ESA Lab Workshop on Data Space Management

Estimate the ice volume of Earth's glaciers with deep learning and remote sensing

N. Maffezzoli[1,2]

[1]Institute of Polar Sciences, CNR-ISP
[2]Ca' Foscari University of Venice

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SKYNET project

N. Maffezzoli, G. Lagnese, S. Vascon, Eric Rignot, C. Barbante.

Estimating the ice volume of Earth's glaciers via AI and remote sensing

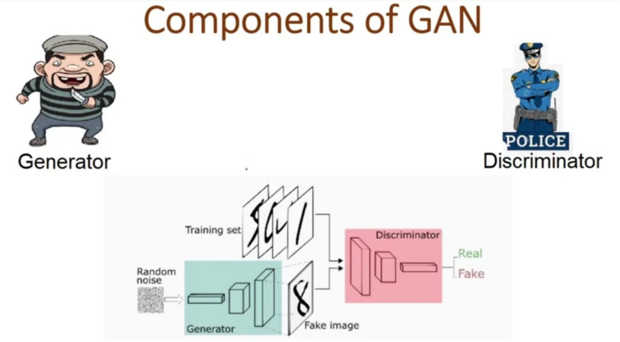
Satellite products give us a lot of information about the Earth surface, but to which extent can we use such information to extract fingerprint of what is below the surface ?

Image inpainting

Uddin and Jung, Sensors, 2020

- Image Inpainting is a task of reconstructing missing regions in an image.
- Deep neural networks are the state-of-the-art technique for such a task.

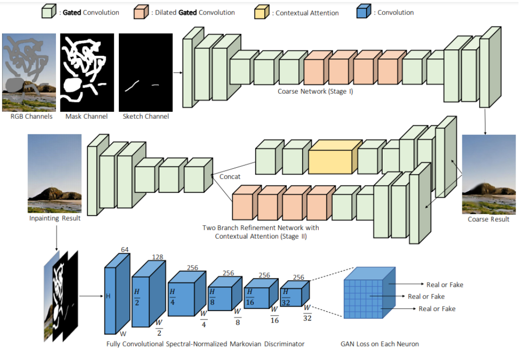
Generative Adversarial Networks (GANs)



$$\min_G \max_D V(D,G)$$

$$V(D,G) = \mathbb{E}_{x \sim p_{data}(x)}[log(D(x))] + \mathbb{E}_{z \sim p_z(z)}[log(1 - D(G(z)))]$$

Generative Adversarial Networks (GANs)



Yu et al., 2019

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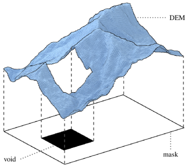
Image inpainting

Suvorov et al., Resolution-robust Large Mask Inpainting with Fourier Convolutions, arXiv, 2021.

AliQureshi et al., Journal of Visual Communication and Image Representation, 2017.

DEM image inpainting



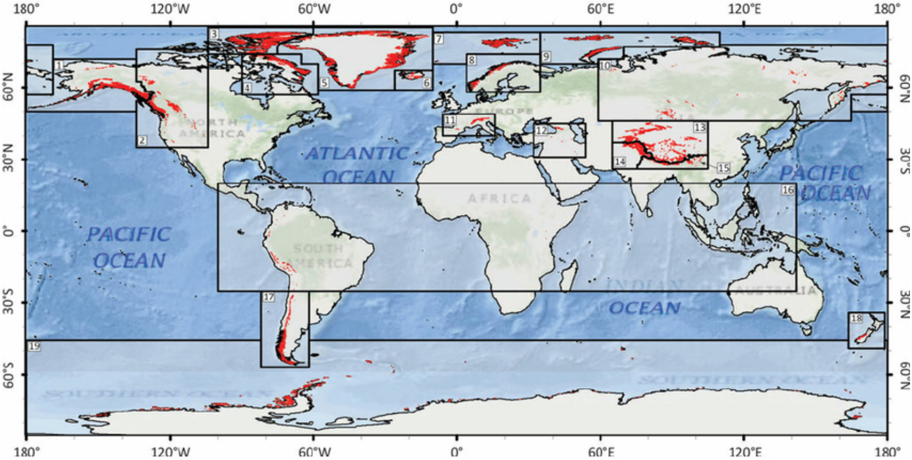
Gavriil et al., arXiv, 2019.

