

Des glaciers aux rivières : ODINN.jl, un modèle hybride pour relier dynamique glaciaire et bilan de fonte



Alban Gossard

Congrès eau & "IA"
Grenoble

04/03/2026

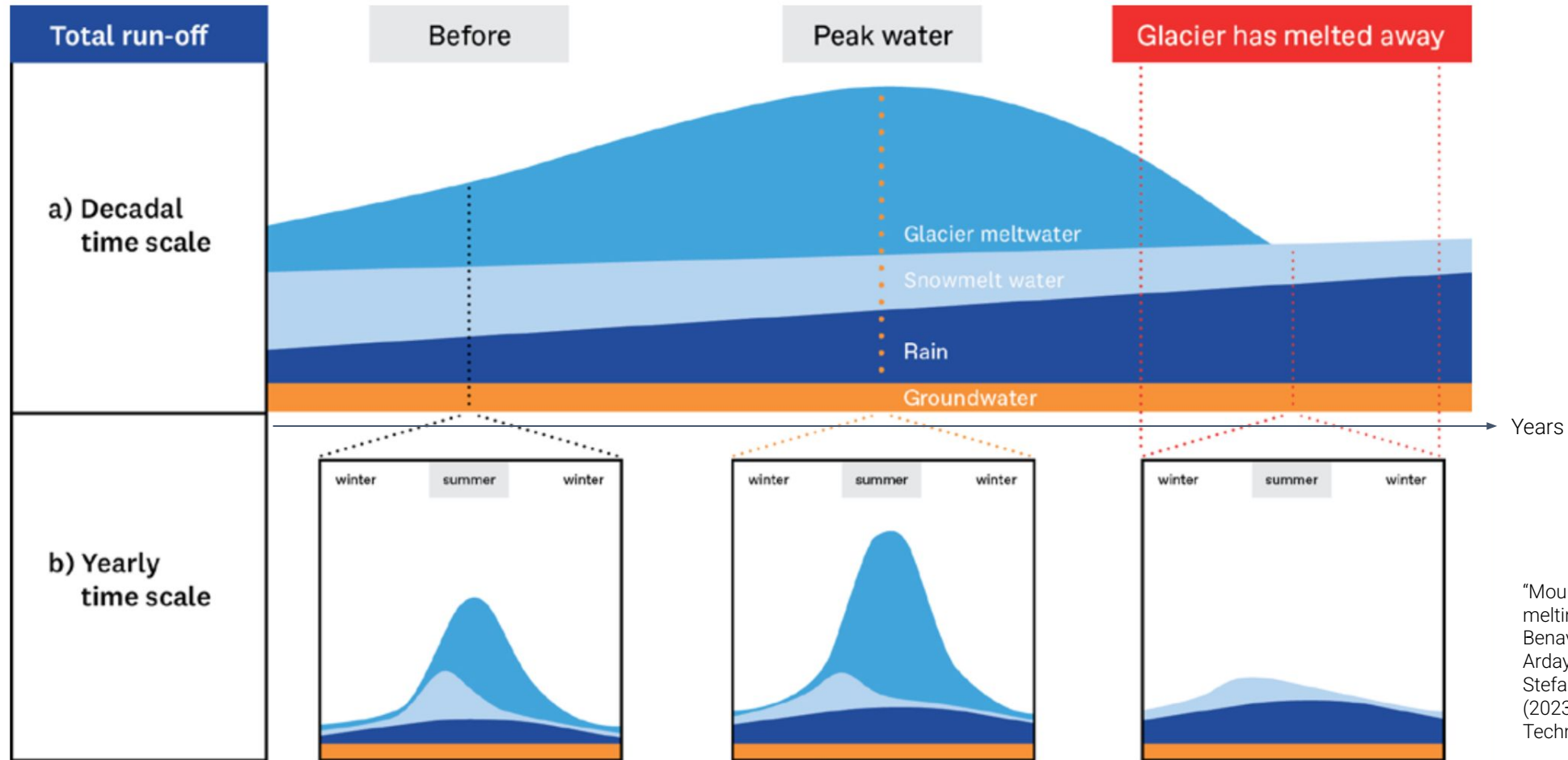
Post-doctoral researcher

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En collaboration avec entre autres Jordi Bolibar et Facundo Sapienza

