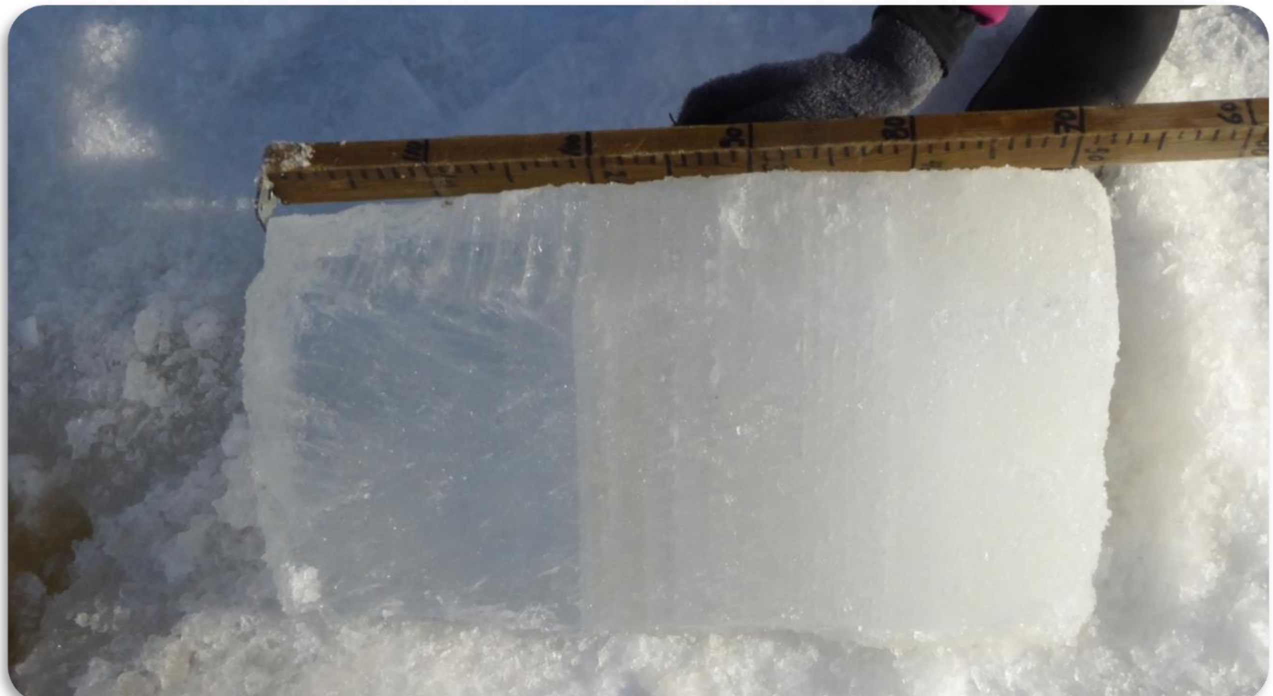
7th LAKES Workshop / 20-21-22 November / Milan
Parameterization of Lakes in Numerical Weather Prediction and Climate Modelling 2024

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

S. Piccolroaz[1], M. Fregona[1,2], M. Leppäranta[2], I. Mammarella[2]



UNIVERSITÀ DI TRENTO
INAR Institute for Atmospheric and Earth System Research
UNIVERSITY OF HELSINKI

s.piccolroaz@unitn.it
https://www.linkedin.com/in/sebastianopiccolroaz/

Motivation

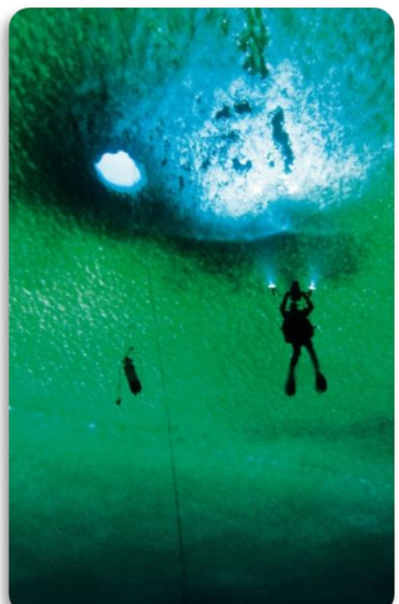
Why is lake ice important?

