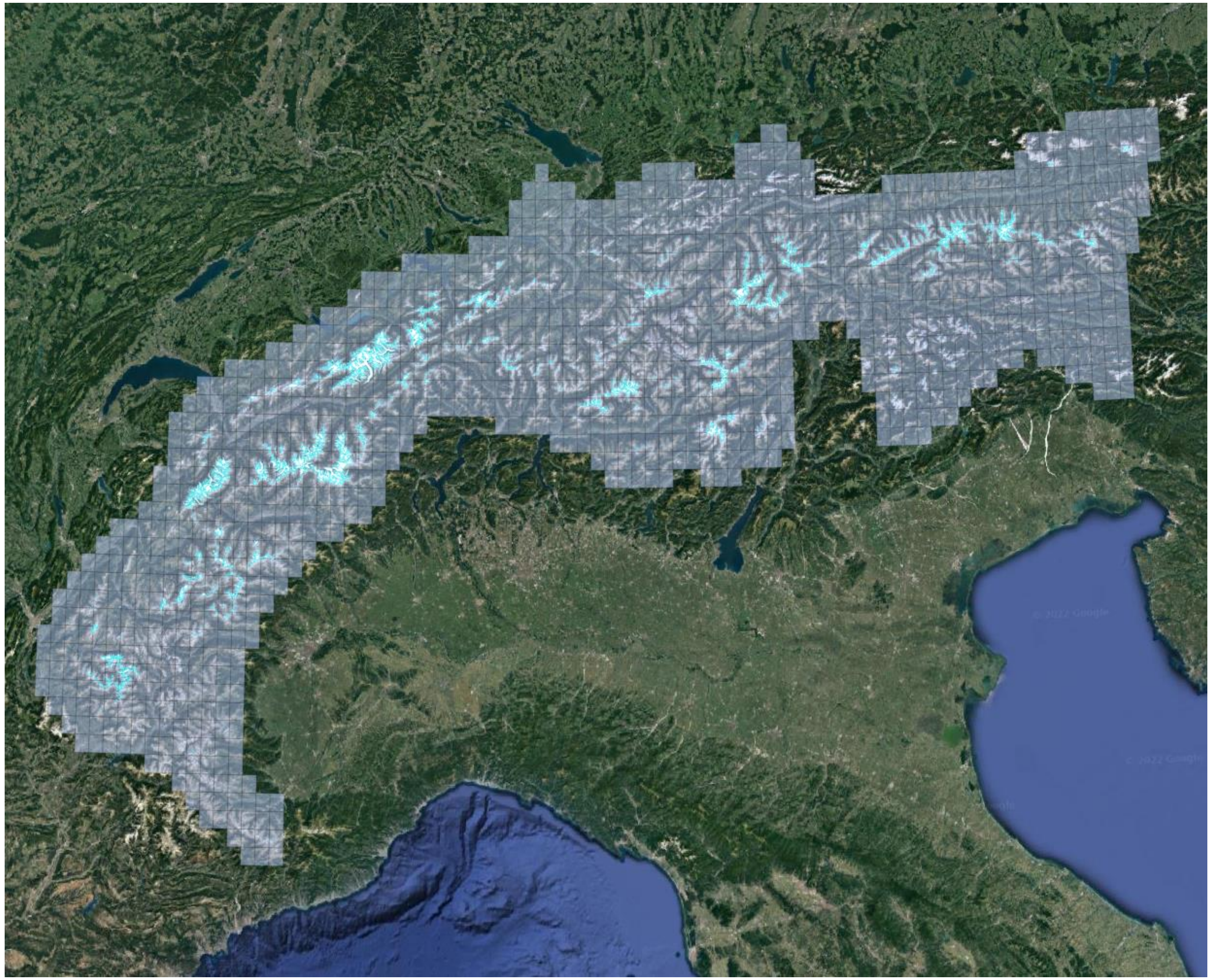
Research Objective

Build multitemporal large-scale glacier inventories and glacier mass balance datasets

MASSIVE Project: The overarching goal is to produce large-scale inventories, including detailed glacier maps and surface mass balance time series and to make them available to the wider scientific community

- We focus on developing fully-automated methods for glacier mapping based on deep learning
- To achieve global-scale mapping, we plan to deploy these methods in a cloud computing environment