Glaciers as water towers

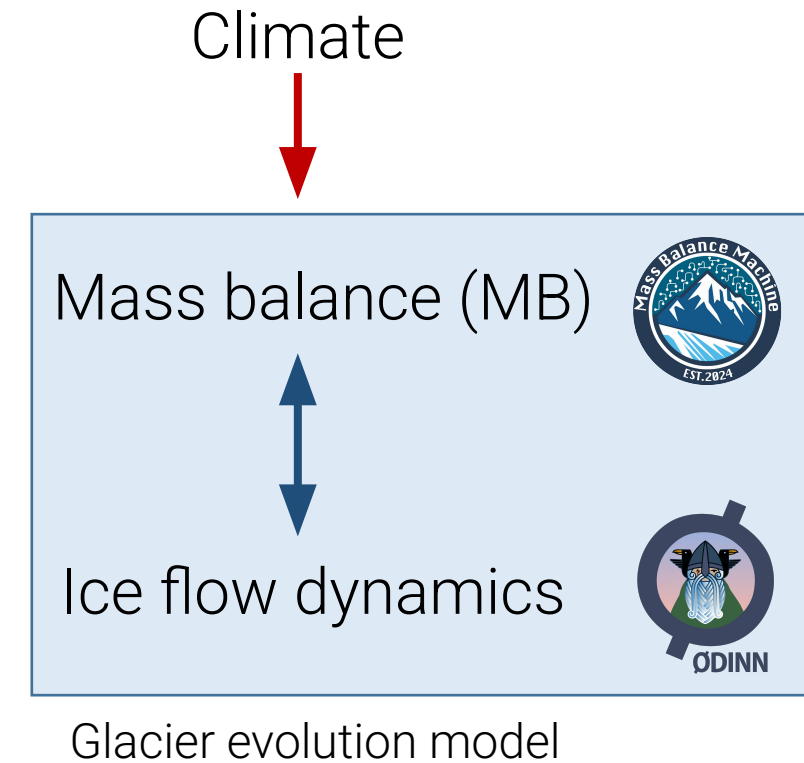
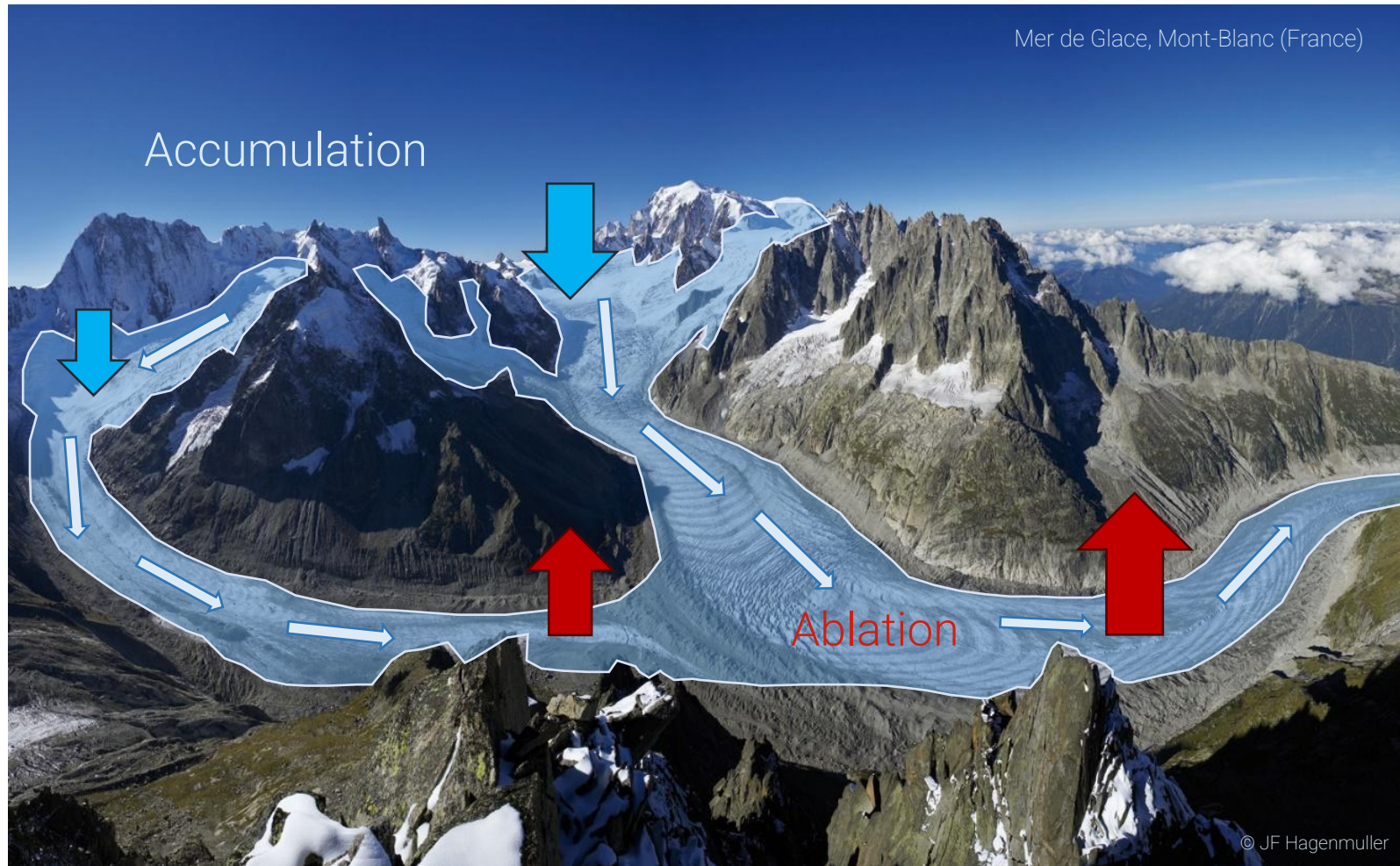


