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TerraByte-DNN2Sim: AI Detection and Simulation of Ice Sheet Calving Fronts

Introduction

Ice sheet models are an important part of the scientific effort to understand Earth system dynamics. How to best represent calving (the process of ice breaking off the edge of glaciers) is a n active area of research. Project TerraByte-DNN2Sim (Fig. 1, [6]) aims to improve the modelling of motion of fronts of ice sheets by combining machine learning and numerical simulation methods.

We employ a deep neural network to extract the calving front positions. An inverse problem is then solved numerically to estimate parameters of the calving laws. With efficiently parallelized implementations, we will apply these methods to large scale models of the Antarctic Ice Sheet and improve the projections of the ice sheet's contribution to sea level rise. The developed methods and produced data, individually or in combination, can greatly benefit other research areas. Front tracking is an important part of modelling many different physical processes, e.g., the spread of oil spills and wildfires.

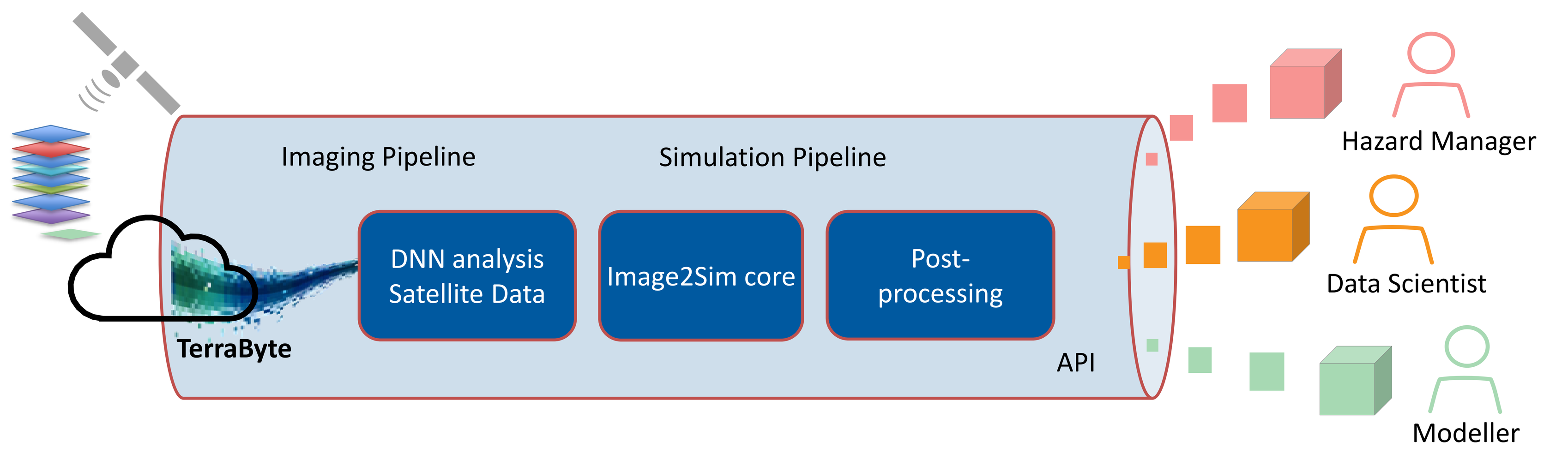

Figure 1: The pipeline for detection and simulation of calving fronts, including data storage, image analysis, simulation core, and post processing.

DNN Analysis of Satellite Data

Mapping calving front positions in satellite imagery is a challenging and very subjective task even for experts. We automated this task on the basis of radar satellite data to produce continuous time series of frontal change independent from polar night and cloud cover.

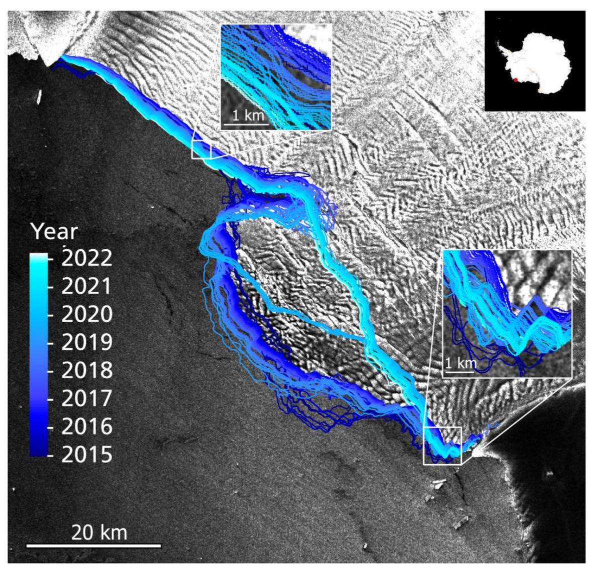

Figure 3: Time series of calving front positions of DeVicq Glacier, Getz Ice Shelf, Antarctica from the *IceLines* data set [2] extracted by HED-UNet

The key element for front extraction is the deep neural network HED-UNet (Fig. 2) combining segmentation and edge detection in one task. To improve the HED-UNet performance for front detection, deep supervision is applied to widen the receptive field for better capturing larger features.