Case Study: Mapping the Alps



Input data:

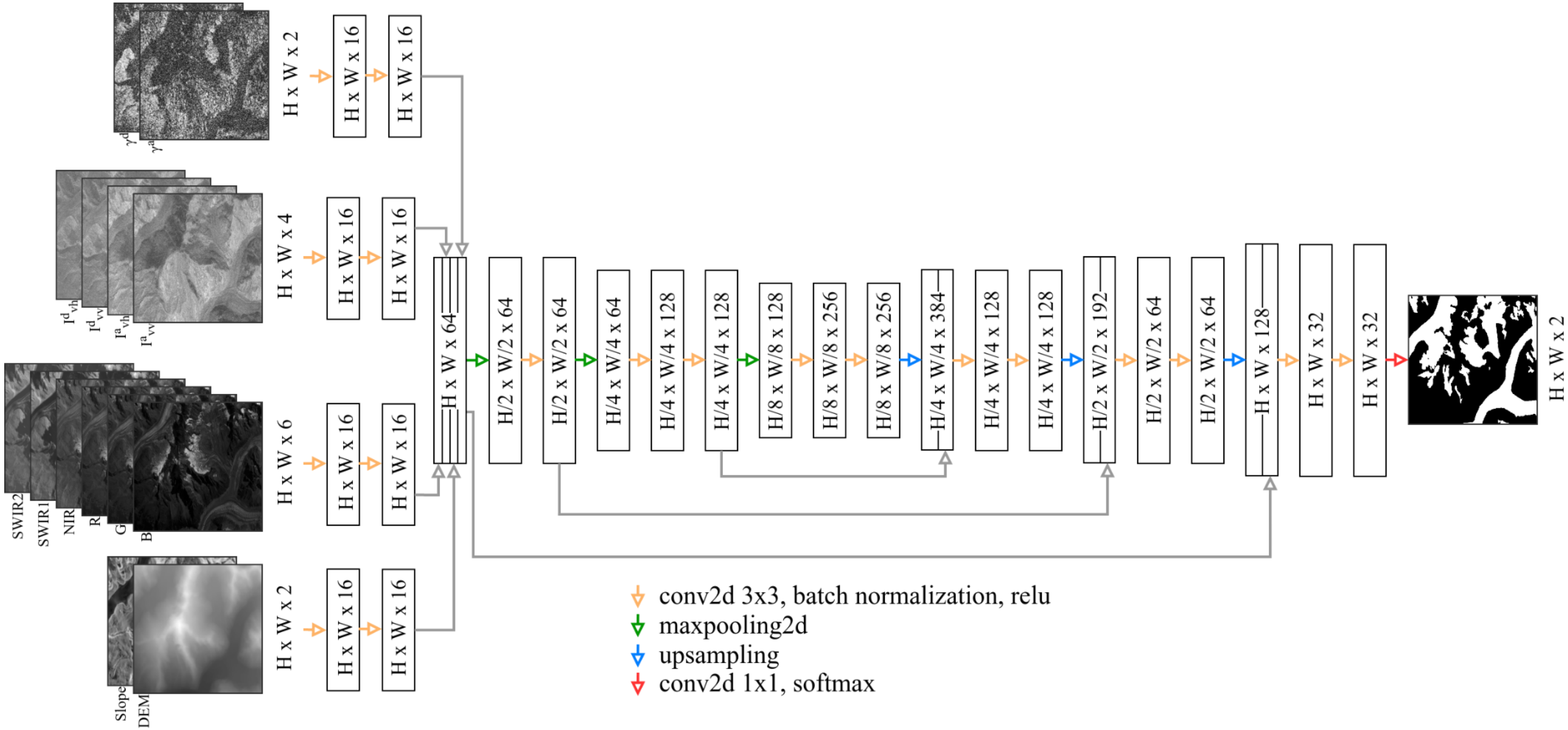
- Sentinel1/2 (optical + SAR)
- DEM
- Reference data: inventory by Paul et al., 2020

Challenges:

- debris-covered parts

Deep Learning Approach

In-network fusion of multi-source data



Case Study Results: Mapping the Alps

Data	Precision	Recall	F1-score	IoU
Random forest				
Optical	0.929	0.828	0.876	0.779
Optical+DEM	0.941	0.857	0.897	0.813
Optical+DEM+SAR	0.944	0.870	0.905	0.827
U-Net-based method				
Optical	0.946	0.893	0.919	0.850
Optical+DEM	**0.950**	0.906	0.928	0.865
Optical+DEM+SAR	0.948	**0.917**	**0.932**	**0.873**

