living planet symposium | BONN 23–27 May 2022

TAKING THE PULSE OF OUR PLANET FROM SPACE

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Numerical ice sheet temperature emulator for present time in Antarctica

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Motivation and Outline

3D Temperature within the ice sheet: is a key variable to understand the ice sheet processes which is available in few boreholes only or models. Is time dependent in response to past climate evolution, coupled with ice flow (thermomechanical) and sensitive to the geothermal flux which is a badly known boundary condition (100% of difference among different models in some places) .

Objective of this work: develop a fast tool for 3D temperature to be used in data interpretation

- used for a retrieval algorithm based on satellite information (SMOS)
- work initiated in the framework of ESA project - 4D-Antarctica

Method: Take advantage of 3D present temperature fields simulated by a thermomechanical model (GRISLI)

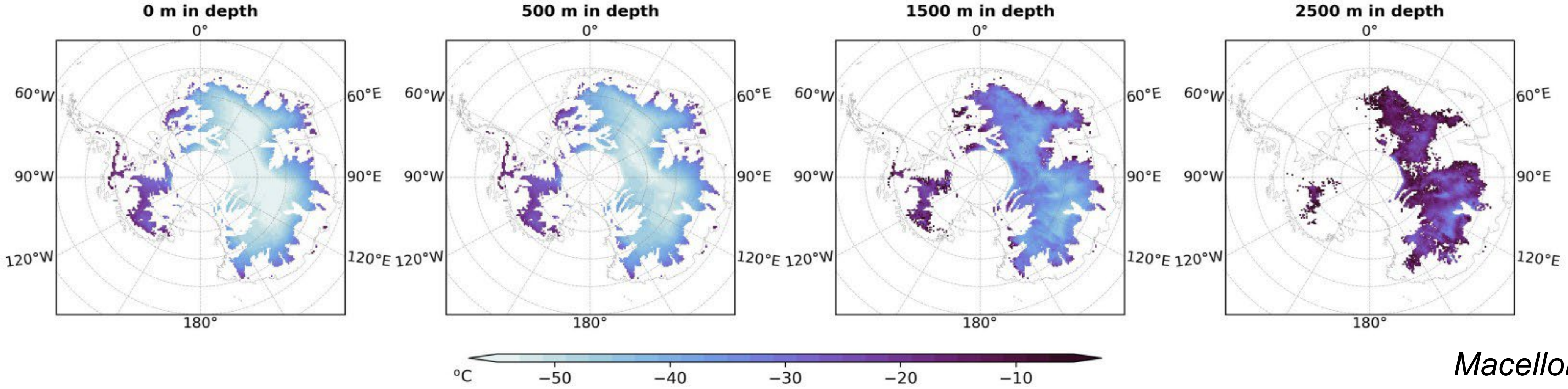
- GRISLI simulations account for past climate, ice sheet evolution and thermomechanical coupling
- drawbacks of this type of model : computer time demanding

- Train a deep neural network (DNN) to reproduce these temperature fields (regression)

Retrieval of 3D ice sheet temperature in Antarctica with Satellite data

- Because of high penetration depth (low dielectric constant of ice) - **Brightness temperature at L-Band** (satellite SMOS) depends on ice temperature over a thickness of several hundred meters

- **Associating SMOS measurements and thermal modelling** opens the possibility to retrieve the 3D temperature field



Macelloni et al., 2019

- Feasibility has been tested in the central regions of Antarctica using a simplified model (Robin et al. 1959) an analytical solution for temperature profiles. But presents Limitations:

- **Restricted to central regions because is valid when the velocity is low**
- **Steady climate assumption**

Retrieval of 3D ice sheet temperature in Antarctica - next

To go further we need a better thermal model that takes into account horizontal flow and past ice sheet changes:

- Steady state approach (Pattyn, 2010). Extension accounting for past surface temperature forcing (Van Liefferinge, 2018).

