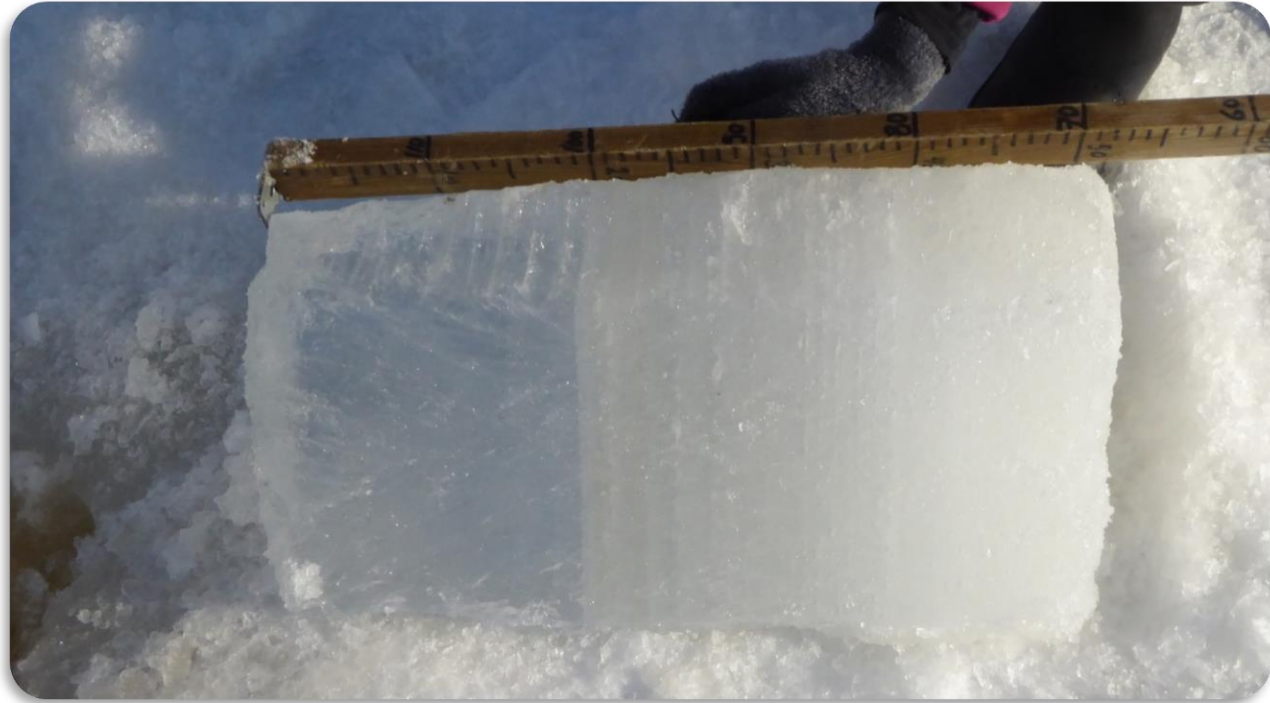


A simple model for predicting ice formation timing, thickness, and quality in lakes

S. Piccolroaz¹, M. Fregona^{1,2}, M. Leppäranta², I. Mammarella²



7th LAKES Workshop / 20-21-22 November / Milan
Parameterization of Lakes in Numerical Weather
Prediction and Climate Modelling 2024



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Motivation

Why is lake ice important?



Safety reasons
(transportation)



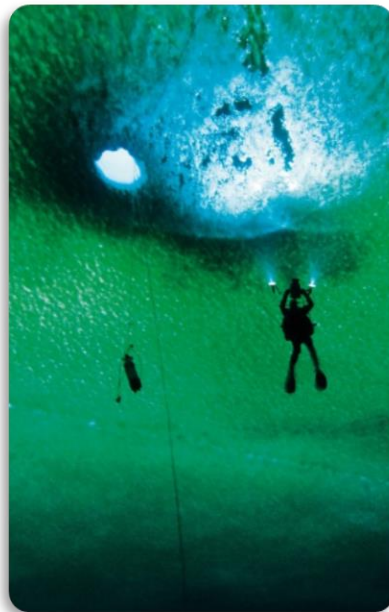
Impact on aquatic ecosystems
(light penetration, turbulence)



Human activities
(fishing, skating, culture)
Knoll et al. (2019)



Climate change
(relevant indicator)

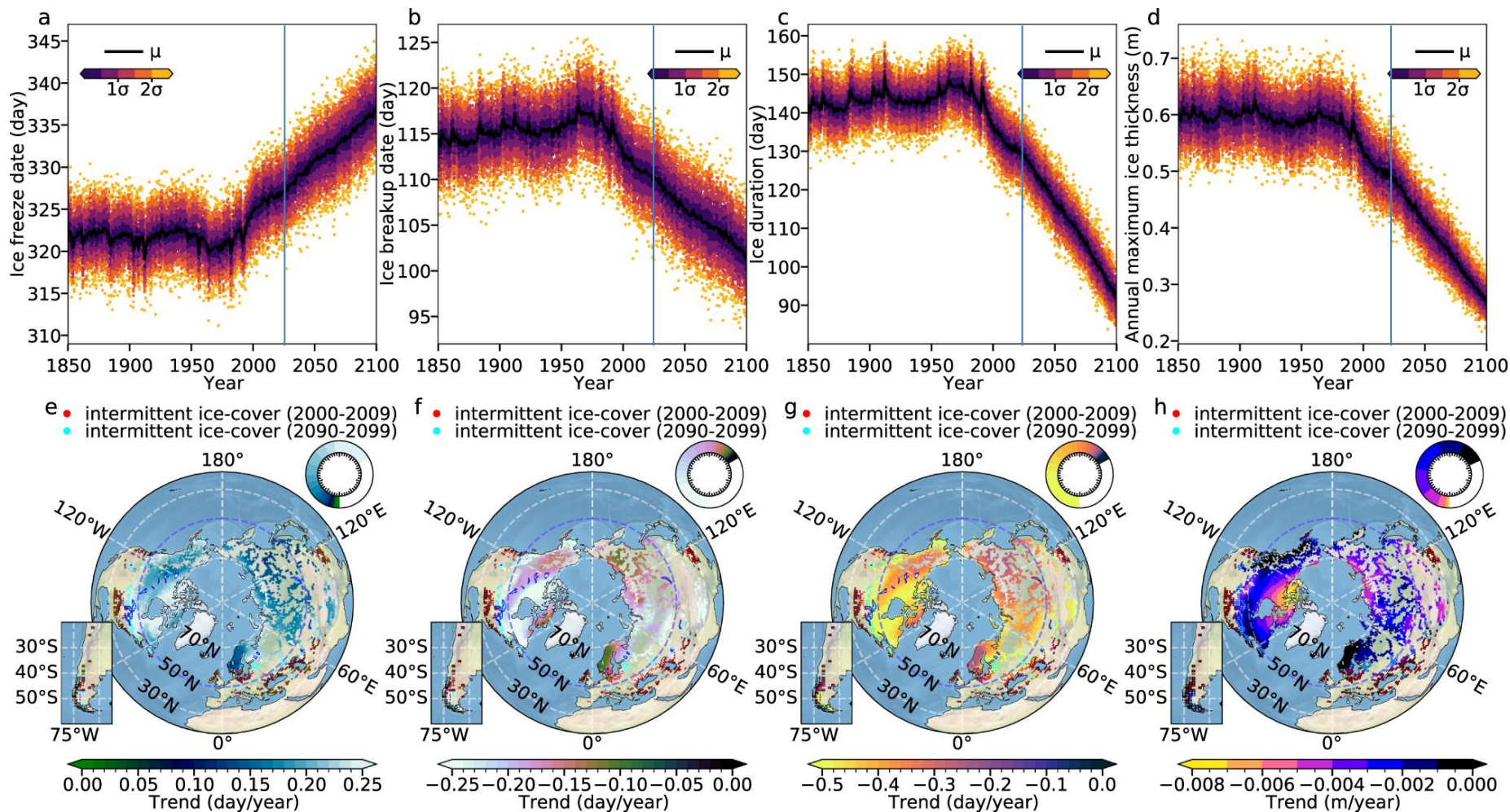


Motivation

In the next 80 years

Ice coverage: - **38 days**

Maximum ice thickness: - **0.23 m**



The *air2water* model

Hybrid physically-based/statistical model for **LSWT** prediction

Relies on **few input data** (only air temperature), while retaining the same **high performance** of deterministic models

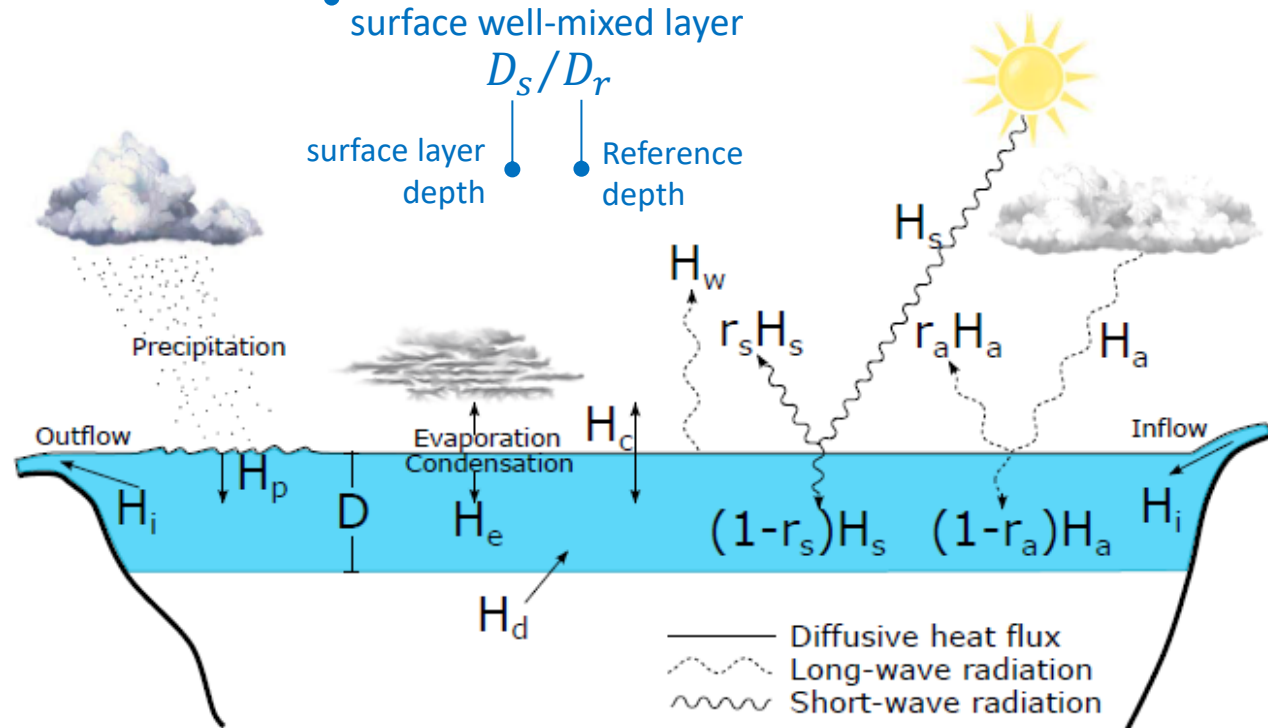
$$\rho_w c_p V_s \frac{dT_w}{dt} = \phi_{net} A$$