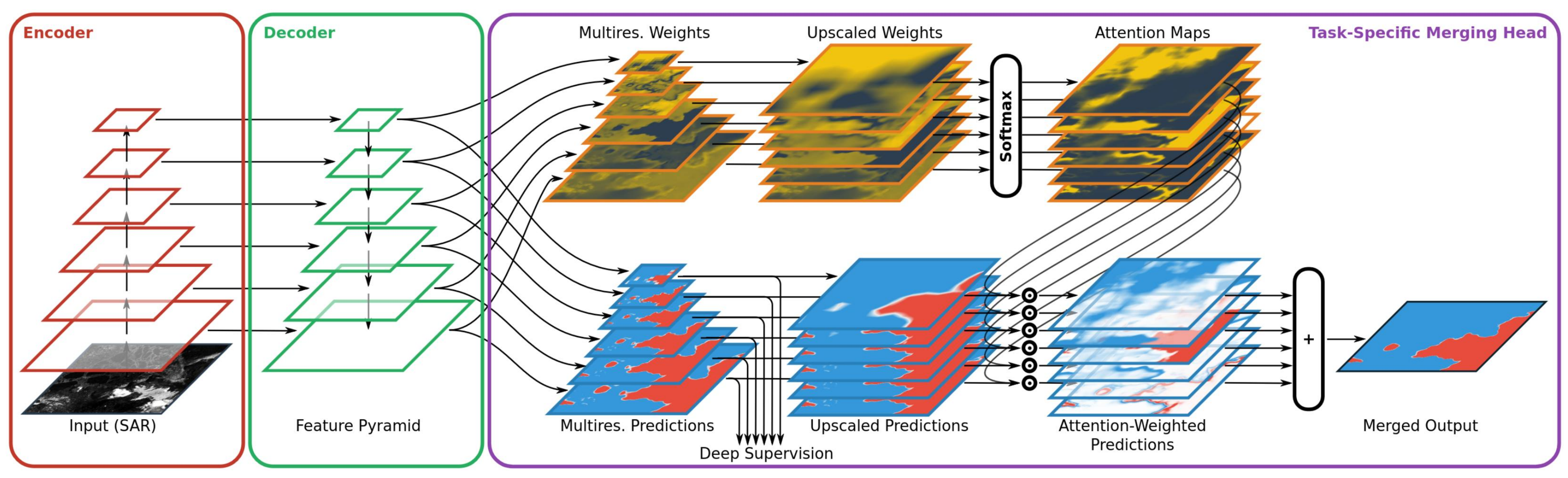

Figure 2: Architectural details of HED-UNet's segmentation merging head showing deep supervision and attention merging (Heidler et al. 2021 [1]).

Finally, hierarchical attention merging heads allow to attend to different resolution levels. That means coarse predictions are used for marginal areas and high-resolution predictions for the coastline itself. HED-UNet was trained on 81 Sentinel-1 radar images over the Antarctic coastline. This deep learning approach delivers accurate results (209 ± 12 m (5.2 pixel) on dual polarized imagery and 432 ± 21m (8.8 pixel) on single-pol imagery) for a variety of Antarctic ice shelves.

Image2Sim Core: Parameter Estimation

The calving front is simulated using a Level-set Method. The front is implicitly captured by the field φ (Fig.3) and evolved by the PDE

$$\frac{\partial \varphi}{\partial t} + \vec{v} \cdot \nabla \varphi - (m + c)\|\nabla \varphi\| = 0$$

with horizontal velocity $\vec{v}$, calving/melting rates m, c (in normal dir.)

We are developing an optimization method that solves the unique challenges of the Level-set Method. Parameters of the calving law, e.g., von Mises [3], can be estimated from known front positions:

$$c = \|\vec{v}\| \frac{\sigma_{VM}}{\sigma_{max}} \qquad \min_{\sigma_{max}} \frac{1}{2} \sum_i \|(\varphi(t_i) - \varphi_i^*) w_i\|^2$$

with observations φ^*, gaussian weights $w_i = \exp(-\frac{|\varphi_i^*|}{\alpha})$ to focus the objective function on the area around the front.