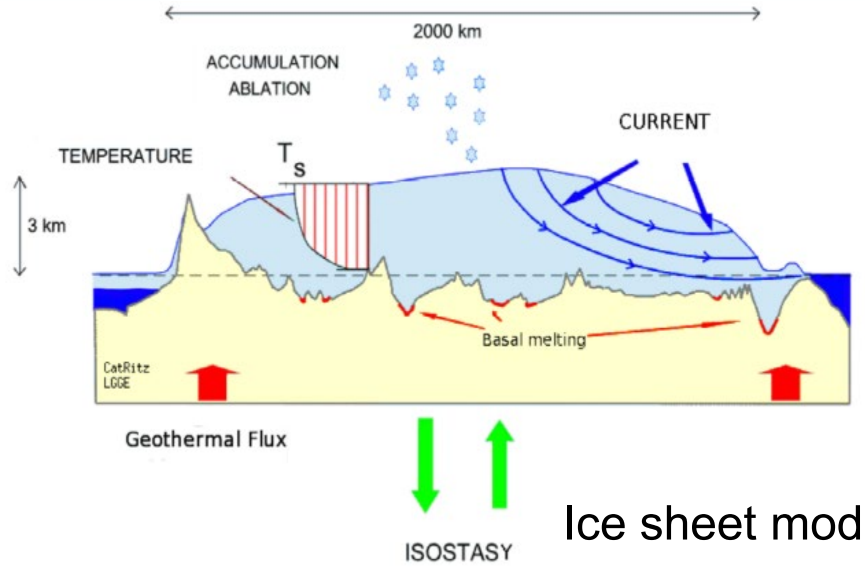
→ Limitations: temperature field and velocity fields not fully consistent,no time dependent ice thickness

- 3D thermomechanical ice sheet evolution model (here we propose **GRISLI** model)

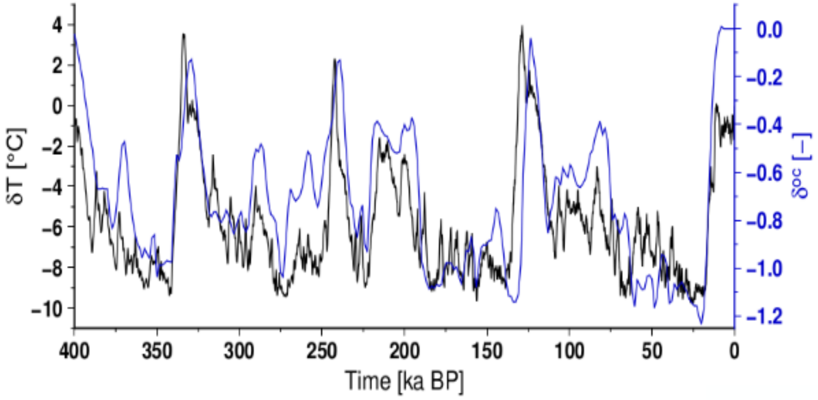
Quiquet, A., Dumas, C., Ritz, C., Peyaud, V., and Roche, D. M.: The GRISLI ice sheet model (version 2.0): calibration and validation for multi-millennial changes of the Antarctic ice sheet, Geosci. Model Dev., 11, 5003–5025, https://doi.org/10.5194/gmd-11-5003-2018, 2018.

Numerical resolution with an ice sheet model (here GRISLI)

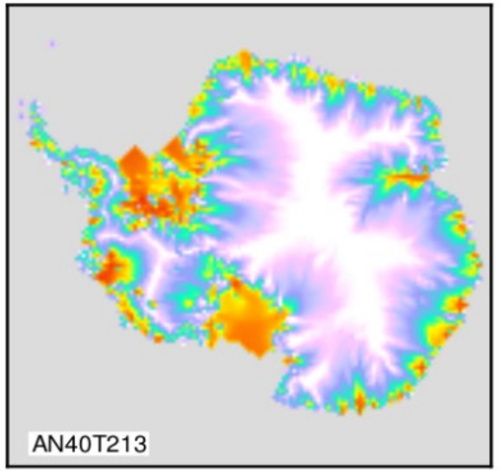
- **Solves the whole time dependent thermomechanical system**