• net heat flux
 • surface area
 • surface layer volume
 • specific heat
 • water density

$$\frac{dT_w}{dt} = \frac{1}{\delta} \left\{ a_1 + a_2 T_a - a_3 T_w + a_5 \cos \left[2\pi \left(\frac{t}{t_y} - a_6 \right) \right] \right\}$$

• dimensionless depth of the surface well-mixed layer

D_s/D_r
 surface layer depth Reference depth



Piccolroaz et al., (2013)

Hydrol. Earth Syst. Sci., 17, 3323–3336, 2013
 www.hydrol-earth-syst-sci.net/17/3323/2013/
 doi:10.5194/hess-17-3323-2013
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Hydrology and Earth System Sciences

A simple lumped model to convert air temperature into surface water temperature in lakes

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Advances in Oceanography and Limnology, 2016, 7(1): 38–50
 doi: 10.4137/aol.2016.7(1)

Piccolroaz (2016)

ARTICLE

Prediction of lake surface temperature using the *air2water* model: guidelines, challenges, and future perspectives

Substantino Piccolroaz

Department of Civil, Environmental and Mechanical Engineering, University of
 Corresponding author: s.piccolroaz@unitn.it

ABSTRACT

Water temperature plays a primary role in controlling a wide range of physical, geochemical and ecological processes in lakes, with considerable influences on lake water quality and ecosystem functioning. Being able to reliably predict water temperature is therefore a desired goal, which stimulated the development of models of different type and complexity, ranging from simple regression-based models to more sophisticated process-based numerical models. However, both types of models suffer of some limitations: the first are not able to address some fundamental physical processes (e.g., thermal stratification), while the latter generally require a large amount of data to be applied, which are not always available. In this work, lake surface temperature is estimated by means of *air2water*, a hybrid physically based-statistical model, which is able to provide a robust, predictive understanding of LST dynamics knowing air temperature only. This model-based approach provides results that are comparable with those obtained by using process-based models (i.e., root mean square error on the order of 1°C, at daily scales), while retaining the simplicity and parsimony of regression-based models, thus making it a good candidate for long-term applications. The aim of the present work is to provide the reader with useful and practical guidelines for proper use of the *air2water* model and for critical analysis of results. Two case studies have been selected for the analysis: Lake Superior and Lake Erie (USA). These are clear and emblematic examples of a deep and a shallow temperate lake characterized by markedly dif-

The *air2water* model

Hybrid physically-based/statistical model for **LSWT** prediction

Relies on **few input data** (only air temperature), while retaining the same **high performance** of deterministic models

$$\rho_w c_p V_s \frac{dT_w}{dt} = \phi_{net} A$$

• net heat flux
 • surface area
 • surface layer volume
 • specific heat
 • water density

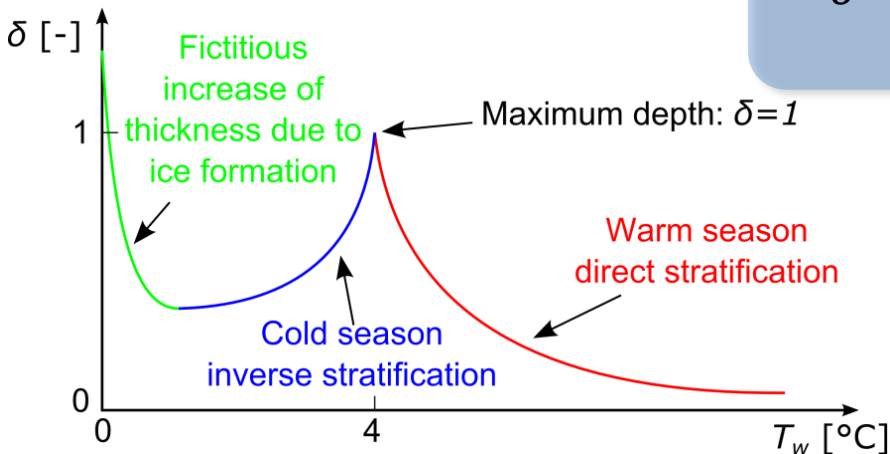
$$\frac{dT_w}{dt} = \frac{1}{\delta} \left\{ a_1 + a_2 T_a - a_3 T_w + a_5 \cos \left[2\pi \left(\frac{t}{t_y} - a_6 \right) \right] \right\}$$

• dimensionless depth of the surface well-mixed layer

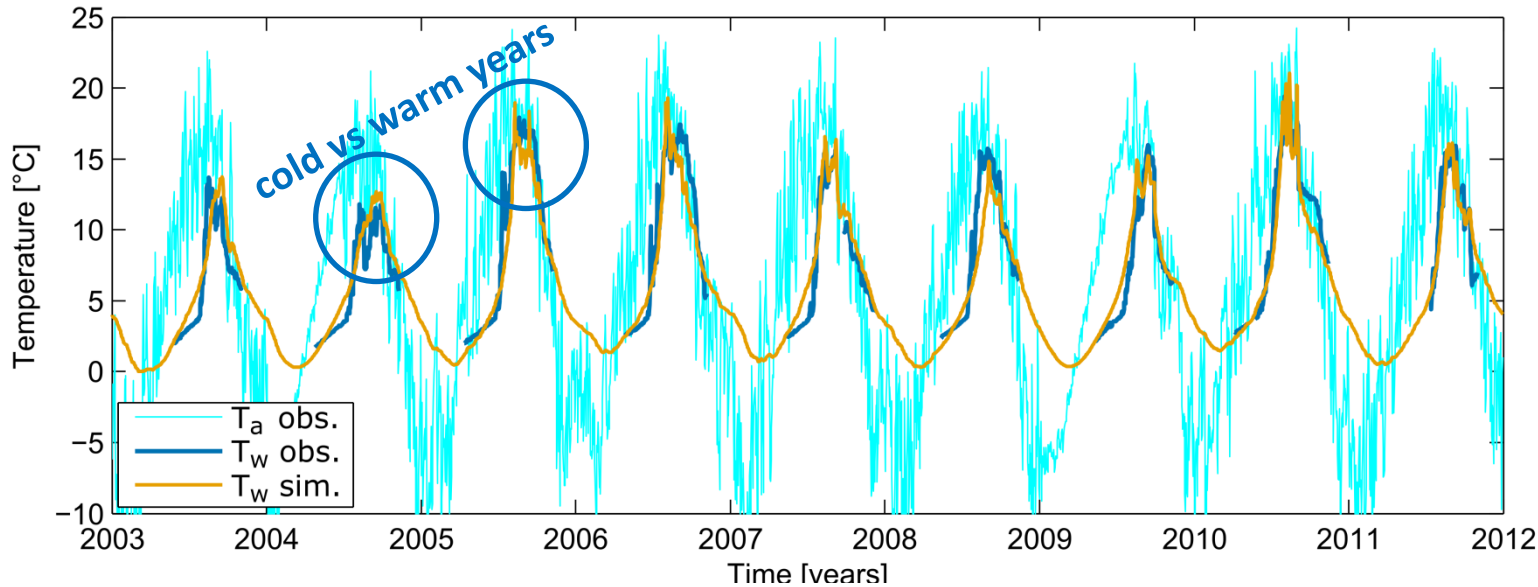
$$\delta = \exp \left(- \frac{T_w - T_h}{a_4} \right) \quad \text{for } T_w \geq T_h$$

$$\delta = \exp \left(- \frac{T_h - T_w}{a_7} \right) + \exp \left(- \frac{T_w}{a_8} \right) \quad \text{for } T_w < T_h$$