Safety reasons
(transportation)

Impact on acquatic ecosystems
(light penetration, turbulence)

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

Climate change
(relevant indicator)

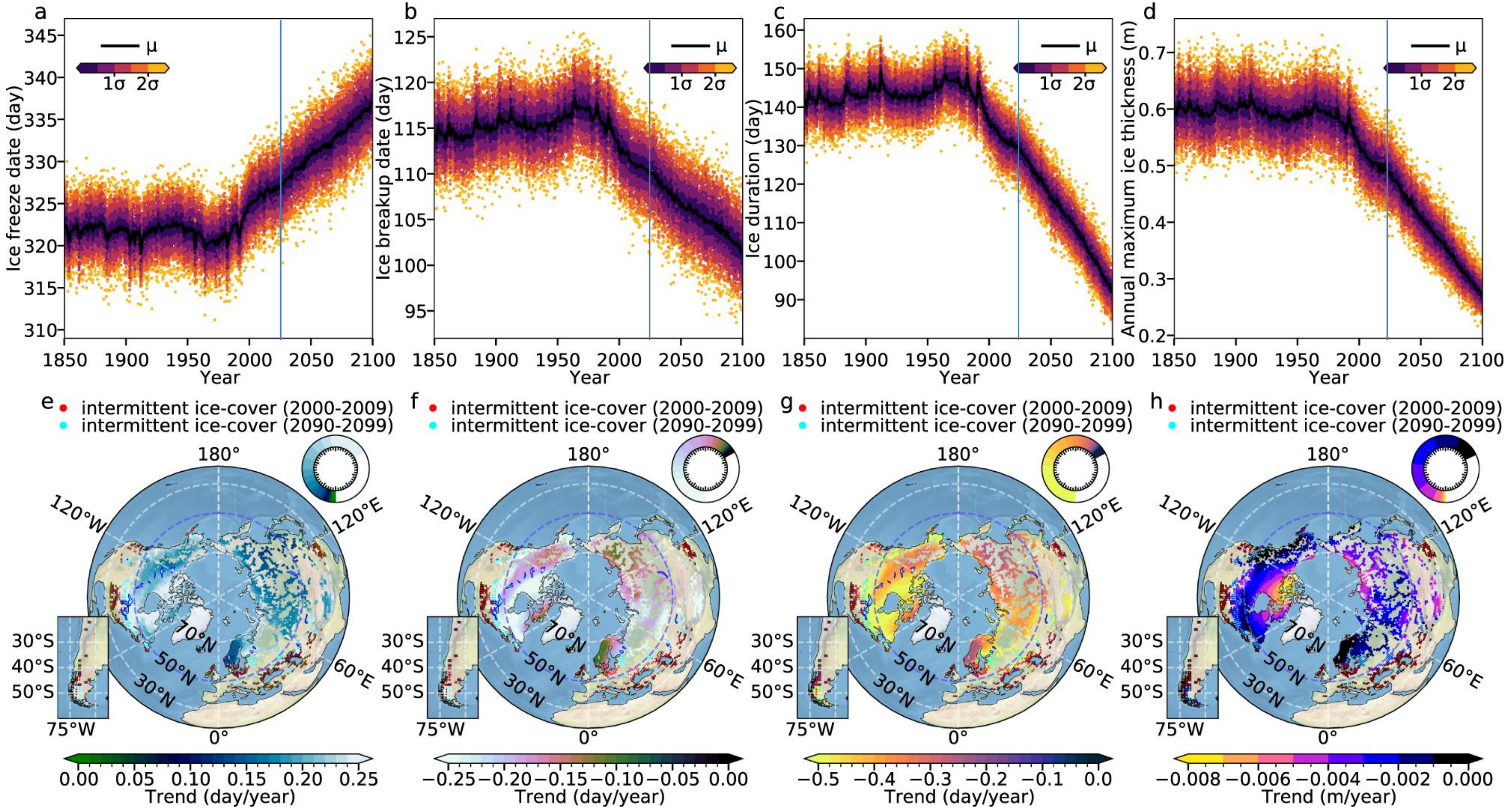


Motivation

In the next 80 years

Ice coverage: **- 38 days**

Maximum ice thickness: **- 0.23 m**



Huang et al., (2022)