- U-Net-based methods outperform random forest
- Adding DEM and SAR data increases the performance (especially, for the glacier tongues)

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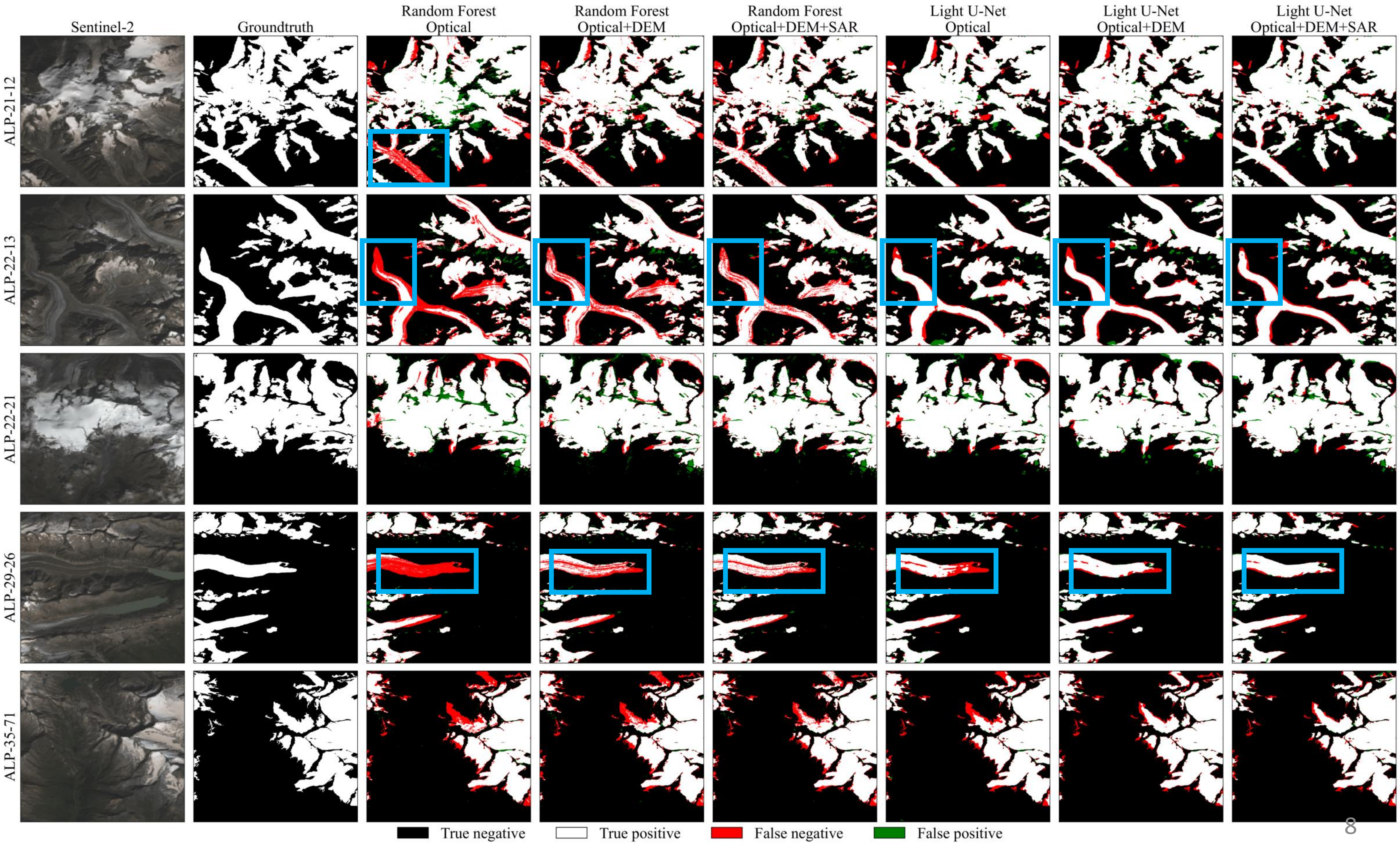
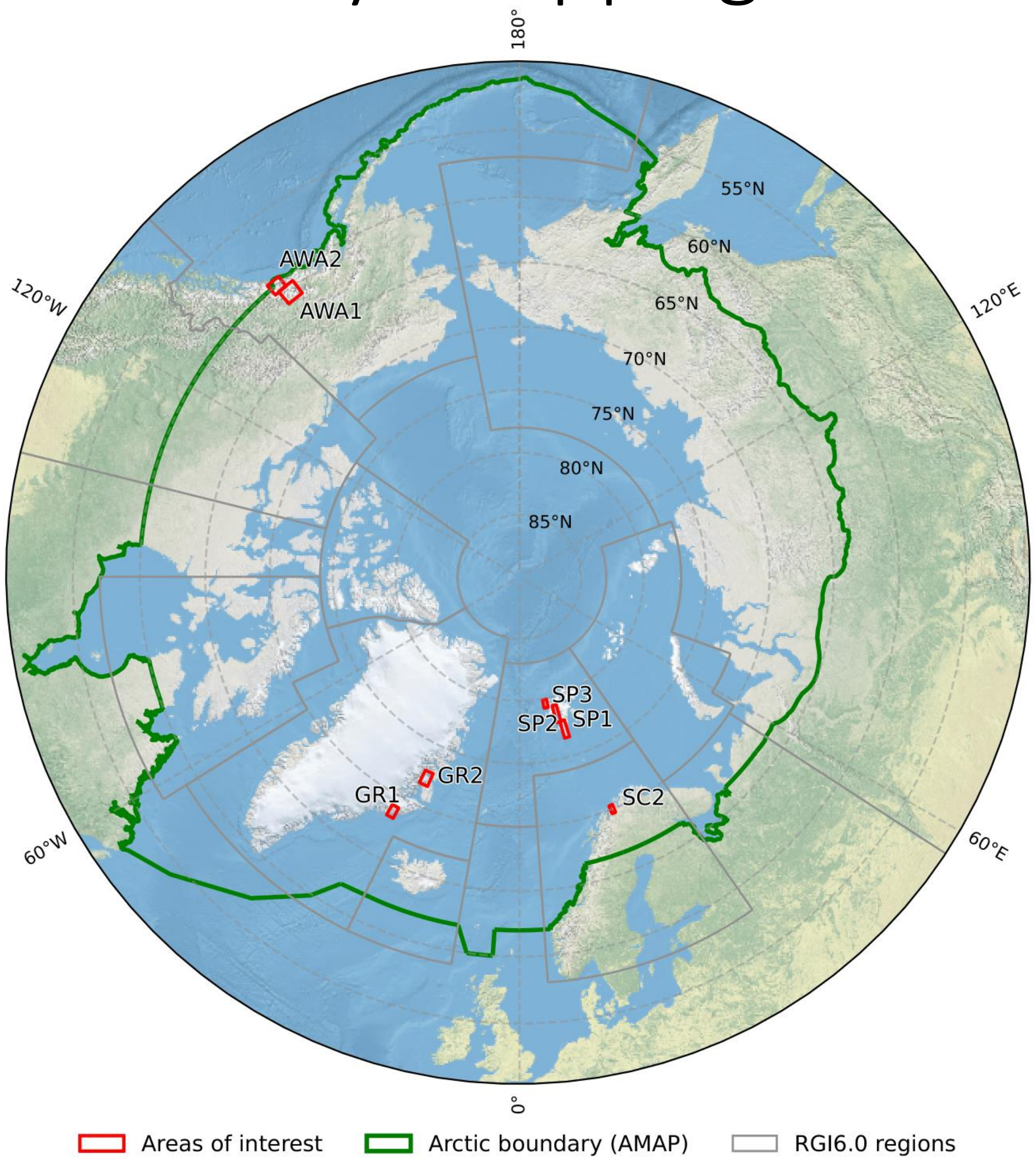