Ice sheet model



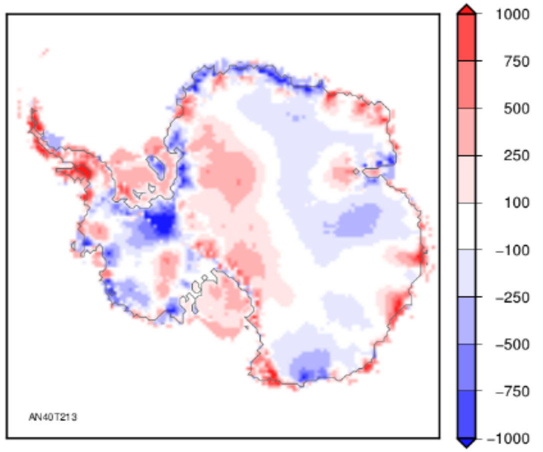
Maps of bed, ghf, Ts, Acc + Climatic forcing



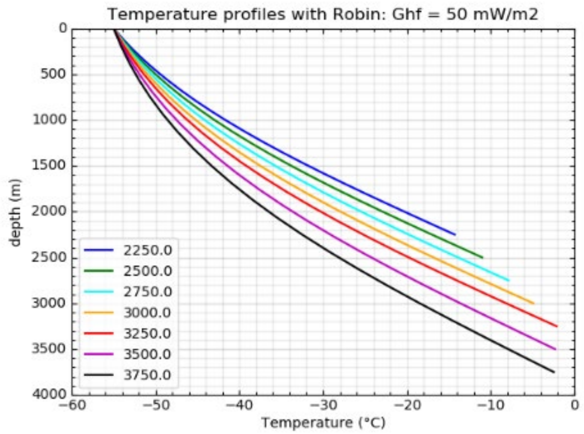
Present state of Ice Sheet including 3D field of temperature

- **Advantage : fields are fully consistents**

- **Limitations**
  - Computing time (problem for satellite inversion algorithm)
  - Ice thickness simulated for present different from observed
  - Coarse grid (here 40 km) → ok for SMOS



Example of thickness difference between simulation and observation



An example of the impact of ice thickness on temperature profile

Building an emulator of temperature profiles

Method

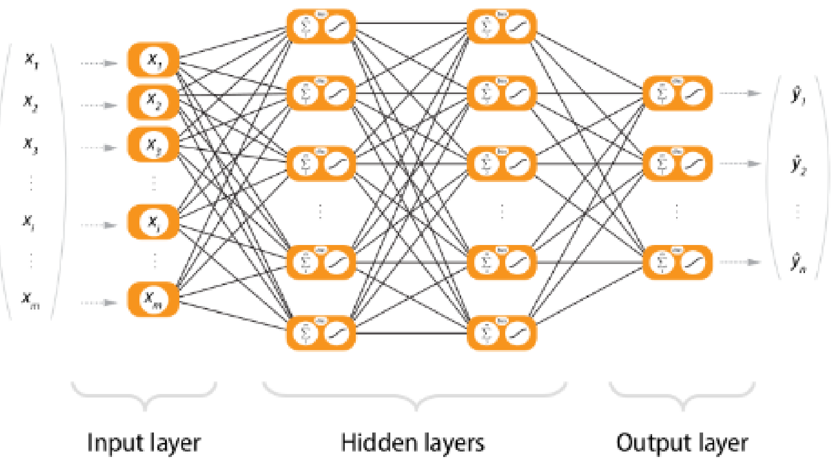
- Use Python packages Tensor Flow and Keras
- First version tested on 10000 realisations of the Robin equation → works well
- For building the emulator we use GRISLI outputs was configurated in different conditions:

- 4 runs with various maps of GHF, with 3 snaphots each (Present time, LGM (20kyrs ago) and steady state)
- **That makes about 40 000 columns of 21 vertical poi**nts.