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

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

- ρ_w: water density
- c_p: specific heat
- V_s: surface layer volume
- ϕ_{net}: net heat flux
- A: surface area

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

δ: dimensionless depth of the surface well-mixed layer

$$D_s / D_r$$

- D_s: surface layer depth
- D_r: Reference depth

Piccolroaz et al., (2013)

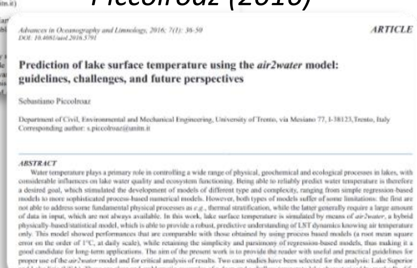

Hydrol. Earth Syst. Sci., 17, 3323–3338, 2013

Hydrology and Earth System Sciences

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

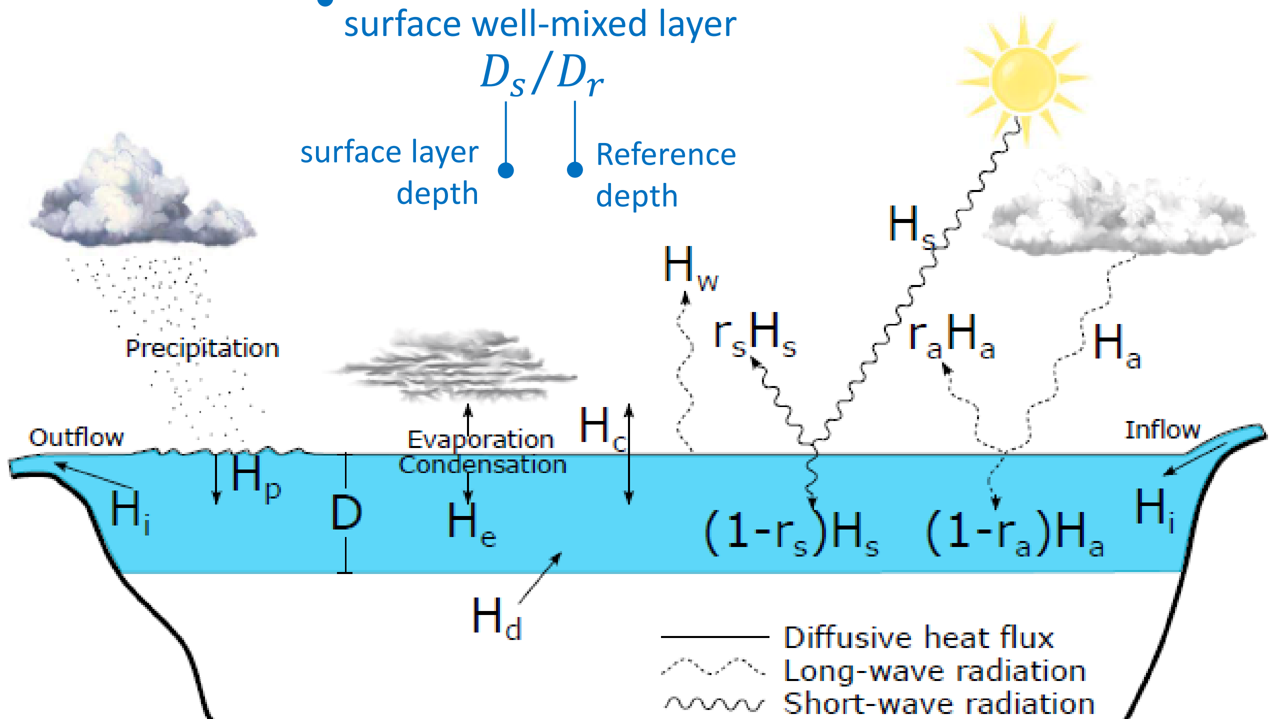
S. Piccolroaz, M. Toffolon, and B. Majone