"Mountain glaciers melting", Melisa Mena Benavides, Alicia Bustillos Ardaya, Caitlyn Eberle, Stefan Schneiderbauer (2023), UNU-EHS Technical Report

Argentière glacier



The glacier system



Observations

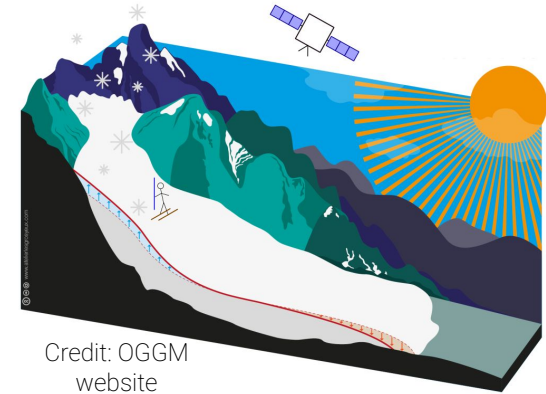
- Glaciological

- Stakes measurements
- Ice thickness
- Many others: seismometers, boreholes (temperature, stress, strain), inclinometers, surface velocity (GNSS), ...

- Remote sensing

Different
spatio-temporal
resolutions

- Image correlation (surface displacement)
- DEM differencing
- InSAR
- Gravimetry
- ...



Credit: OGGM
website

ODINN.jl: hybrid glacier model

Ice flow dynamics



Geophysical Research Letters*

Research Letter | [Open Access](#) | [CC BY](#)

Do Existing Theories Explain Seasonal to Multi-Decadal Changes in Glacier Basal Sliding Speed?

F. Gimbert, A. Gilbe

What is glacier sliding?

Robert LAW^{1,2}, David CHANDLER^{3,2}, Andreas BORN^{1,2}

¹Department of Earth Science, University of Bergen, Bergen, Norway

²Bjerknes Centre for Climate Research, Bergen, Norway

³NORCE Norwegian Research Centre, Bergen, Norway

<robert.law@uib.no>

Toward a universal glacier slip law

A new friction rule may describe ice flow over rigid or deformable surfaces

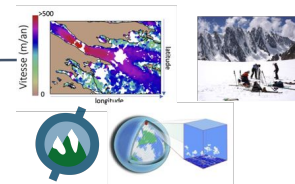
BRENT MINCHIEW AND JAN JOUGHIN [Authors Info & Affiliations](#)



Physical knowledge prescription

Data assimilation

Earth data

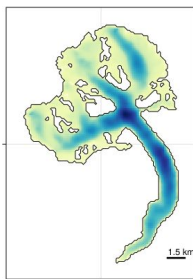


Discovery of new laws

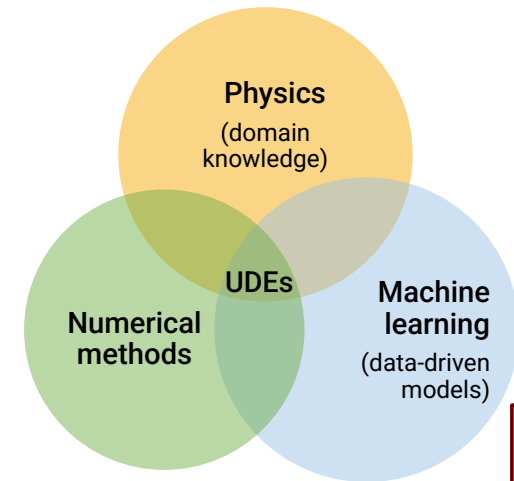
Universal Differential Equations
(Rackauckas et al., 2020; Bolibar, Sapienza, et al., 2023)