The goal

- The goal is develop a model able to reconstruct the bedrock topography of mountain regions
- We can then use the trained model to reconstruct the bedrock topography below a glacier, hence infer its thickness distribution.
- The glacier volume V over its area A is given by the difference between the surface elevation (DEM) and the bedrock elevation (BED) estimated by the network:

$$V = \iint_A [DEM(x, y) - BED(x, y)]dxdy$$

Randolph Glacier Inventory (6.0)

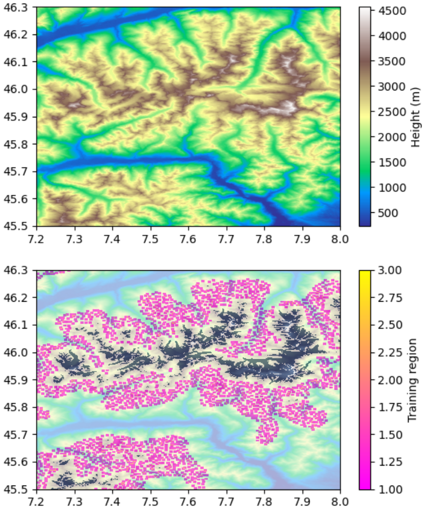


Summary of Regional Glacier Counts and Areas

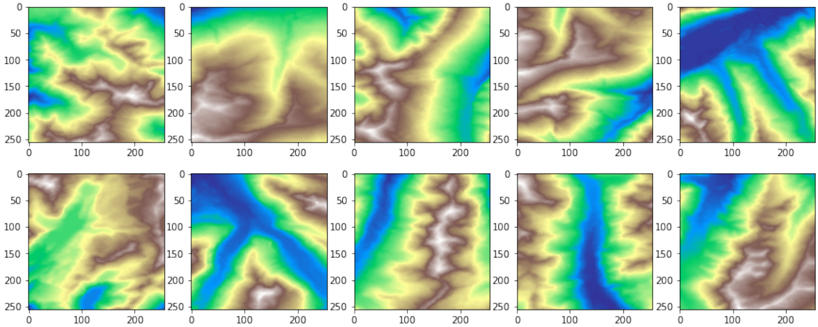
Region number	Region name	Glacier count	Area (km2)
00	World	215547	705738
01	Alaska	27108	86725
02	Western Canada and US	18855	14524
03	Arctic Canada North	4556	105110
04	Arctic Canada South	7415	40888
05	Greenland Periphery	19306	89717
06	Iceland	568	11059
07	Svalbard	1615	33958
08	Scandinavia	3417	2949
09	Russian Arctic	1069	51591
10	North Asia	5151	2410
11	Central Europe	3927	2092
12	Caucasus and Middle East	1888	1306
13	Central Asia	54429	49303
14	South Asia West	27988	33568
15	South Asia East	13119	14734
16	Low Latitudes	2939	2341
17	Southern Andes	15908	29429
18	New Zealand	3537	1161
19	Antarctic and Subantarctic	2752	132867

Train/val datasets creation pipeline

- ASTER Global Digital Elevation v3. 1/3600 deg, ∼30m at 0lat. 2000-03-01 to 2013-11-30
- Randomly located 256x256 DEM patches
- Constraint1: average or max patch > threshold (e.g. 2000 m)
- Constraint2: central 96x96 box should not contain any existing glacier
- Some degree of overlap between created patches is allowed
- 90% (10%) images for training (validation)