Piccolroaz (2016)


ARTICLE

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

Sebastiano Piccolroaz



The *air2water* model

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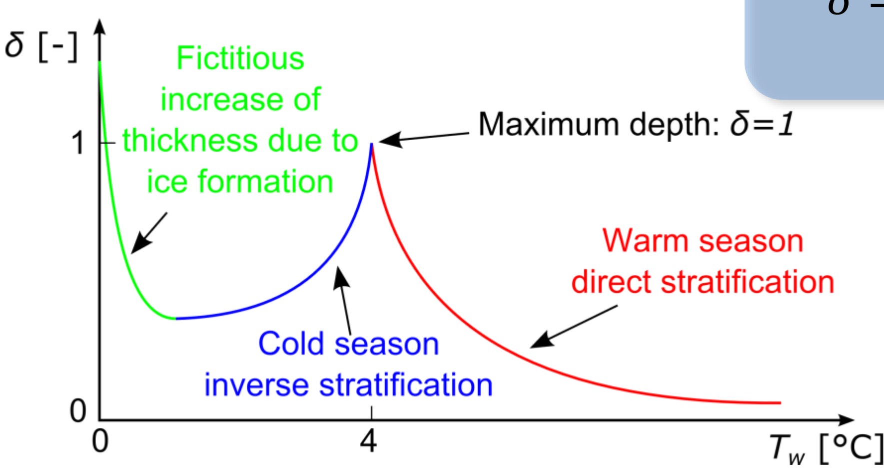
δ: dimensionless depth of the surface well-mixed layer

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

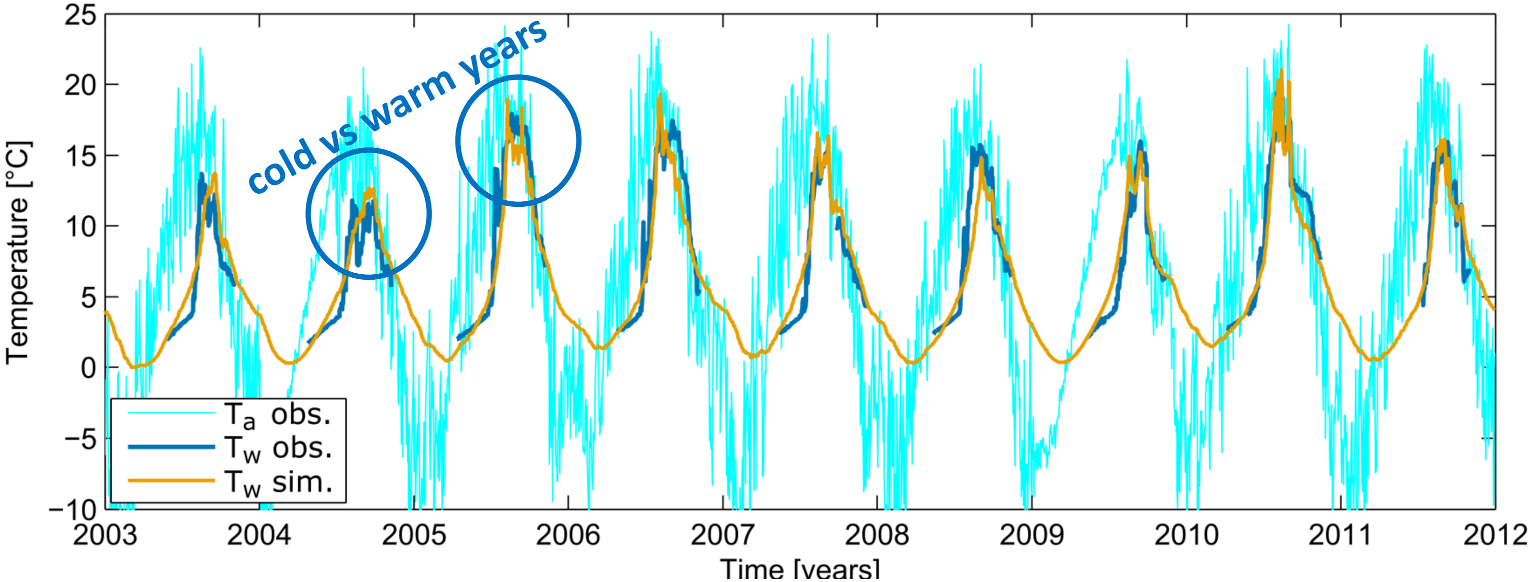
$$\delta = \exp\left(-\frac{T_h - T_w}{a_7}\right) + \exp\left(-\frac{T_w}{a_8}\right) \quad \text{for} \quad T_w < T_h$$