- Parametrize key/subgrid physical processes
- Learn missing physics

Initial condition inversion



Universal Differential Equations



H = ice thickness
S = surface elevation
b = mass balance

$$\frac{\partial H}{\partial t} = \dot{b} + \nabla \cdot (D \nabla S)$$

New modelling philosophy

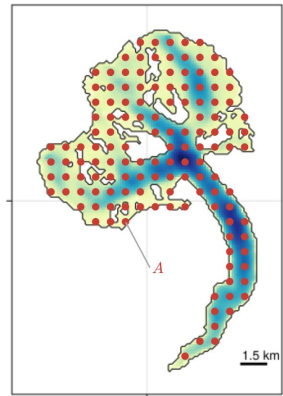
1. Make use of as much existing knowledge as possible
2. ONLY use regressors (e.g. machine learning) for what you DON'T know

Transient functional inversion



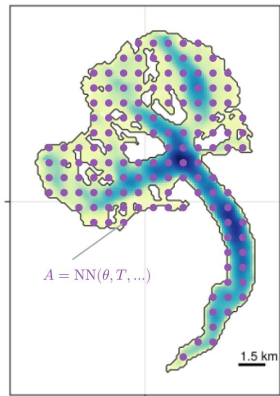
Example with the Shallow Ice Approximation (Hutter, 1983) $\frac{\partial H}{\partial t} = \dot{b} + \nabla (D \nabla S)$

Classical inversion



Grid points with parameters to invert

Functional inversion



Grid points with values parameterized by θ

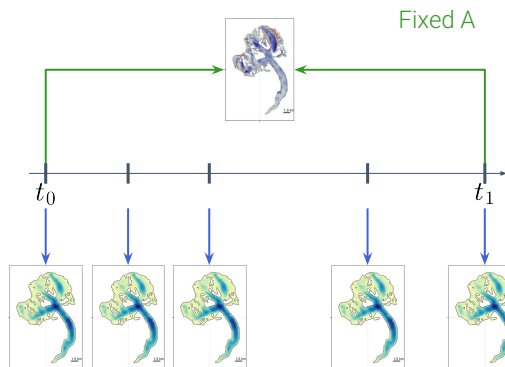
H = ice thickness
S = surface elevation
b = mass balance
A, n = Glen coefficients
C = basal sliding coefficient

T = local long-term temperature
 θ = parameters of the neural network

$$D = \left(C + 2 \frac{A}{n+2} H \right) (\rho g)^n H^{n+1} \|\nabla S\|^{n-1}$$

$$D_\theta = \left(C + 2 \frac{NN(\theta, T)}{n+2} H \right) (\rho g)^n H^{n+1} \|\nabla S\|^{n-1}$$

Single snapshot inversion



Time varying A

Transient inversion

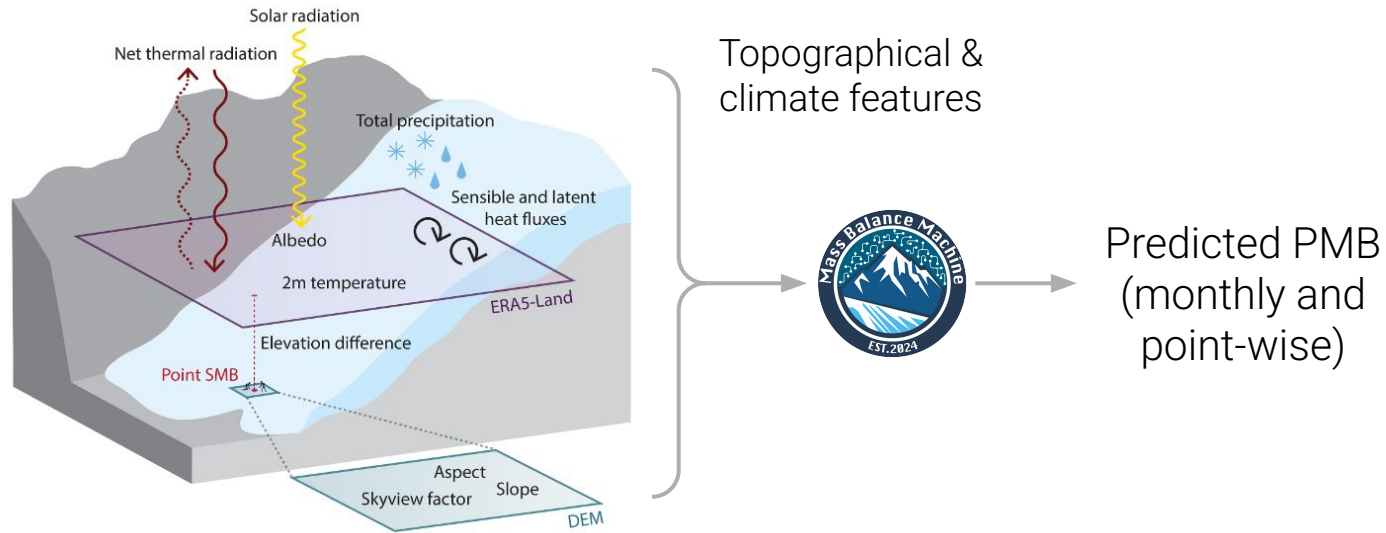
Leverage seasonality in satellite observations