Input Parameters x from GRISLI

Ts, H, Ghf, acc
surface velocity
surface slope, …

Same parameters used in SMOS retrieval algorithm



Predicted output ŷ

Temperature profiles

Optimized by comparison with GRISLI temperature profiles **Y**

All input parameters except Ghf are « observables » (could be observed in the real world)

Past climate conditions: we had to take into account past surface temperature changes (over 25 kyears) because EAIS and WAIS did not have the same thickness changes and this affects how GRISLI reconstructs surface temperature in the past.

Every ice column is taken as one sample independently

Data preprocessing

Use GRISLI outputs for present day (based on Quiquet et al. 2018) :

- 40 km resolution, 900 000 years
- 4 simulations differing by the geothermal flux map
- All simulation outputs are used together

Remove some ice columns

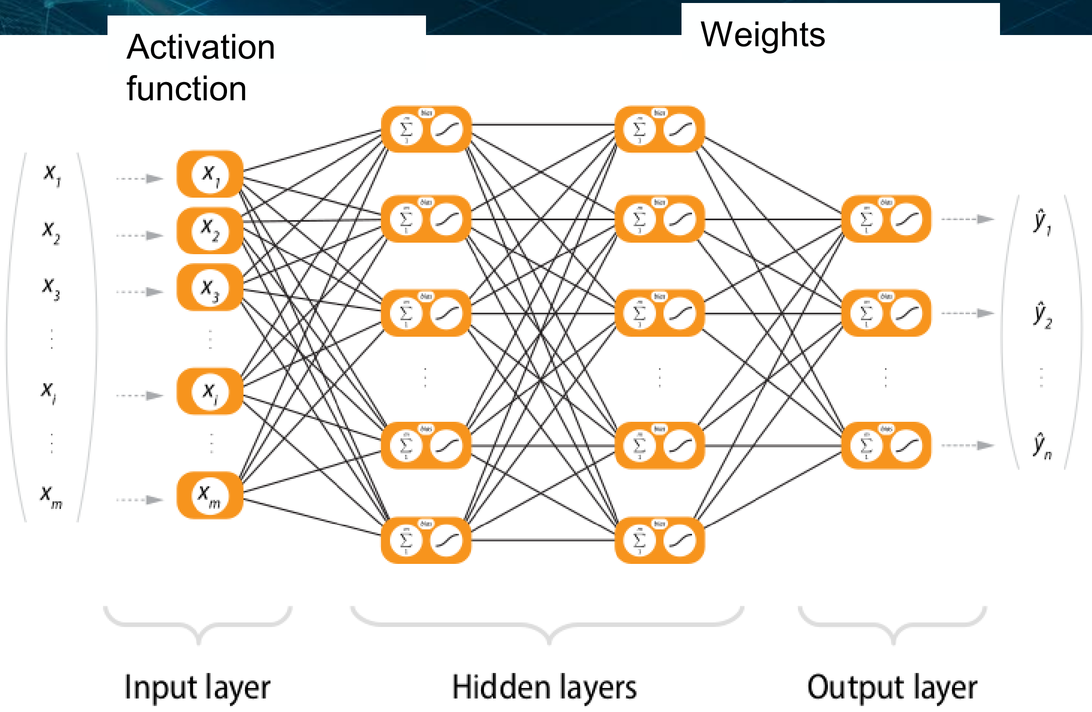
- Floating point and Thickness < 1000 m → 16000 ice columns
- Work in difference with surface temperature

Split train (70%) and test (30%) → **Xtrain and Xtest**

Normalize Xtrain Ts, H, GHF, acc, surface velocity, surface slope,… (mean = 0 and sigma =1)

- Acc, velocity, slope → log before normalization
- Normalise Xtest with train method