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

8 parameters

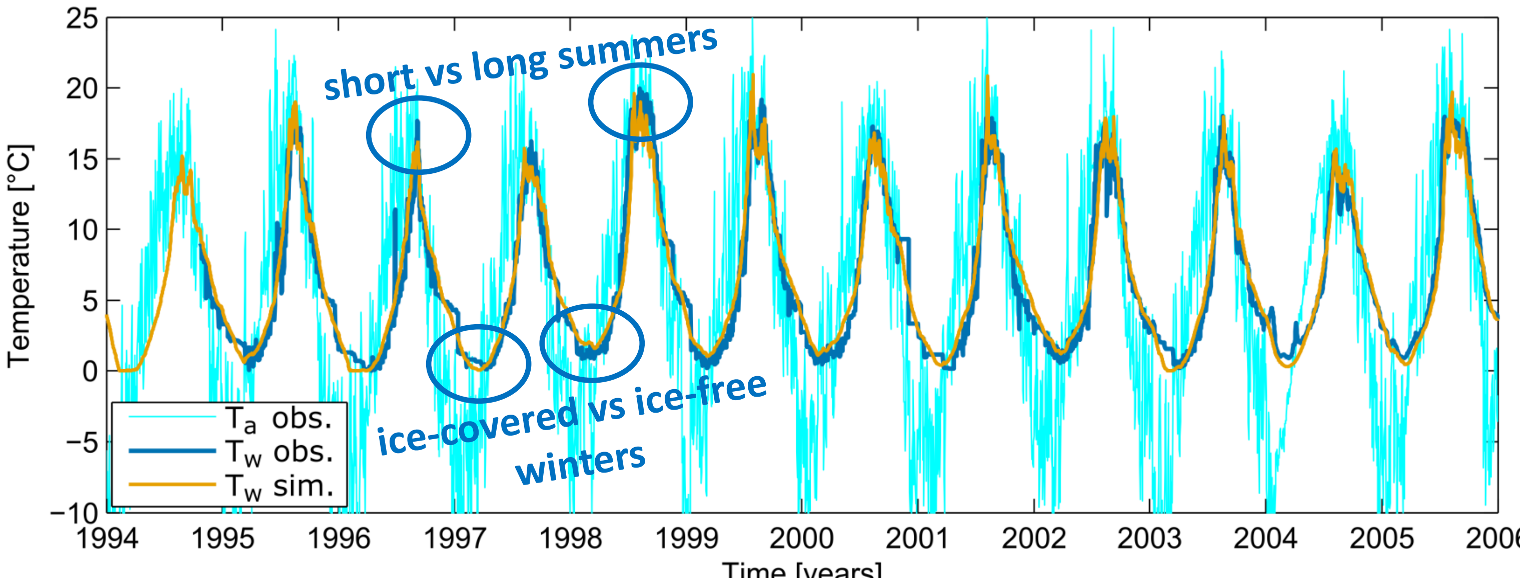
Application to Lake Superior



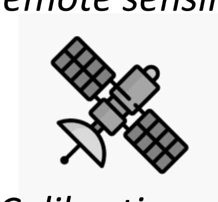
In-situ

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

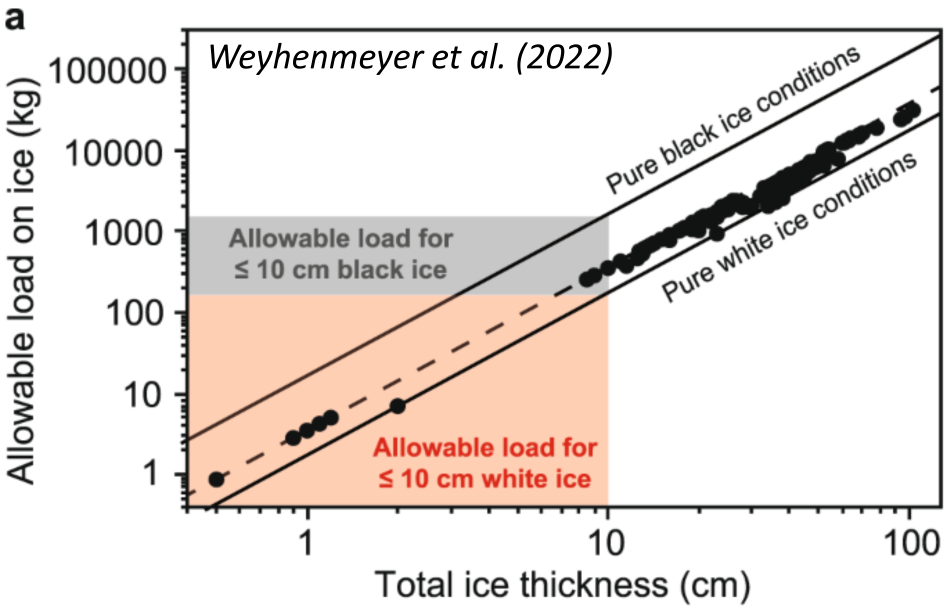
The ice module