Sentinel-2
Groundtruth
Random Forest Optical
Random Forest Optical+DEM
Random Forest Optical+DEM+SAR
Light U-Net Optical
Light U-Net Optical+DEM
Light U-Net Optical+DEM+SAR
ALP-21-12
ALP-22-13
ALP-22-21
ALP-29-26
ALP-35-71
True negative
True positive
False negative
False positive

Case Study: Mapping the Arctic



- In total, 8 AOIs in the Arctic
- As input features, we combined Landsat 5, Landsat 7, Landsat 8 and Sentinel-2 TOA images and several DEMs (depending on the data availability)
- As reference data, we use GLIMS entries everywhere except Svalbard, where we utilise an inventory by NPI, unpublished
- For mapping, we train a fully-convolutional model with the in-network fusion of multi-source data

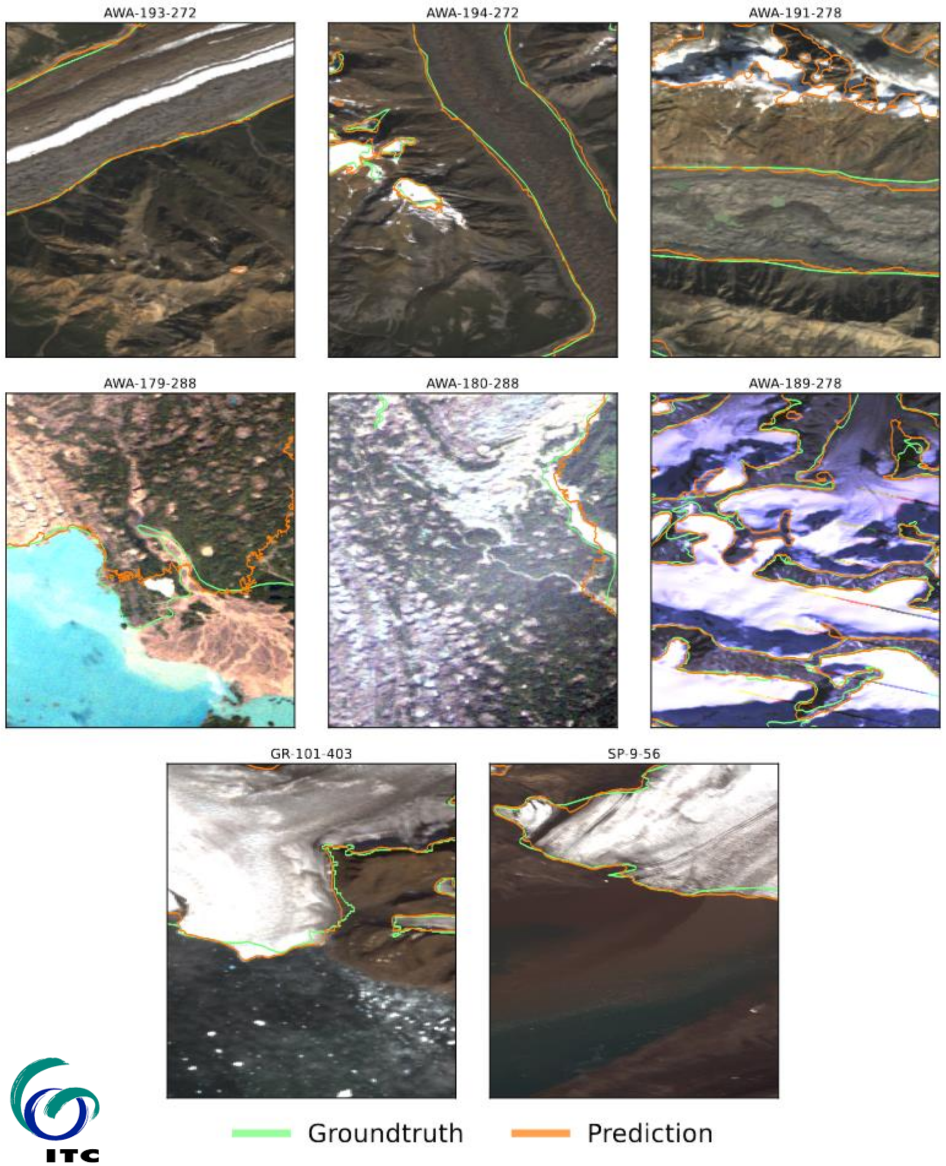
Case Study: Mapping the Arctic

- In general, the model performance is very good, except in some particular cases

Region	Precision	Recall	F1-score	IoU
Scandinavia	0.966	0.919	0.942	0.889
Svalbard	0.966	0.961	0.963	0.929
Greenland	0.975	0.950	0.963	0.928
Alaska	0.954	0.950	0.952	0.908
Overall	0.962	0.953	0.959	0.921