DNN Construction: typical for regression



Predicted output ŷ
Temperature profiles

Weights are optimized by comparison with GRISLI temperature profiles **Y**

Some technical points

Each hidden layer has 256 neuron

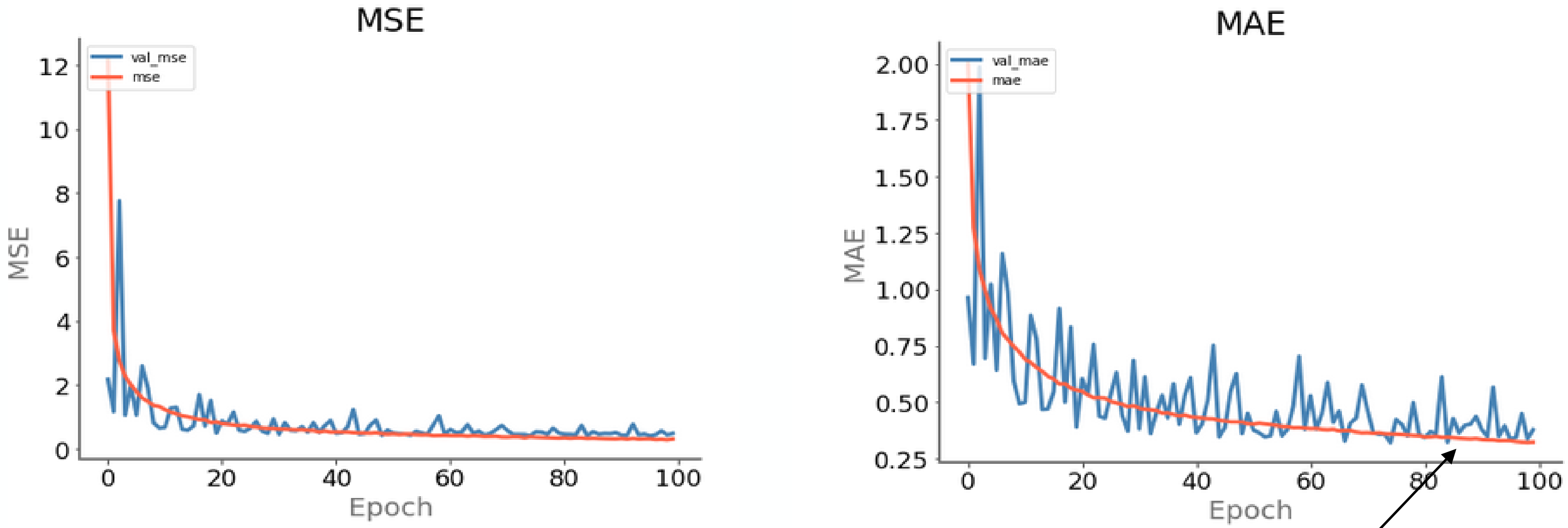
100 Epochs

Tests with 2-4-6 internal layers
→ not very sensitive (but needs more epochs for 2 layers)

Several activation functions tested → « Relu » seems the best

Loss is MSE (Mean squared error) but we keep the best model according to the MAE (mean absolute error)