A simple **ODE** with an **empirical closure** for stratification
8 parameters



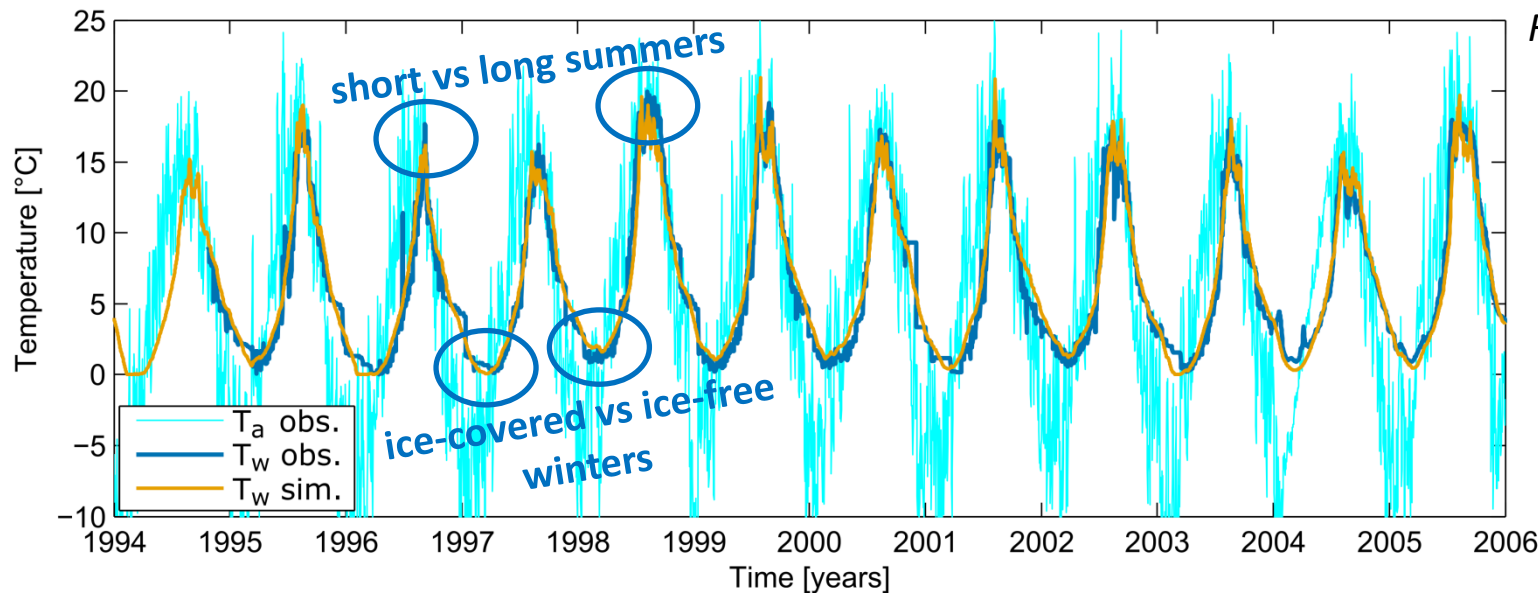
Application to Lake Superior



In-situ

Calibration:
RMSE = 1.40 °C
NSE=0.91

Validation:
RMSE = 1.71 °C
NSE=0.90



Remote sensing



Calibration:
RMSE = 1.17 °C
NSE=0.95

Validation:
RMSE = 1.02 °C
NSE=0.97

The ice module

Weyhenmeyer et al. (2022)



Black ice

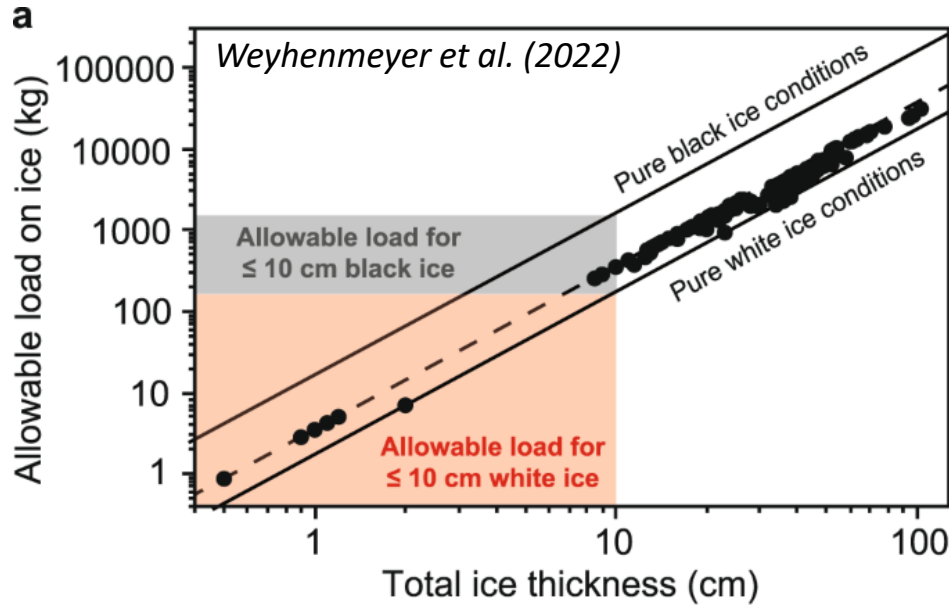
Formed from the lake water freezing



White ice

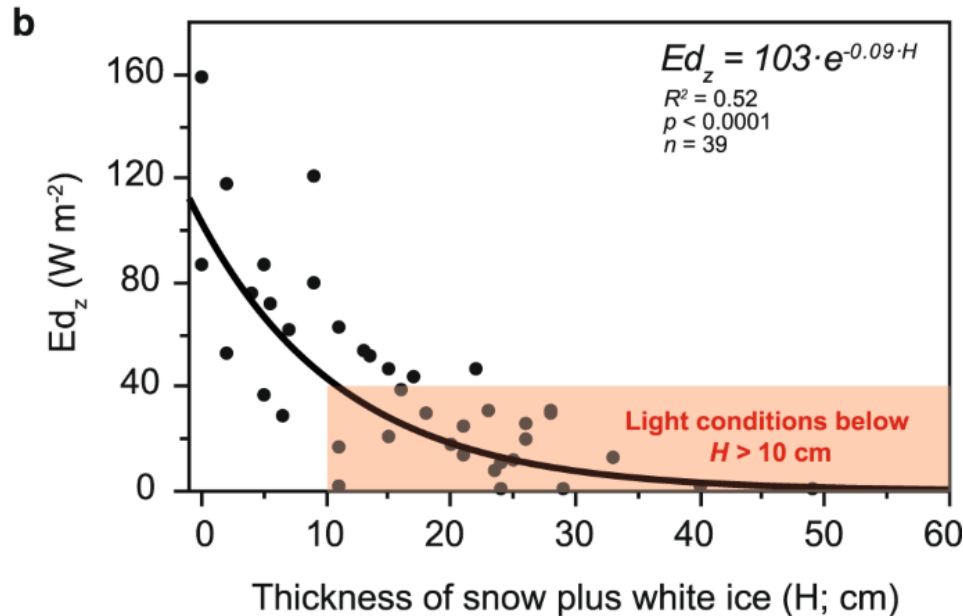
Formed when snow accumulates on ice, melts, and refreezes. Or when rain falls on the snow layer or the snow layer is flooded.

The ice module



Safety

White ice is unstable with a low bearing capacity than black ice



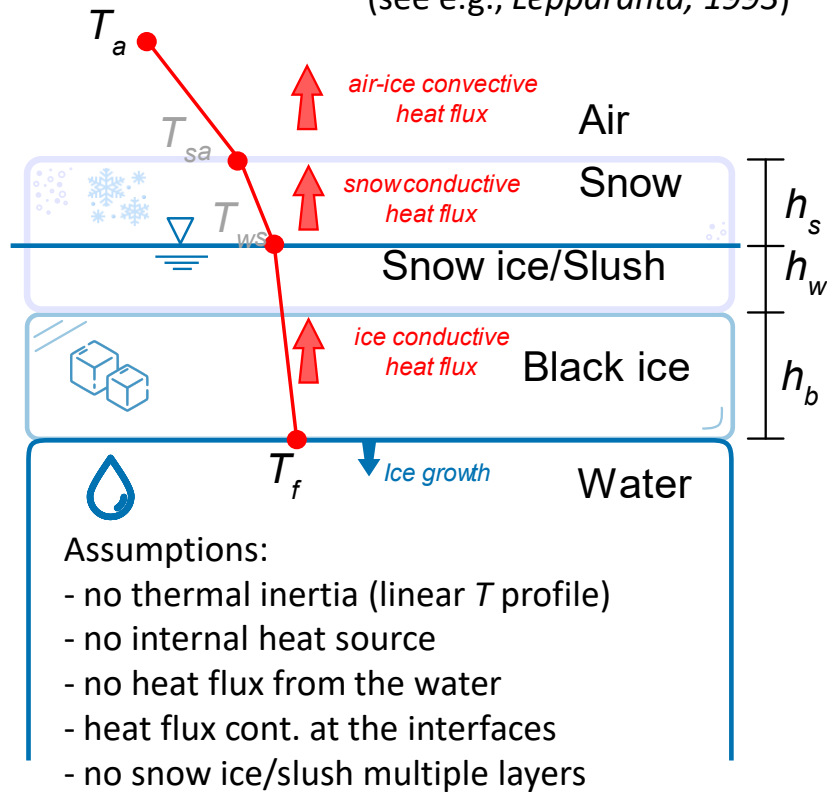
Under-ice ecology

White (*opaque*) ice has higher reflectance than black (*clear*) ice, reducing the amount of sunlight penetrating through ice.



The ice module

Growth equation Stefan's Law including **ice-snow-atmosphere coupling**
 (see e.g., Leppäranta, 1993)



<https://www.klikk.no/produkt/hjemmesider/villmarksliv/viltogvariart/stalis-3136455>



Algorithm for flooding
(buoyancy)



Observed/modelled precipitation
(liquid and solid)

$$\frac{dh_b}{dt} = \frac{1}{L_f \rho_i h_b / (k_i) + h_w / (k_i) + h_s / (k_s) + 1/a_{10}} (T_f - T_a + a_9)$$

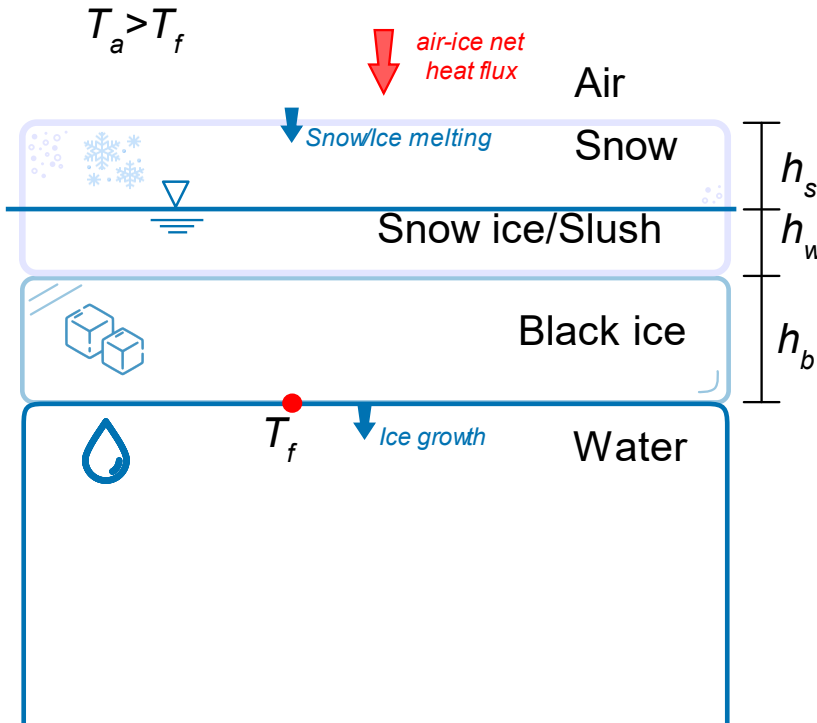
Known thermophysical
properties of ice

a_9 : to account for possible bias correction of the (only) forcing T_a
 a_{10} : air convective heat transfer coefficient