- Further fine-tuning the model to a specific region can potentially improve the situation for this region

Case Study: Mapping the Arctic



- Accurate classification of debris-covered ice
- Surprisingly, reasonable boundary estimates for vegetation-covered glaciers (still not ideal)
- The model is robust to Landsat 5 artefacts at the scene boundaries
- Predictions for calving fronts are even better than the reference

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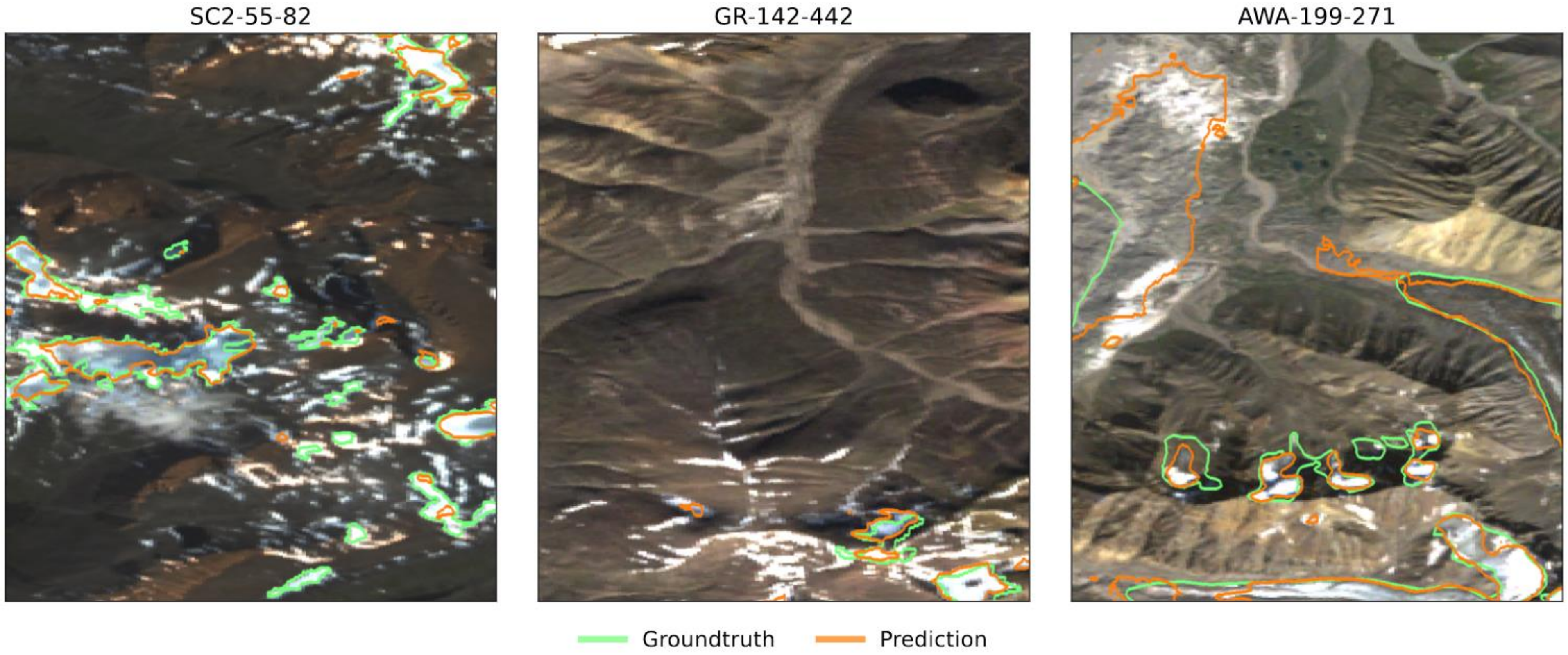
Case Study: Mapping the Arctic



- Predictions for small ice (snow) chunks are not consistent
- Some dirty glacier tongues are still problematic to classify