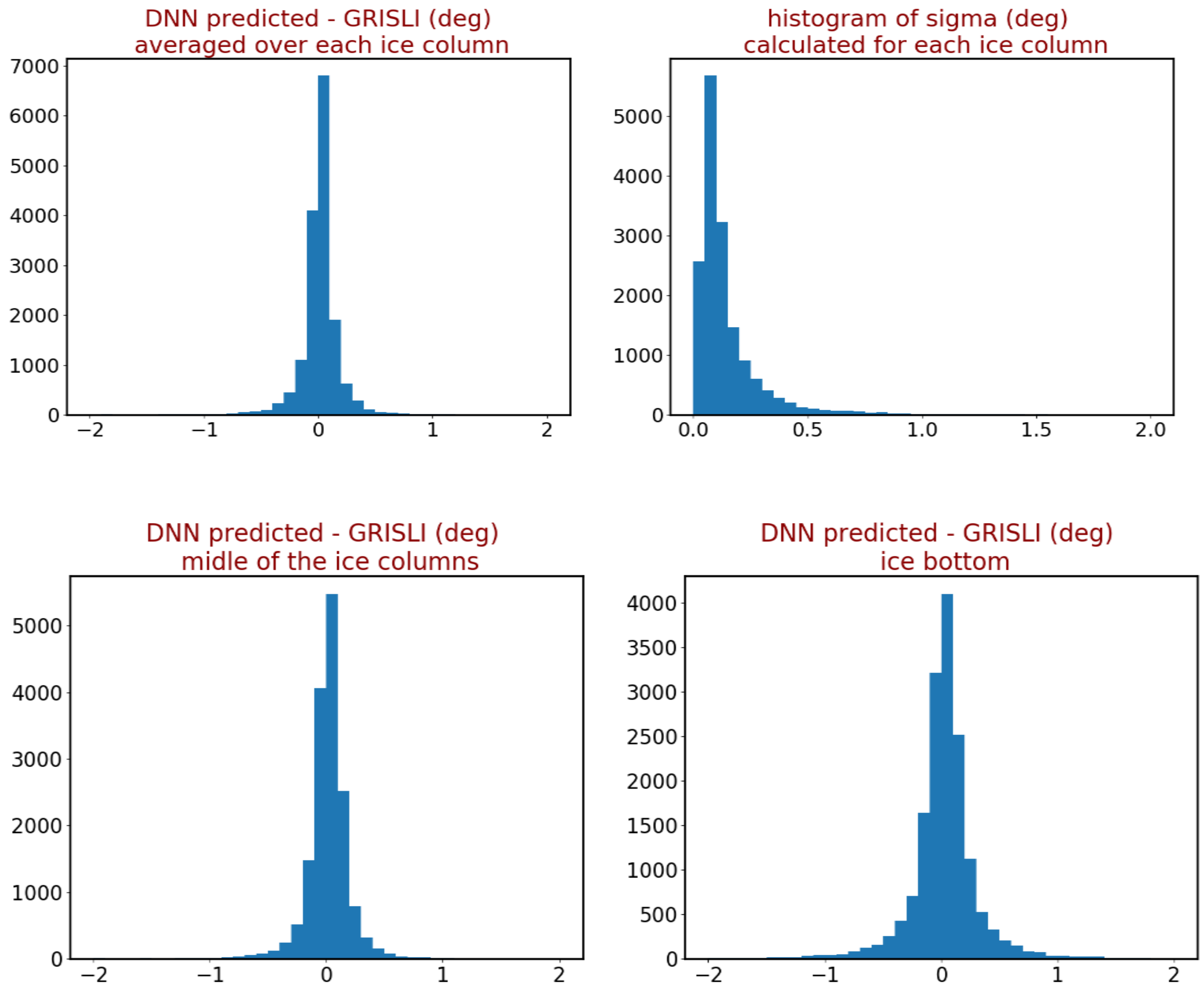
Train the DNN and evaluate



Evolution of MAE (mean absolute error) and MSE (mean squared error) along epochs

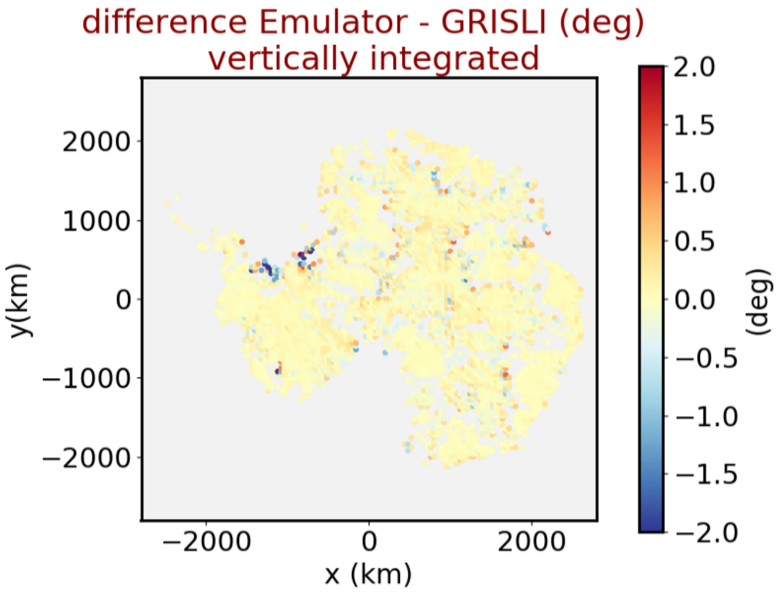
- In red, for the Xtrain set
- In blue, for the Xtest set (val_mae and val_mse)
- Keep the best MAE to selec the DNN model among the tested ones (a model includes the network geometry and all the weights)
- Due to the stochastic aspect of the method, 10 realisations are stacked (each with a different split of Xtrain and Xtest)