The ice module

Melting equation Surface melting is triggered whenever the surface temperature is at the **melting point**

$T_a > T_f + a_9$



$$\frac{dh_l}{dt} = -\frac{\phi_{net}}{L_f \rho_l}$$

The net surface heat flux determines the rate of melting.
(l = upper layer)

$$\begin{aligned} \rho_w c_p V_s \frac{dT_w}{dt} &= \phi_{net} A \\ \frac{dT_w}{dt} &= \frac{\phi_{net} A}{\rho_w c_p V_s} = \frac{\phi_{net}}{\rho_w c_p D_s} \\ &= \frac{1}{\delta} \left\{ a_1 + a_2 T_a - a_3 T_w + a_5 \cos \left[2\pi \left(\frac{t}{t_y} - a_6 \right) \right] \right\} \\ \delta &= D_s / D_r \end{aligned}$$

$$\begin{aligned} \phi_{net} &= D_r \rho_w c_p \left\{ a_1 + a_2 T_a - \cancel{a_3 T_w} + a_5 \cos \left[2\pi \left(\frac{t}{t_y} - a_6 \right) \right] \right\} \\ T_w &= T_f = 0^\circ\text{C} \end{aligned}$$

$$\frac{dh_l}{dt} = -\frac{a_{11} D_r \rho_w c_p}{L_f \rho_l} \left\{ a_1 + a_2 T_a + a_5 \cos \left[2\pi \left(\frac{t}{t_y} - a_6 \right) \right] \right\}$$

Known thermophysical properties of water/ice

a_{11} : a parameter mainly accounting for possible differences between ϕ_{net} parameterization during ice-free/ice-on seasons (see e.g., albedo)

The complete model

A system of two independent ODEs, with a total of 10 parameters:

$$\frac{dT_w}{dt} = \frac{1}{\delta} \left\{ a_1 + a_2 T_a - a_3 T_w + a_5 \cos \left[2\pi \left(\frac{t}{t_y} - a_6 \right) \right] \right\}$$


LSWT
6 par

Growth

$$\frac{dh_b}{dt} = \frac{1}{L_f \rho_i h_b / k_i + h_w / k_i + h_s / k_s + 1/a_{10}} (T_f - T_a - a_9)$$

Melting

$$\frac{dh_l}{dt} = - \frac{a_{11} D_r \rho_w c_p}{L_f \rho_l} \left\{ a_1 + a_2 T_a + a_5 \cos \left[2\pi \left(\frac{t}{t_y} - a_6 \right) \right] \right\}$$


Ice
4 par

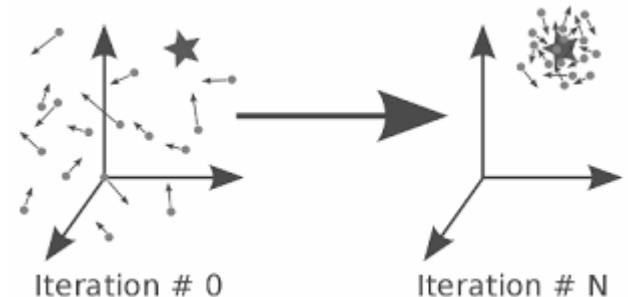
Model calibration and performance:

Multi-objective optimization problem:

$$NSE_{tot} = \beta NSE_{LSWT} + (1 - \beta) NSE_{Ice}$$

$$NSE = 1 - \frac{\sum_{i=1}^n (obs_i - sim_i)^2}{\sum_{i=1}^n (obs_i - \overline{obs})^2}$$

PSO (Particle Swarm Optimization)

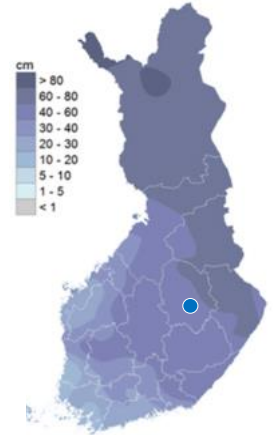


Results | Lake Kallavesi

- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m

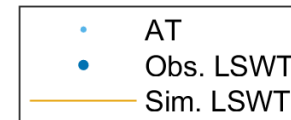
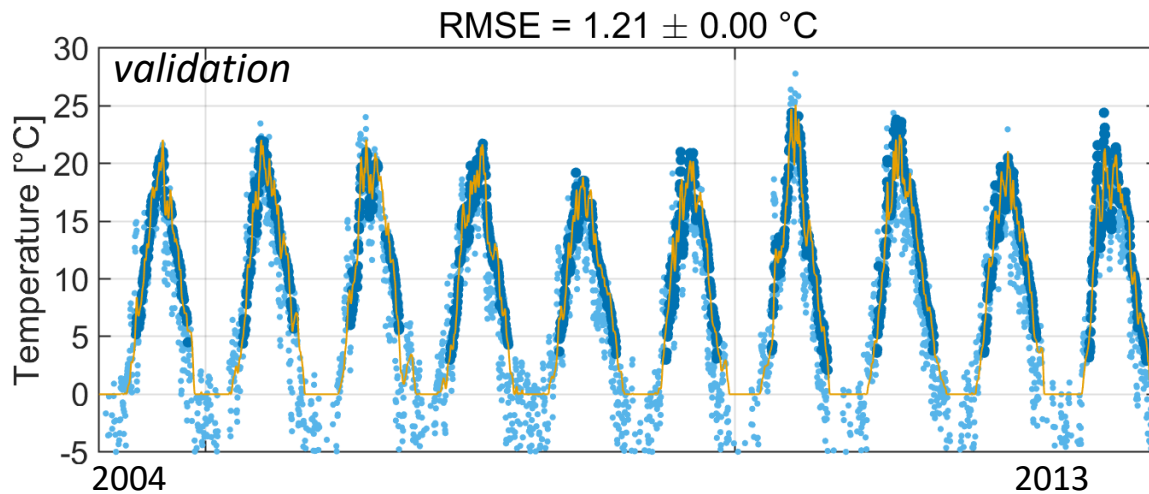
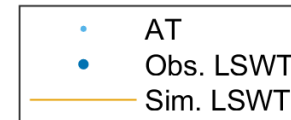
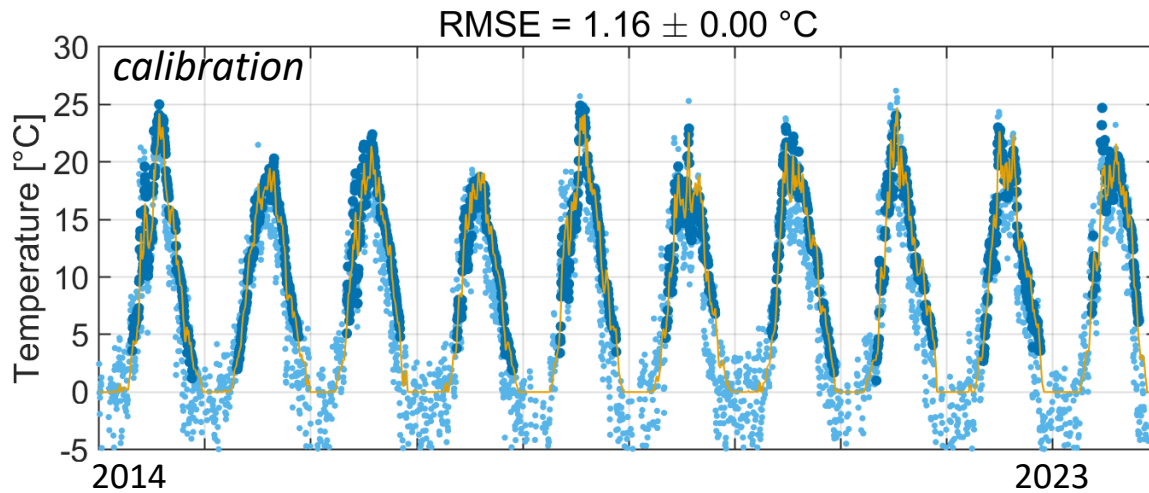
$$NSE_{tot} = NSE_{LSWT}$$

air2water model with 6 parameters



Avg. Snow depth on March 15

Neuenschwander et al. (2020)