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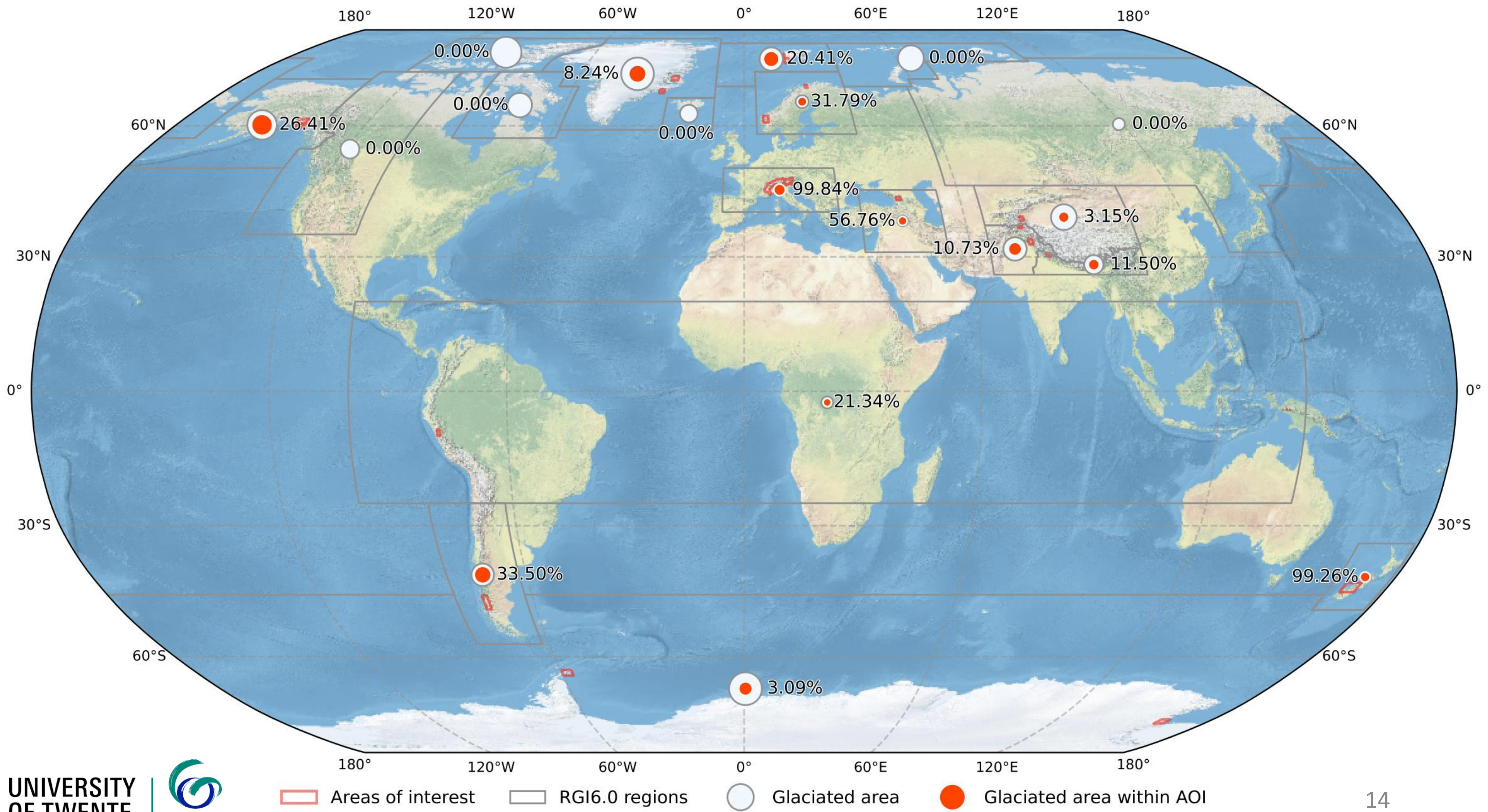
Preparing a Multi-Regional Large-scale Dataset

We have collected a large-scale dataset for glacier outlines according to

- **Diversity**: different kinds of glaciers (e.g., clean, debris-covered, vegetation-covered, small/large, blue ice) and their surroundings (e.g., alpine, marine)
- **Coverage**: 8% of glaciers worldwide (~273,900 km^2) - 10% of the glaciated area (not counting Greenland and Antarctic ice sheets)
- **Reference data**: GLIMS and two regional inventories for the Alps and Svalbard
- **Earth Observation Data**: six optical bands (B, G, R, NIR, SWIR1 and SWIR2) from Landsat 5, 7, 8 and Sentinel-2, elevation and slope data from SRTM, ALOS DEM, Copernicus DEM and some regional DEMs. Where available, SAR intensities and InSAR coherence from ENVISAT and Sentinel-1 as well as brightness temperature from Landsat
- **Tiles:** near-squared tiles (≈10x10 km^2) randomly split into training (1614 tiles), validation (540) and testing (585)