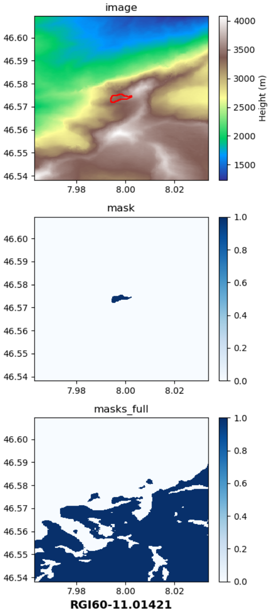
Training and validation datasets creation pipeline



- Current regions of interest: RGI11 (Central Europe), 13/14/15 (High Mountain Asia), 08 (Scandinavia), 18 (New Zealand).

Test dataset

- Glacier 11.01421 (Central Europe)
- Neighbouring glaciers
- Size of glaciers



Ground truth and comparison with existing results

- **Ground truth:** Glacier Thickness Database (GlaThiDa). 3.8 million thickness measurements distributed over roughly 3000 glaciers worldwide.
- **Model solution 1:** Farinotti et al., A consensus estimate for the ice thickness distribution of all glaciers on Earth. NatGeo 2019.
- **Model solution 2:** Millan et al., Ice velocity and thickness of the world's glaciers. NatGeo 2022.

Table 1 | Ice volume and SLE of glaciers outside the ice sheets

Region name	RGI region	Glacierized area ($\times 10^3$ km^2)	Coverage (%)	Ice volume[a] ($\times 10^3$ km^3)	SLE[a] (mm)	Regional difference (%)
Alaska and Western Canada	1, 2	101	96	19.2 ± 5.6	46.4 ± 15.3	−4
Arctic Canada North	3	105	99	25.4 ± 7.2	59.9 ± 19.2	−10
Arctic Canada South	4	41	100	7.0 ± 2.1	17.7 ± 5.8	−19
Greenland Periphery	5	90	100	11.8 ± 3.7	26.8 ± 9.5	−25
Iceland	6	11	99	3.7 ± 0.9	9.4 ± 2.6	−1
Svalbard	7	34	97	7.0 ± 2.3	15.4 ± 5.7	−6
Scandinavia	8	3	84	0.29 ± 0.1	0.73 ± 0.3	−4
Russian Arctic	9	52	98	15.5 ± 3.9	33.7 ± 9.6	6
North Asia	10	3	63	0.09 ± 0.05	0.22 ± 0.1	−35
Central Europe	11	2	99	0.12 ± 0.05	0.30 ± 0.1	−11
Caucasus and Middle East	12	1	78	0.06 ± 0.03	0.14 ± 0.1	−8
Asia	13, 14, 15	118	100	9.6 ± 3.7	24.3 ± 10.5	37
Low Latitudes	16	2	82	0.07 ± 0.04	0.16 ± 0.1	−27
Southern Andes	17	29	99	5.9 ± 1.6	14.6 ± 4.4	10
New Zealand	18	1	99	0.07 ± 0.03	0.18 ± 0.1	2
Antarctic and Islands	19	133	100	35.1 ± 9.1	61.3 ± 16.0	−25
Total		727	98	140.8 ± 40.4	257.2 ± 85[b]	