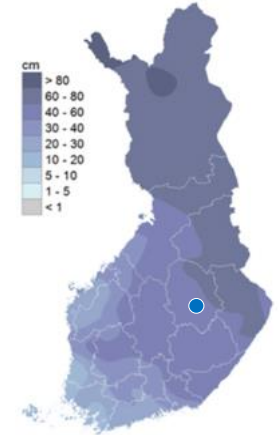


Results | Lake Kallavesi

- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m

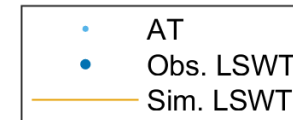
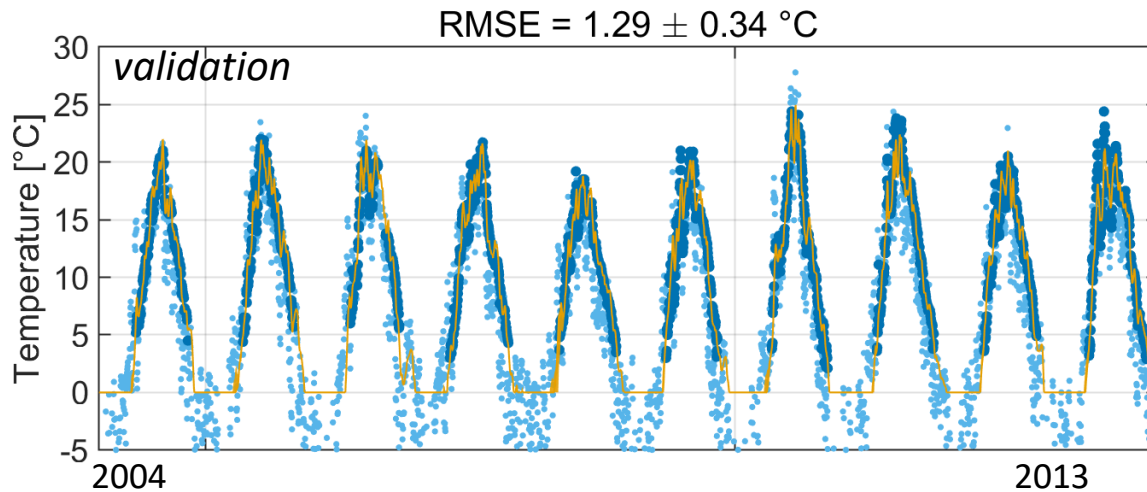
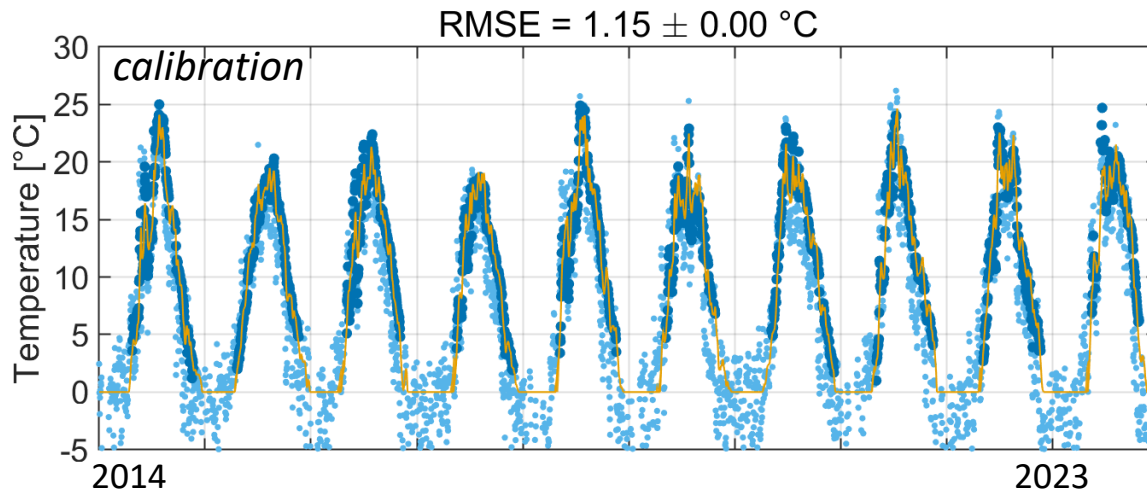
$$NSE_{tot} = \beta NSE_{LSWT} + (1 - \beta) NSE_{Ice}$$

Case when $\beta = 1$



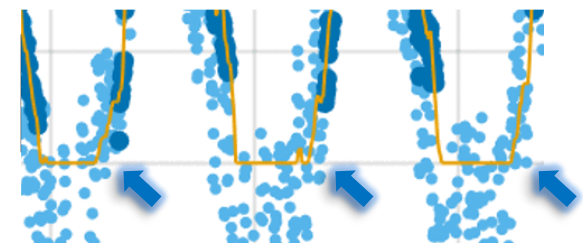
Avg. Snow depth on March 15

Neuenschwander et al. (2020)



*Overall similar performance.
Slight worsening in validation but ...*

air2water

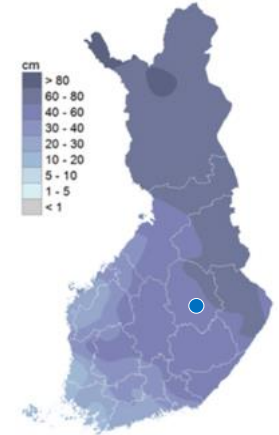


Results | Lake Kallavesi

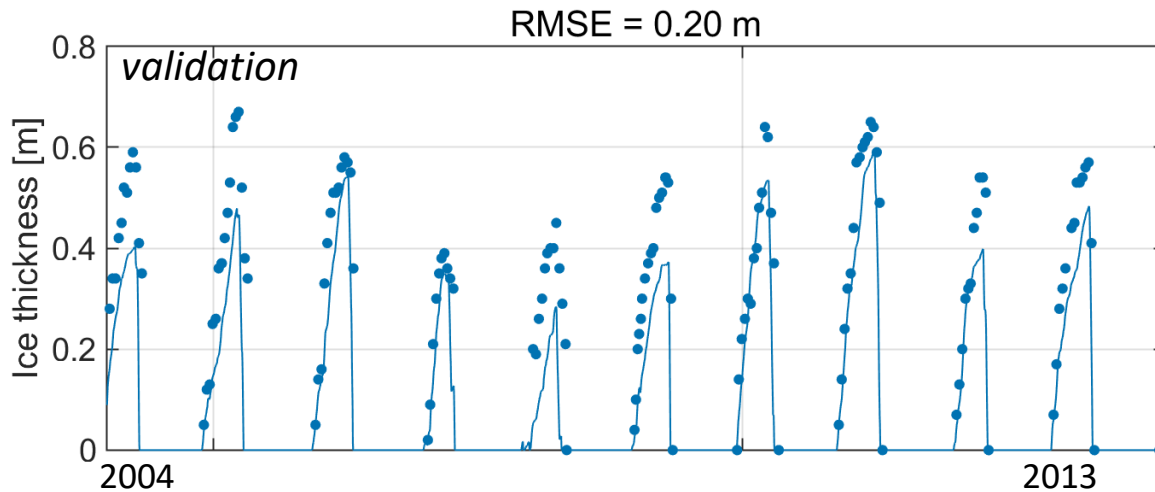
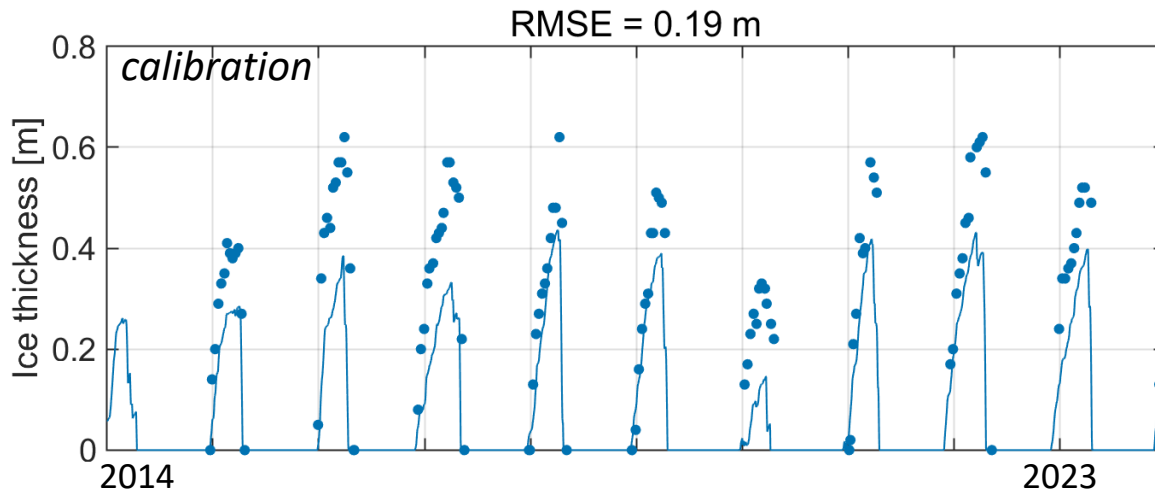
- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m

$$NSE_{tot} = \beta NSE_{LSWT} + (1 - \beta) NSE_{Ice}$$

Case when $\beta = 1$



Avg. Snow depth on March 15



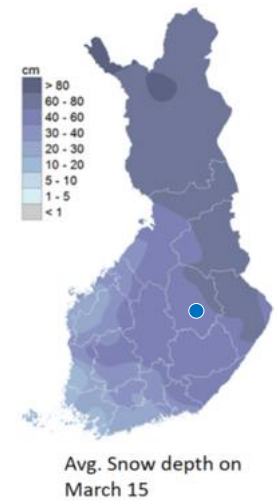
... able to reproduce interannual variability of total ice with a reasonable performance ...