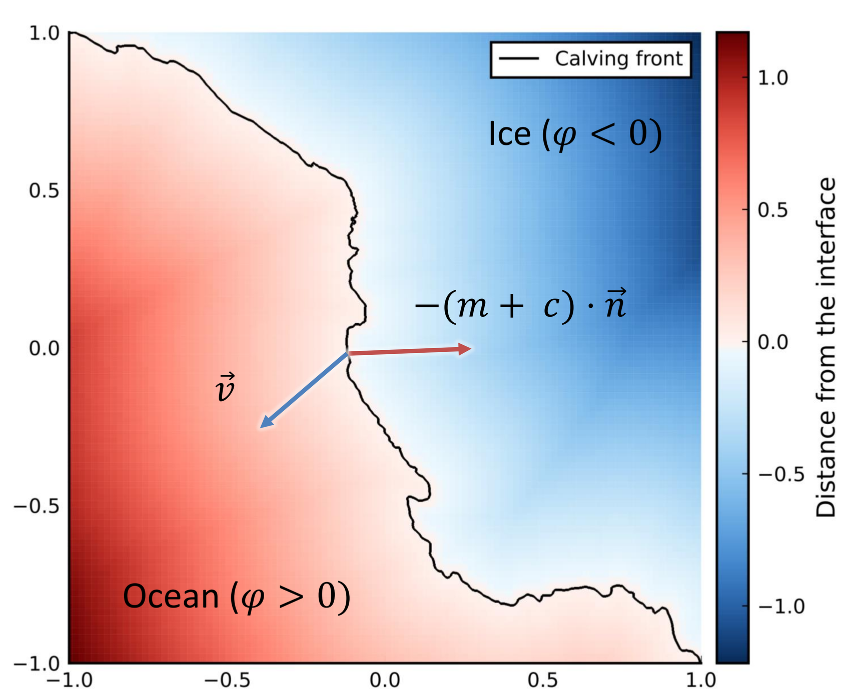

Figure 4: Example of signed distance function used to represent the front in the Level-set Method

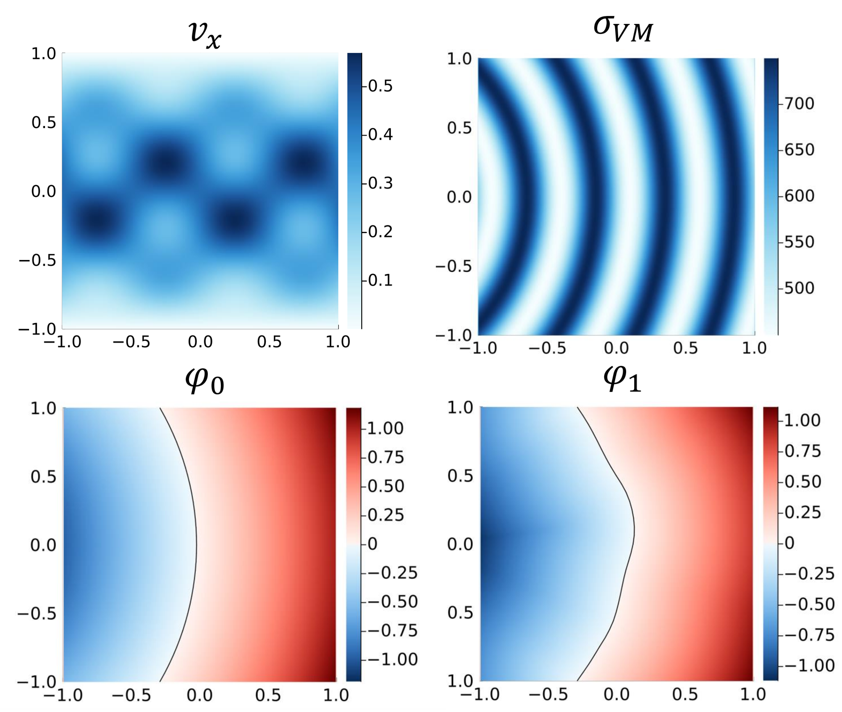

Figure 5: Synthetic data for testing the optimization method: horizontal velocity and stress fields, initial and final front position

α	Δx	$\Delta x/2$	$\Delta x/4$	$\Delta x/8$	$\Delta x/16$	$\Delta x/32$
Opt. σ_{max}	895.5	899.6	900.4	900.2	900.3	900.5

Table 1: Preliminary optimization results using smooth synthetic data (Fig. 5). Estimated calving parameter σ_{max} (expected: 900) for different values of weight parameter α relative to mesh resolution Δx

The solver developed in Julia based on DG framework Trixi.jl [4] will be made available as a high quality open-source software library. The code will be efficiently parallelized to handle large scale ice sheet model setups. A coupling adapter for the ISSM ice sheet model [5] has been developed using the preCICE coupling framework [6] to couple ice sheet and front simulations.

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https://dnn2sim.de/

TerraByte DNN2Sim

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