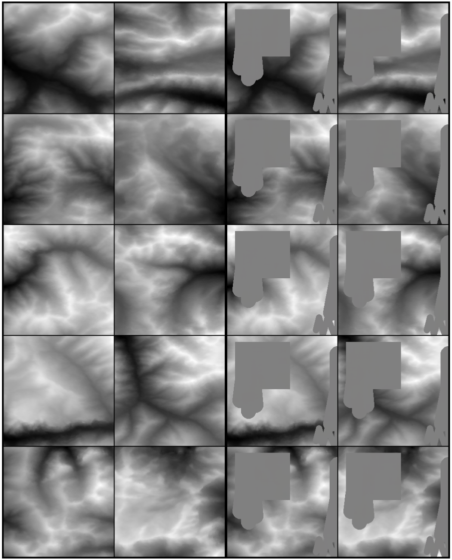
Millan et al., NatGeo, 2022

A recap of the data used

- **DEM:** ASTER GDEM (v3.0, 2019). Approx 30m at 0lat
- **Glacier shapefiles:** Randolph Glacier Inventory v6.0 (2017)
- **Glacier thickness:** GlaThiDa, Glacier Thickness Database (v 3.1.0, 2020). 3.8+ million thickness measurements distributed over roughly 3000 glaciers worldwide.

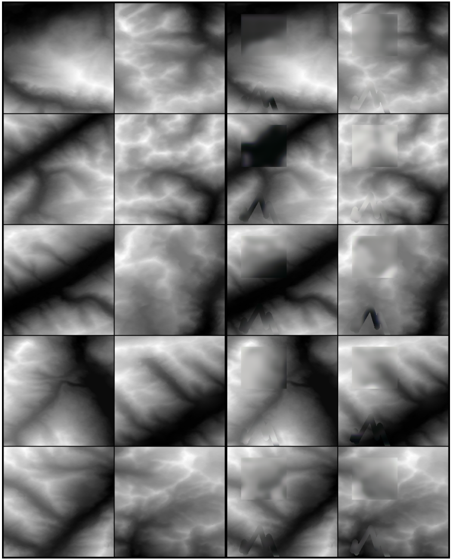
Some training snapshots

Training iteration: 0



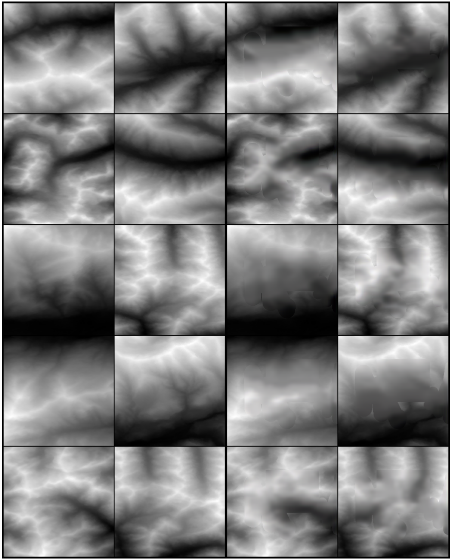
Some training snapshots

Training iteration: 500



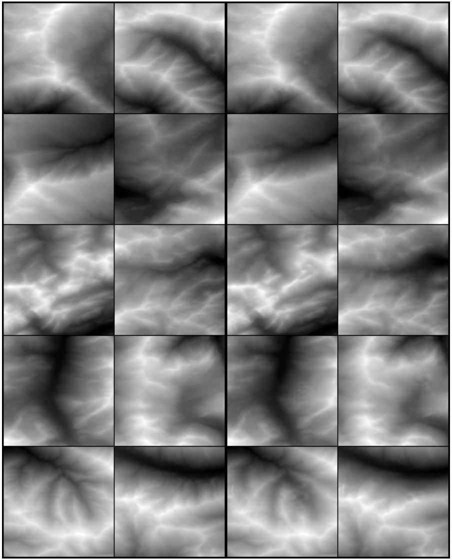
Some training snapshots

Training iteration: 2000



Some training snapshots

Training iteration: 99000



Challenges and improvements

Challenges

- Required accuracy: ice thickness of European glaciers is on the order of 70 meters, at mean elevations no lower than 2000 m: $70/2000 = 3.5\%$.
- If the BED topography is predicted at higher elevation than the DEM, the model yields a negative ice thickness (nonphysical solution).

Improvement: Physics-informed inpainting model

The idea is to "correct/refine" the modelled bedrock by integrating physical constraints/data related to the ice thickness:

- Distance of ice from glacier edge
- Ice velocity
- Slope
- Surface Mass Balance