Results | Lake Kallavesi

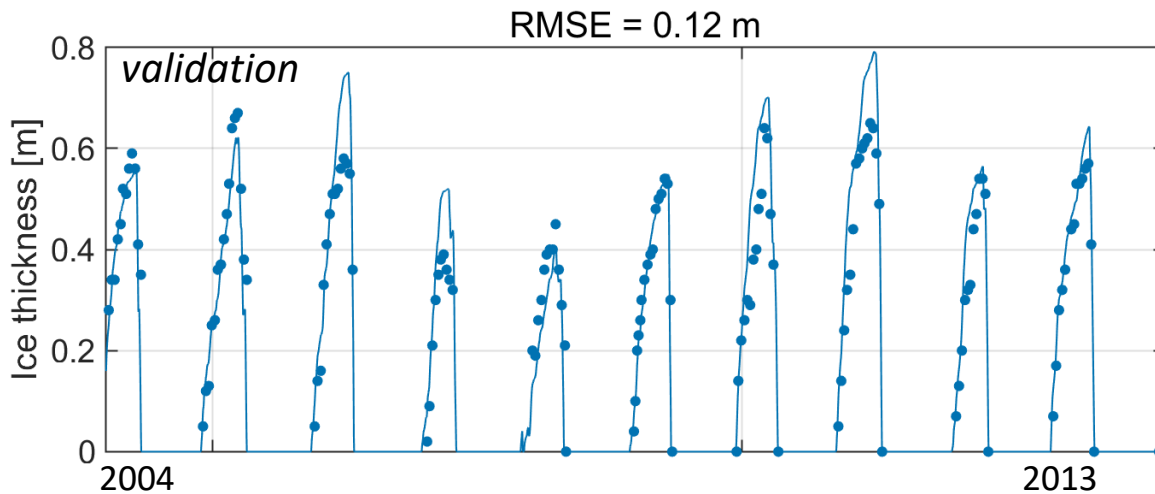
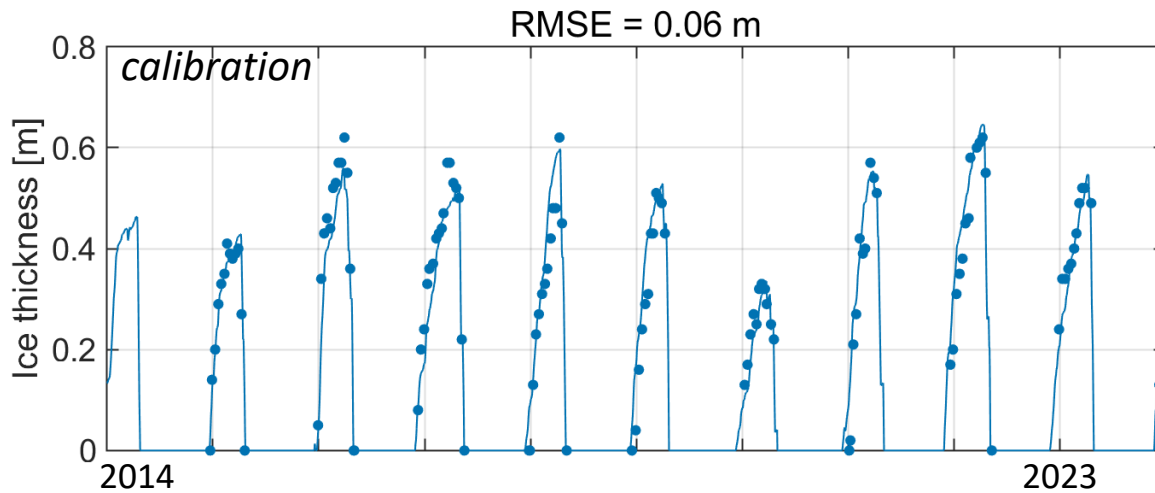
- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m

$$NSE_{tot} = \beta NSE_{LSWT} + (1 - \beta) NSE_{Ice}$$

Case when $\beta = 0.5$



Neuenschwander et al. (2020)



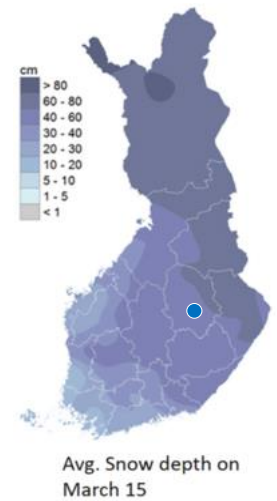
... which increases when using ice thickness data in calibration ...

Results | Lake Kallavesi

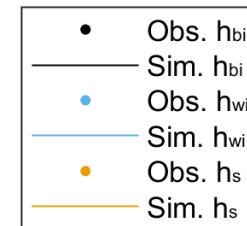
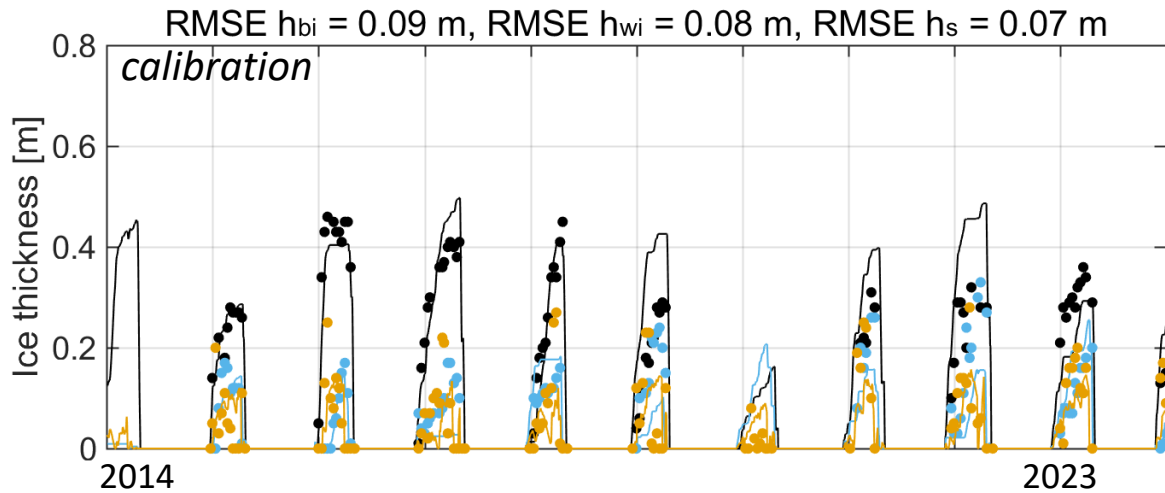
- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m

$$NSE_{tot} = \beta NSE_{LSWT} + (1 - \beta) NSE_{Ice}$$

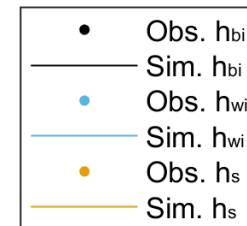
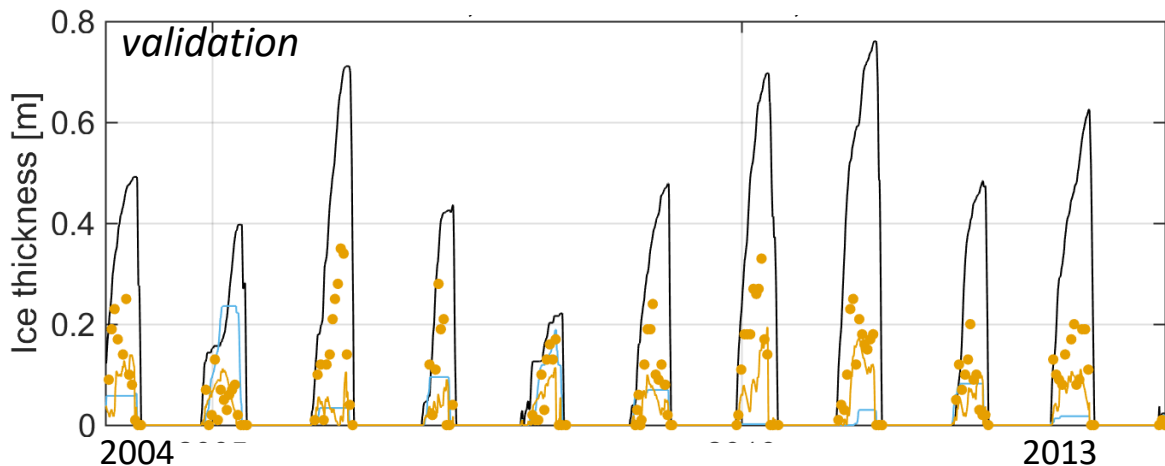
Case when $\beta = 0.5$



Neuenschwander et al. (2020)



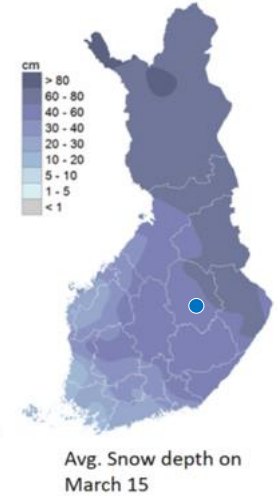
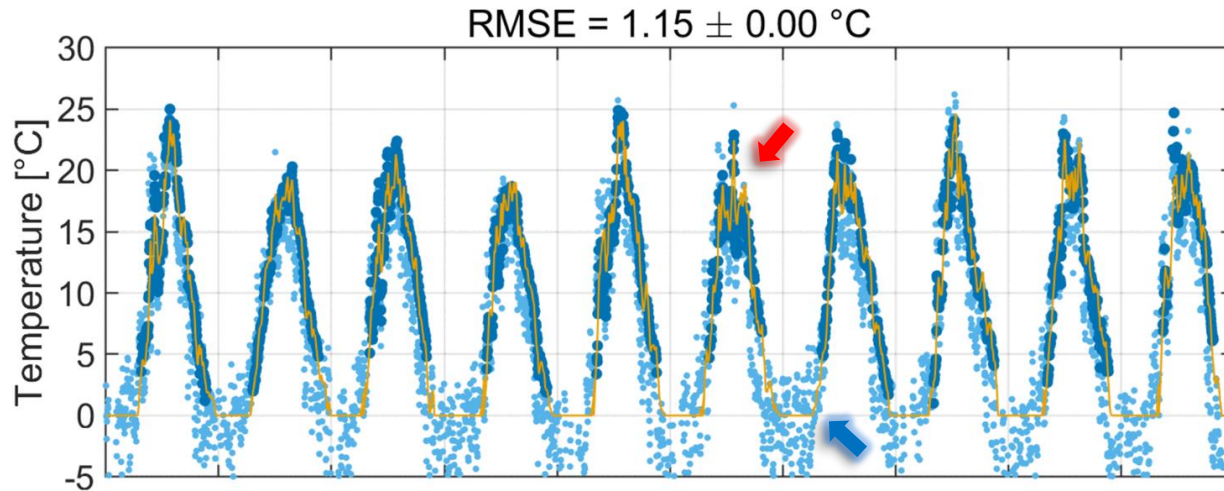
... and allows predicting ice quality as well.



Note: no ice quality data were available for the validation period.