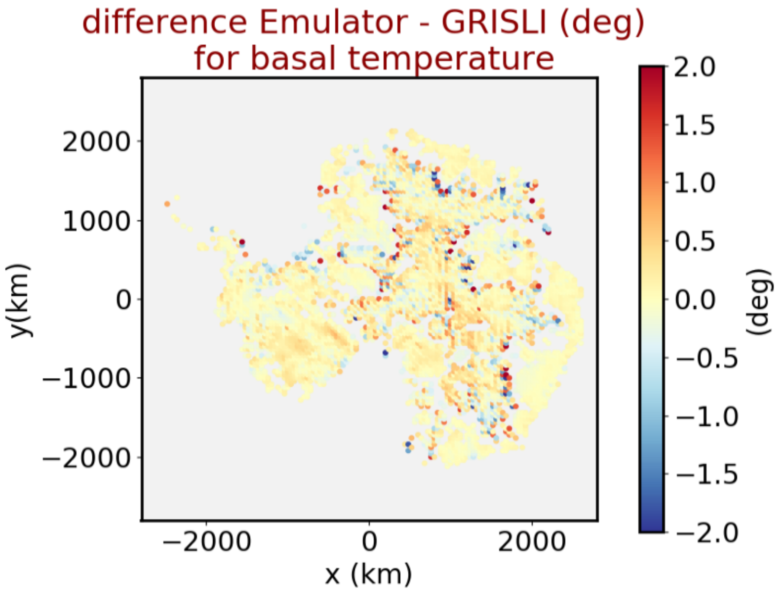
Some results (with 10 DNN stacked)



More outliers in the bottom temperature than in the upper layers

Some results (with 10 DNN stacked)





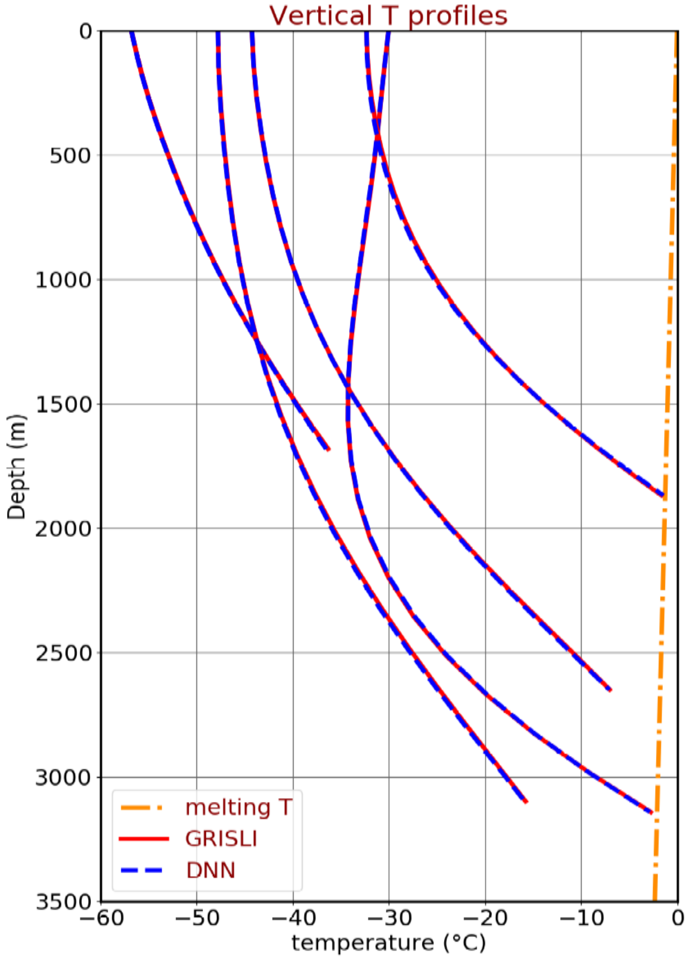
The outliers are mainly where the base is below the melting point (cold base)