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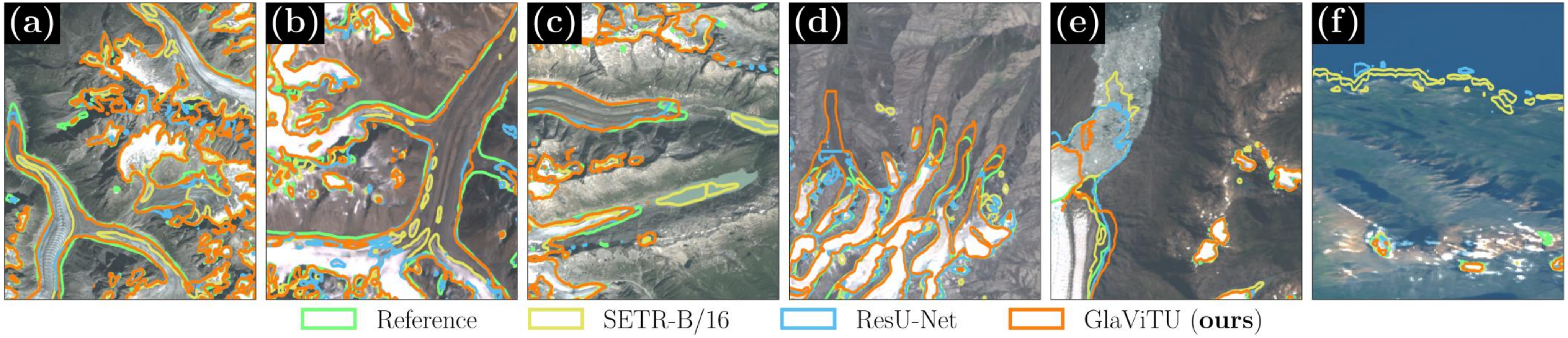
Case Study: Multi-Regional Mapping

- Recently, we proposed a hybrid CNN-transformer model (GlaViTU) for multi-regional glacier mapping
- It has fewer parameters compared to ResU-Net and SETR-B/16 but shows higher performance and generalizes better

Model	Params	IoU						IoU mean	IoU std.dev.
		ALP	HMA	LL	NZ	SA	SC		
SETR-B/16	102M	0.678	0.689	0.635	0.699	0.908	0.702	0.718	0.088
ResU-Net	33M	0.843	0.803	0.837	0.833	**0.955**	0.829	0.850	0.049
GlaViTU	**10M**	**0.844**	**0.812**	**0.864**	**0.855**	0.952	**0.866**	**0.866**	**0.043**



Going Global with Cloud Computing

OCRE Open Clouds for Research Environments

- We plan to scale up our methods to achieve large-scale (global) mapping
- We employ cloud computing environments
- We have funding and an agreement with CloudFerro, they will provide us with access to CREODIAS

CREODIAS powered by CloudFerro

- Within CREODIAS, one can access EO data including products with global coverage (Sentinel-1 GRD, Sentinel-2 L1C, ENVISAT, …)
- Some products (e.g., Landsat) can be downloaded only for Europe, but it is extendable
- They have tools to order additional data products (e.g., 6/12-day InSAR coherence)
- Virtual machines with powerful GPUs

- With these resources, we plan to automate glacier mapping worldwide with a temporal resolution superior to GLIMS

Conclusion

- The MASSIVE project aims at producing large-scale glacier inventories
- Three case studies have shown promising results towards applying deep learning for fully-automated glacier mapping on different scales
- We have collected a large dataset for glacier outlines mapping (to be published soon)
- With CREODIAS, we will scale up the methods to achieve global glacier mapping with a high temporal resolution

Remaining Challenges and Future Work

- Debris/vegetation-covered glaciers
- Generalization ability across different glacier types and environments
- Generate calibrated uncertainties and confidence intervals for area change
- Digital Twin GLACIERS