Results | Lake Kallavesi

- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m



air2water + ice
 $\beta = 1$

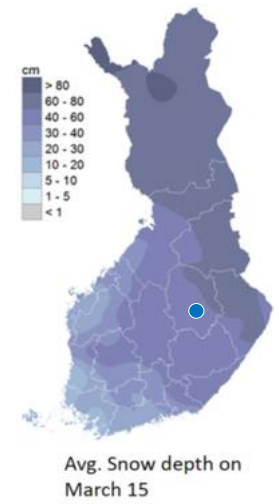


There is no free lunch:

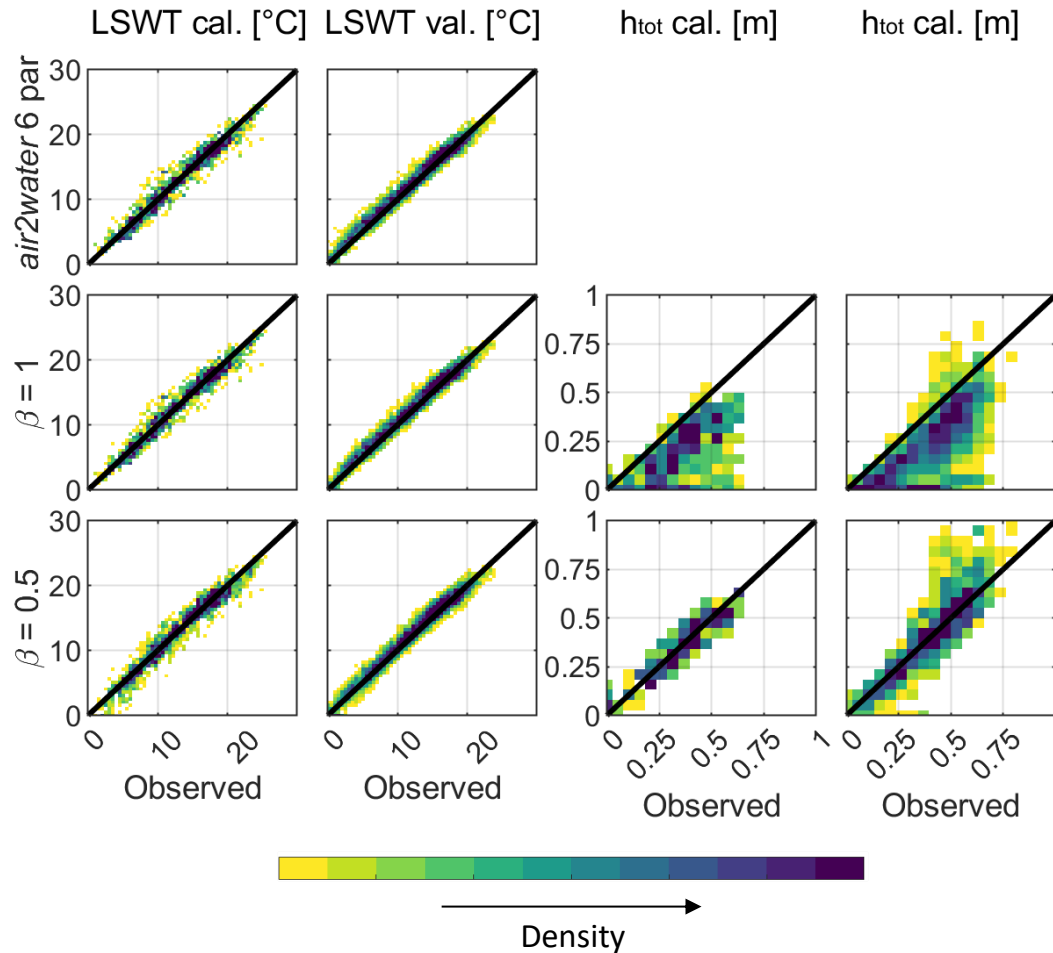
- *slight worsening in LSWT prediction*
- *mainly in the summer period (largest natural variability)*
- *but better capturing of the ice on-off timing*

Results | Lake Kallavesi

- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m

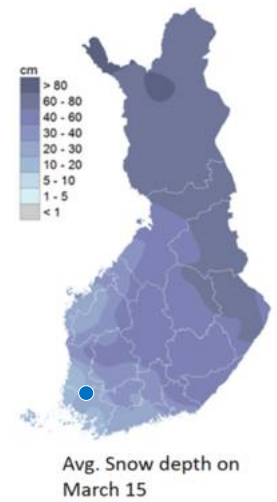


Neuenschwander et al. (2020)

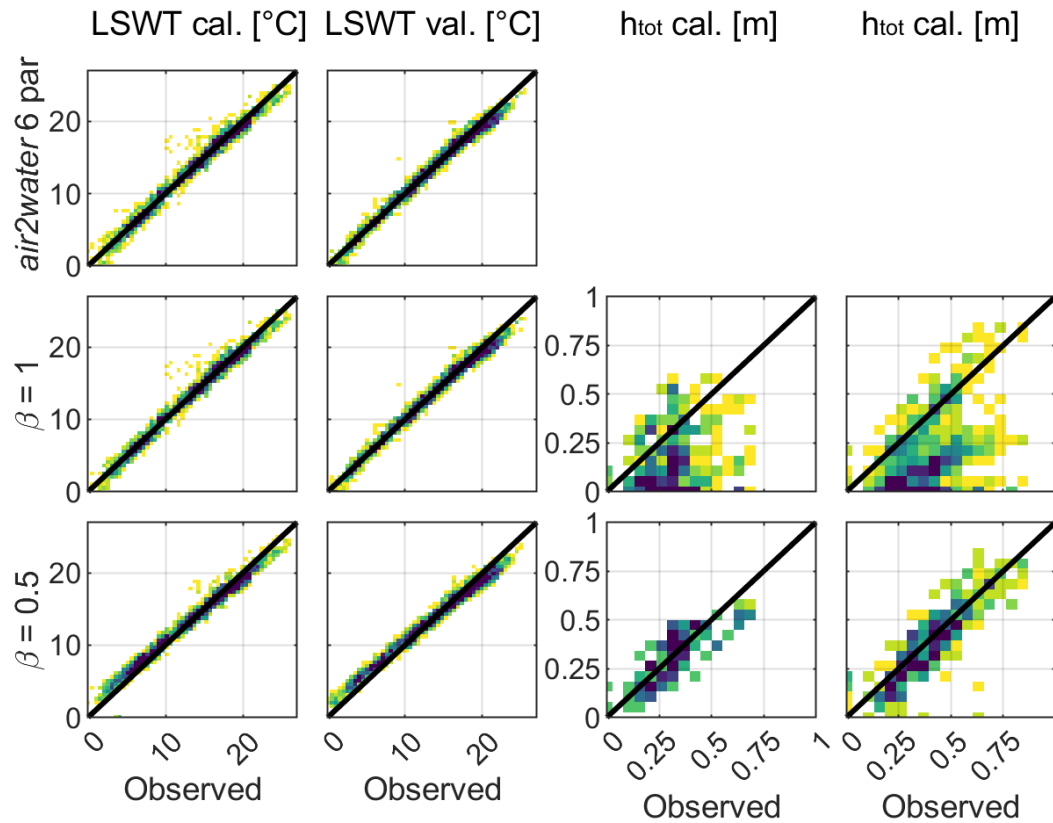


Results | Lake Pyhajarvi

- Eutrophic lake
- Southern Finland
- Mean depth 5.4 m

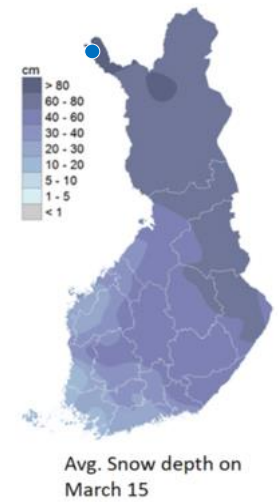


Neuenschwander et al. (2020)