Processes suspected:

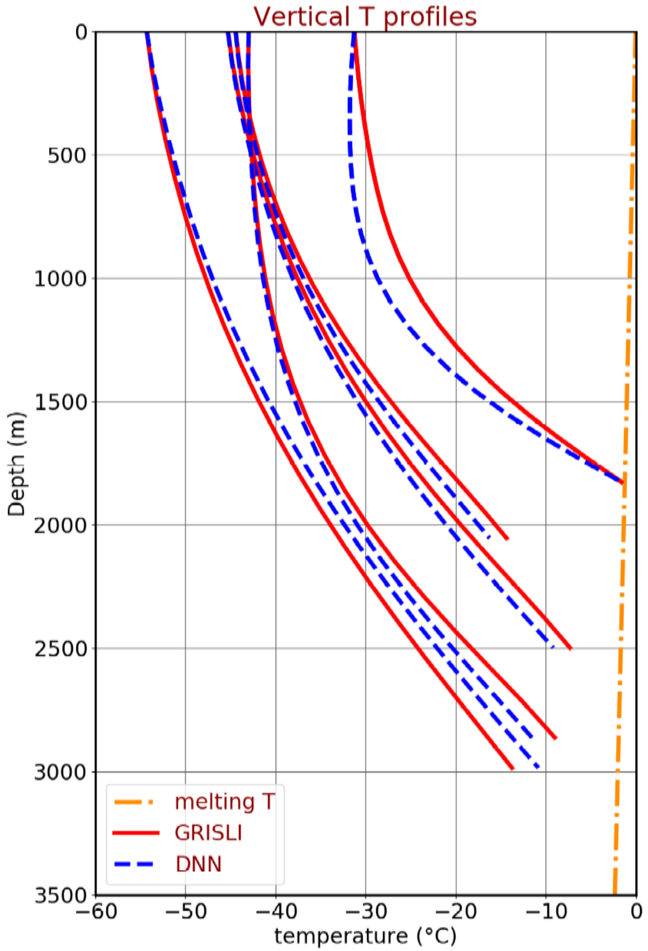
- heat production in GRISLI is made on a staggered grid, and the emulator is based on centered grid for the slope
- vertical velocity shape
- impact of long term temperature changes

In the Weddell sea region, the mismatch is due to a late retreat of the grounding line in GRISLI simulations.

Examples of temperature profiles



Where it works
(most often)



Outliers – mostly in case of cold base
(1-2% have sigma > 1 deg)

The results are encouraging. What is next?

Use this emulator with SMOS data and the Bayesian approach

- New map of the 3D temperature field (with its uncertainty)
- Use ice core records for the surface temperature history

=> displayed in M. Leduc-Leballeur – Thursday 26th 11:25
Session A9.04.2 - Mass Balance of the Cryosphere

Use the emulator with low frequencies (0.5-2 GHz –Cryorad concept)

- To improve the penetration capabilities and reduce the error at the bottom

Use other GRISLI runs with different conditions

- Other maps of GHF
- Various sets of GRISLI dynamical parameters
- Test the impact of horizontal resolution

For questions contact:
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Compare with outputs from other thermomechanical models

Extend the methodology to Greenland

Other applications of such a model

- Initialisation of ice sheet models and downscaling between model resolution
- Take into account other data (presence of subglacial lakes,...) to improve GHF retrieval