Surface ice velocity of Bossons glacier from 50x50cm resolution Pleiades images

Data: Romain Millan, Antoine Rabatel, Laurane Charrier

Video: Facundo Sapienza

Mass Balance Machine (MBM)



Training

Statistical regressor
(e.g. neural network)

$$\min_{\theta} \sum_s \left(y_s - \sum_{m \in \text{months}} f(x_{s,m}; \theta) \right)^2$$

$x_{s,m}$ Features for month m and stake s

y_s Point mass balance measurement

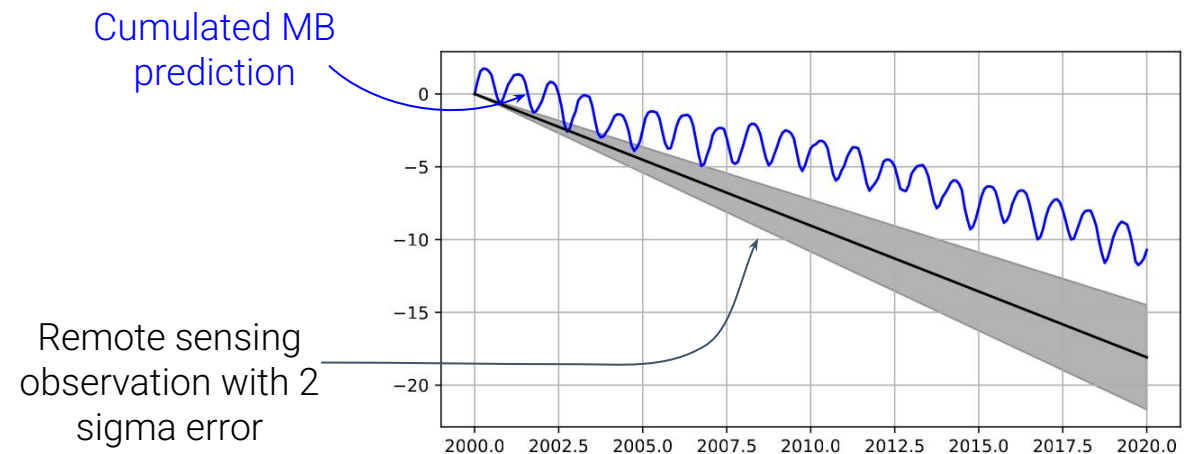
Key properties

- No calibration
- Leverage existing glaciological measurements
- Fill the gaps

Mass Balance Machine: key results



- Can transfer to unseen glaciers with seasonal prediction
outperforming existing models (calibration data dependent)
- LSTM version: ability to learn meaningful temporal pattern
(sensitivity analysis)
- Currently working to make it compatible
with decadal projections



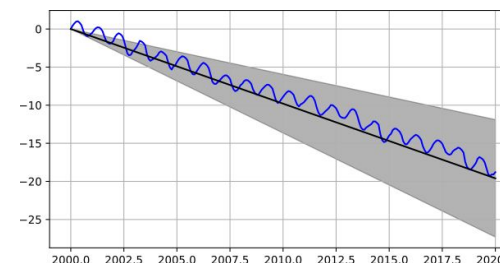
GLADAPT: improving glacio-hydrological projections with ODINN.jl and Mass Balance Machine



1. Monthly surface mass balance model compatible with decadal projections



2. Ice thickness inversion to calibrate initial ice volume



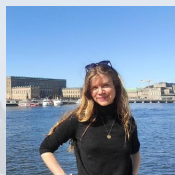
3. High spatio-temporal resolution forecast