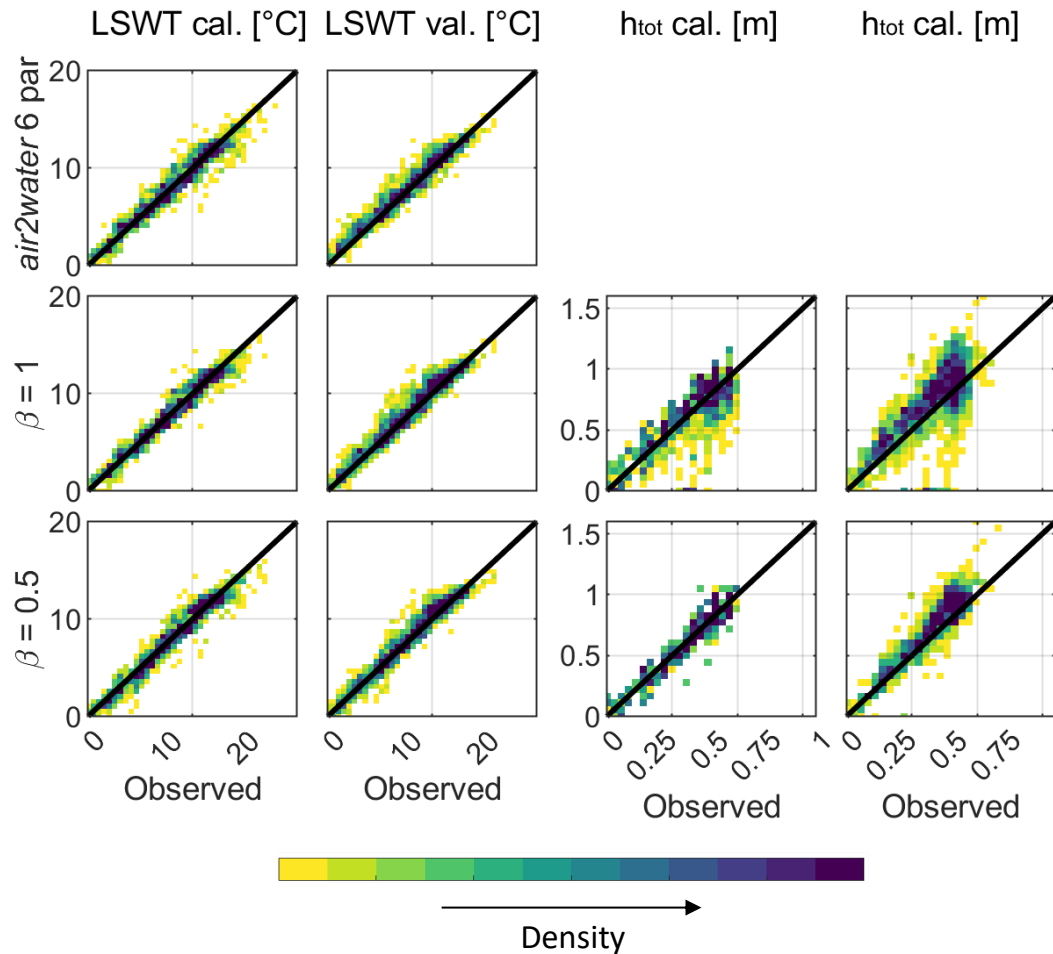


Results | Lake Kilpisjarvi

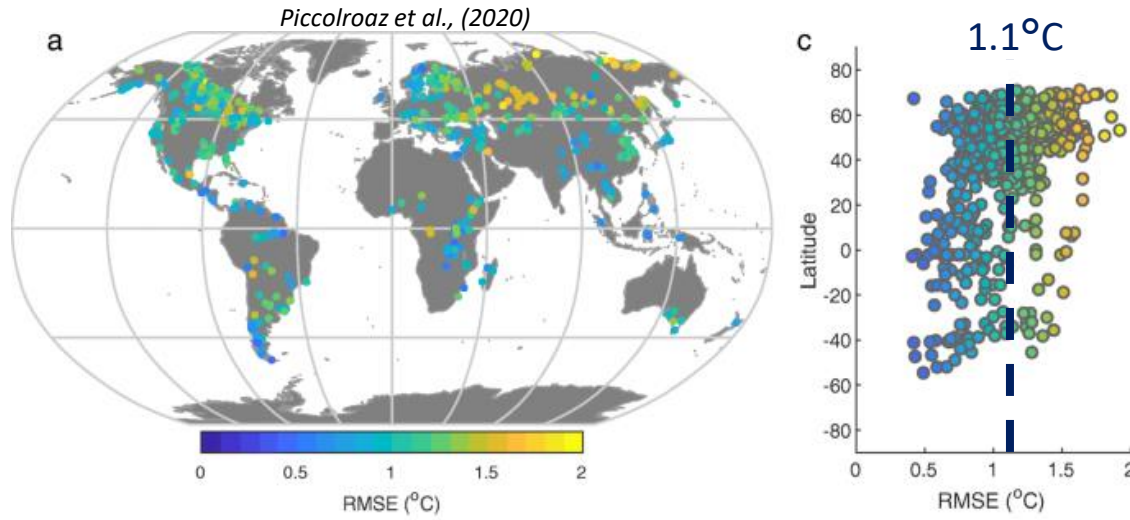
- Oligotrophic lake
- Northern Finland (tundra)
- Mean depth 19.5 m



Neuenschwander et al. (2020)



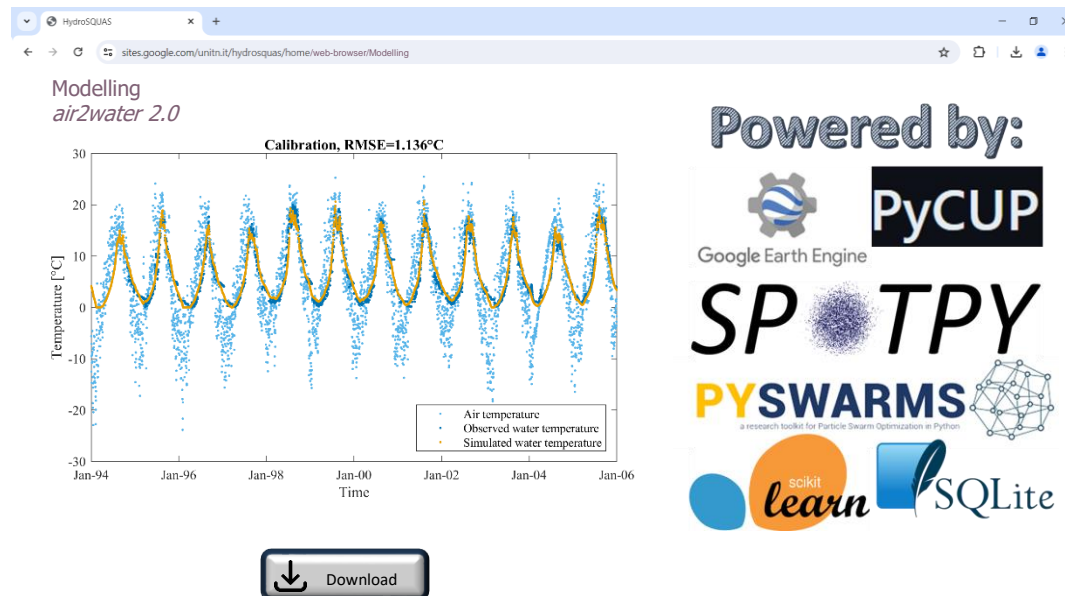
Current developments



Regionalization of the model parameters



- application to non monitored lakes
- coupling with climate models



Release of web portal for running the model on-line



Conclusions

We extended a **simple model** (*air2water*) adding an ice module to predict total **ice thickness**, using **air temperature** as the only input forcing.

We added **precipitation** as input forcing and modified the ice module in order to simulate **ice quality** (black and white ice, but also slush and snow thicknesses)

Good model performance, coherent with that of more complex models:

$$RMSE_{LSWT} \sim 1 \text{ } ^\circ\text{C}$$

$$RMSE_{Ice} \sim 0.1 \text{ m}$$

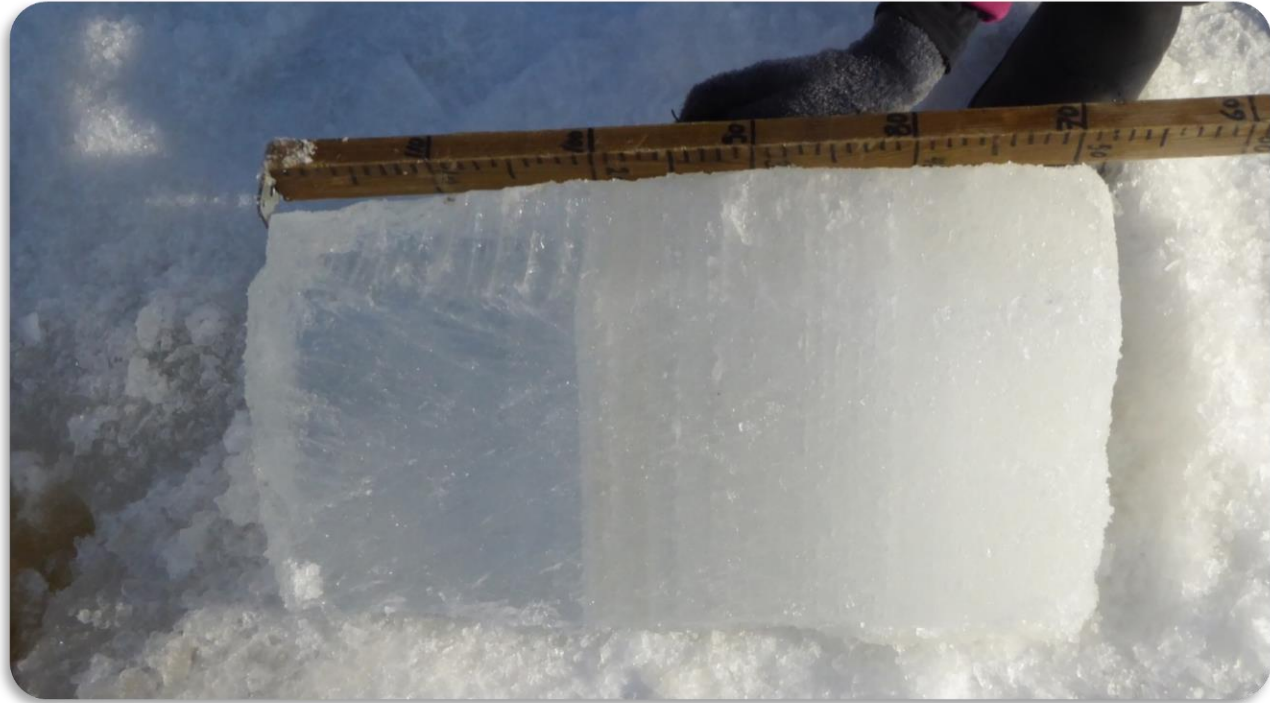
When using **only LSWT observations** for model calibration, the ice thickness model **performance decreases** (but still $RMSE_{Ice} \sim 0.1 \text{ m}$).

In these cases, the performance of ice quality simulation worsens but is still reasonable. Access to good (representative) precipitation data is needed.

The model is **simple** and **parsimonious** but **physically based** and looks robust. It can be a valid tool for large-scale and long-term simulations.

A simple model for predicting ice formation timing, thickness, and quality in lakes

S. Piccolroaz¹, M. Fregona^{1,2}, M. Leppäranta², I. Mammarella²



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Special Collection Call for Submissions

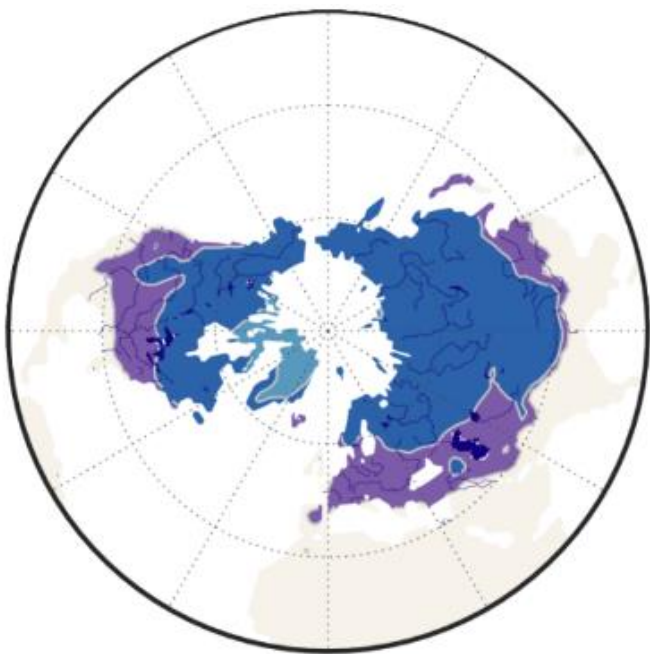
Integrating In Situ, Remote Sensing, And Physically Based Modeling Approaches to Understand Global Freshwater Ice Dynamics

Open for Submissions:

1 April 2023

Submission Deadline:

31 December 2024



SPECIAL COLLECTION ORGANIZERS:

Georgiy Kirillin, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Germany

Sebastiano Piccolroaz, University of Trento, Italy

Joshua Culpepper, York University, Canada

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