4. Use high resolution glacier runoff predictions in a hydrological model (LSTM of a collaborator)

Applications: hydrological predictions in the European Alps and the Andes

Thank you for your attention

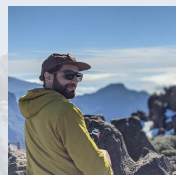
Open source models



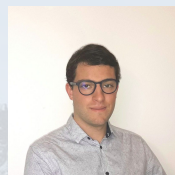
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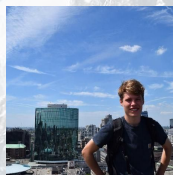
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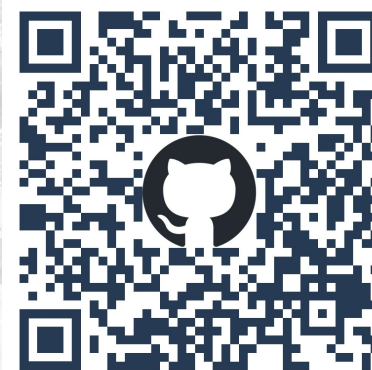
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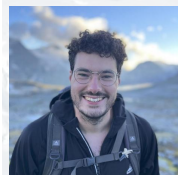
Michel Burlet
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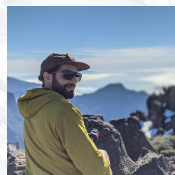
github.com/ODINN-SciML/MassBalanceMachine



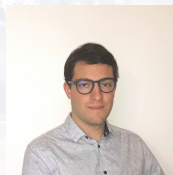
github.com/ODINN-SciML/ODINN.jl/



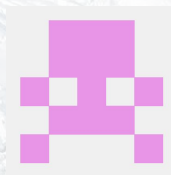
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Thank you for your attention



Mass balance modelling

Mass balance



- Surface mass balance is a key component for glacio-hydrological applications!
- Most literature relies on temperature-index (TI) models

Need calibration data (availability & uncertainties)

- Need a new class of models

Temperature-index models

$$MB = f_{\text{acc}} \times \text{precip}_{\text{snow}} - f_{\text{DDF}} \times \text{PDD}$$

$$\text{PDD} = \sum_{\text{day} \in \text{period}} (T_{\text{day}})_+$$

Requirements

- No calibration
- Leverage existing glaciological measurements
- Fill the gaps
- Compatible with decadal projections

Mass Balance Machine (MBM)



Developers



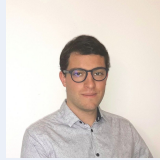
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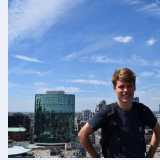
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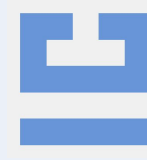
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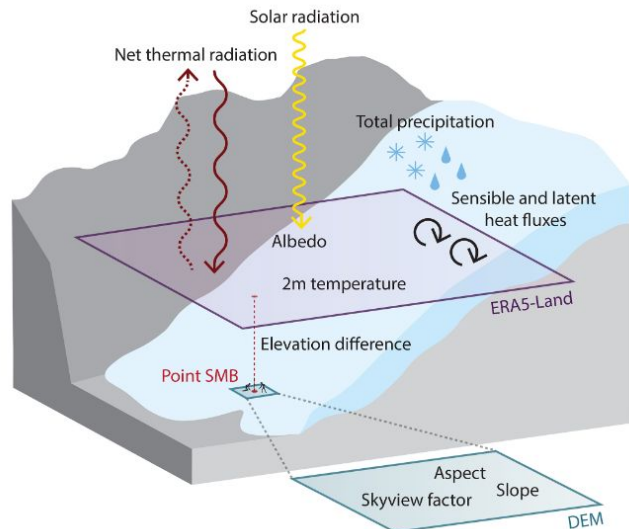
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github.com/ODINN-SciML/MassBalanceMachine



Topographical & climate features



Predicted PMB
(monthly and point-wise)

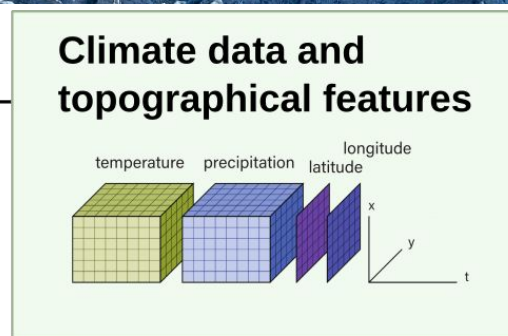
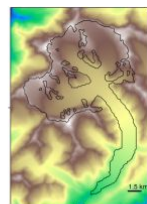
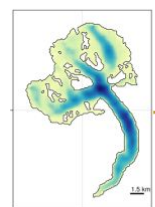
Training

Statistical regressor
(e.g. neural network)

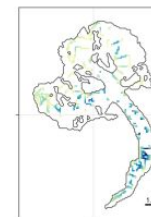
$$\min_{\theta} \sum_s \left(y_s - \sum_{m \in \text{months}} f(x_{s,m}; \theta) \right)^2$$

$x_{s,m}$ Features for month m and stake s

y_s Point mass balance measurement



Ice thickness observations

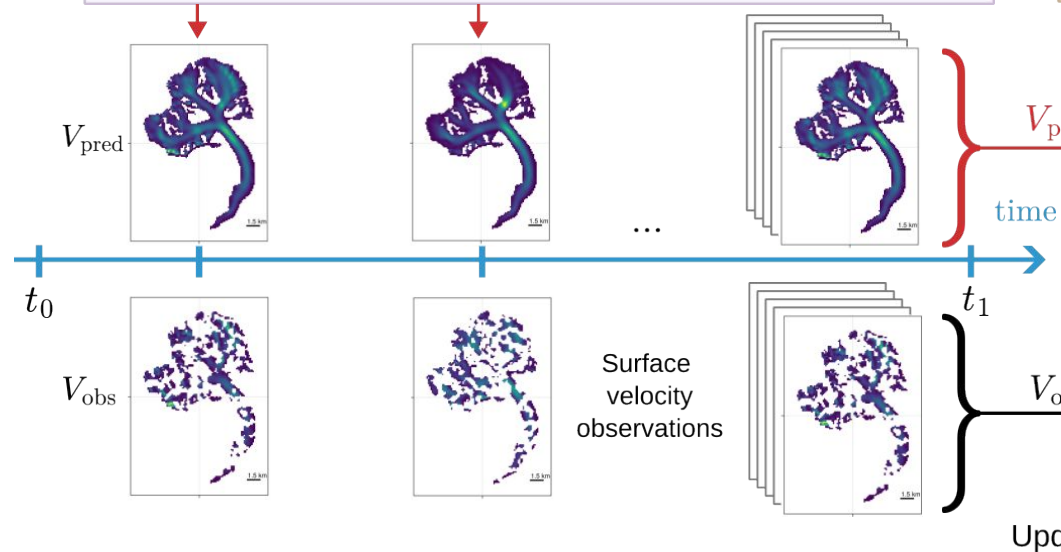
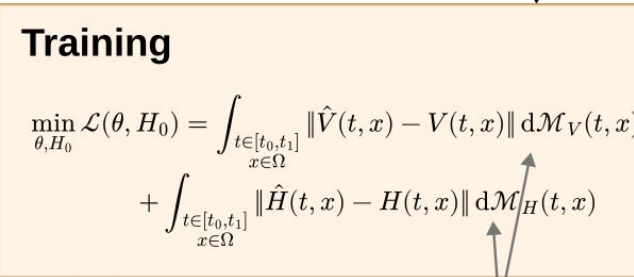
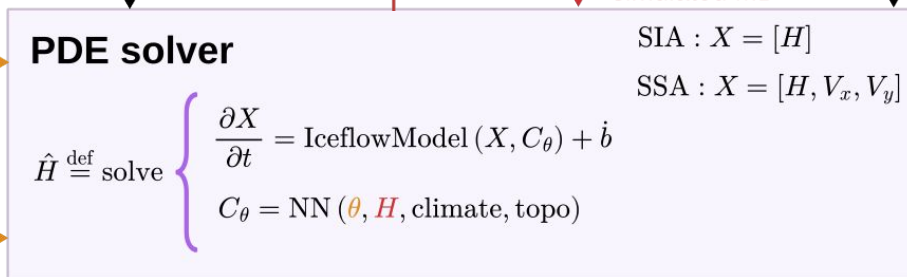


Inputs & forcing



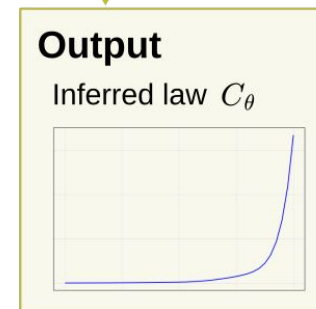
Simulation products

Optimization variables



Mask of available data

Once converged



Automatic Differentiation of PDEs in a nutshell

$$\frac{\partial X}{\partial t} = f(X, \theta, t)$$

2 ingredients:

- A way to compute the VJPs $\partial_X f^T \cdot \lambda$ and $\partial_\theta f^T \cdot \lambda$
- Integrate these two VJPs in the adjoint PDE



“Let’s code the adjoint and the Vector Jacobian Products ourselves”

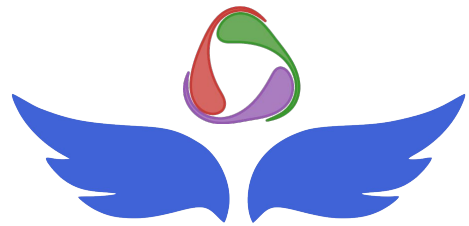
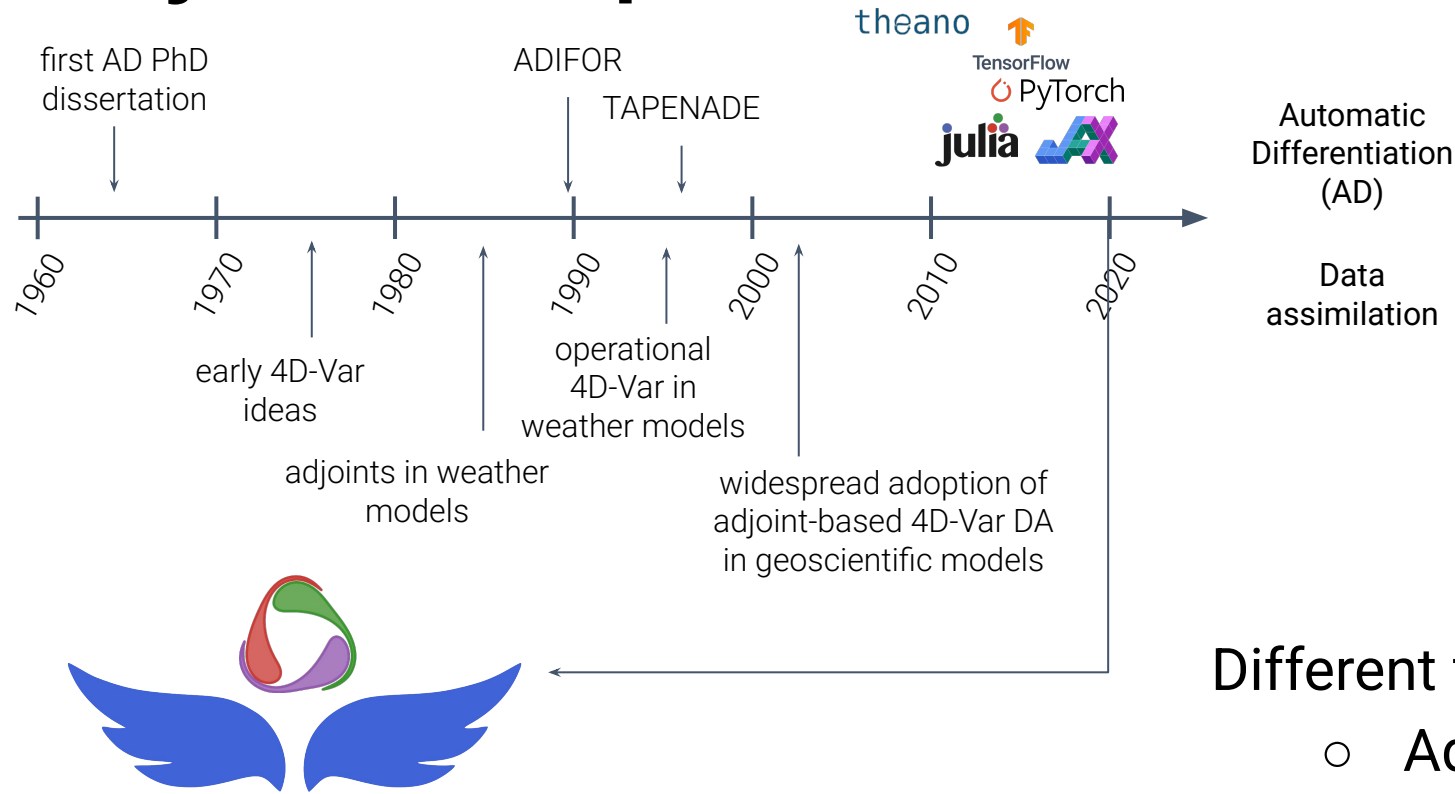


Facundo Sapienza 5:56 AM

In the meanwhile, making progress with the manual implementation of the adjoint.



Adjoint computation



SciML ecosystem

- Numerical solver
- Time stepping
- Adjoint computation

✗ Cannot differentiate complex models

✗ Want more control



Facundo Sapienza 5:56 AM

In the meanwhile, making progress with the manual implementation of the adjoint.



Fabien Maussion 10:24 AM

manual implementation of the adjoint

Back to Fortran77?



Different flavors of adjoints / VJPs

- Adjoint of SIA has SIA form

Fine control over the implementation

Differentiable Programming for Differential Equations: A Review (Sapienza, et al., 2024)

- *Smart* approximation