Weyhenmeyer et al. (2022)

Formed from the lake water freezing

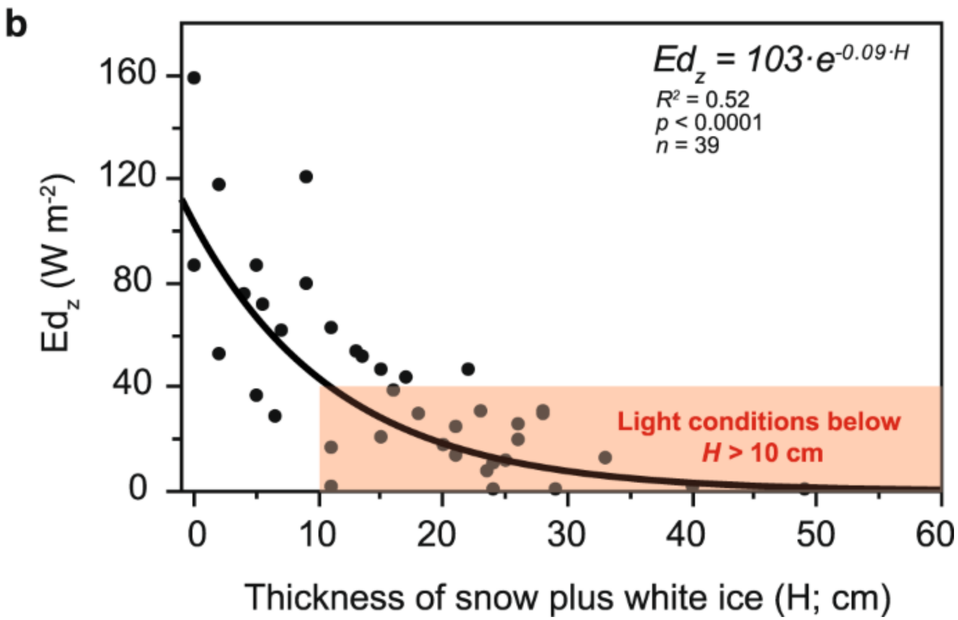
Formed when snow accumulates on ice, melts, and refreezes. Or when rain falls on the snow layer or the snow layer is flooded.

The ice module



Safety

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



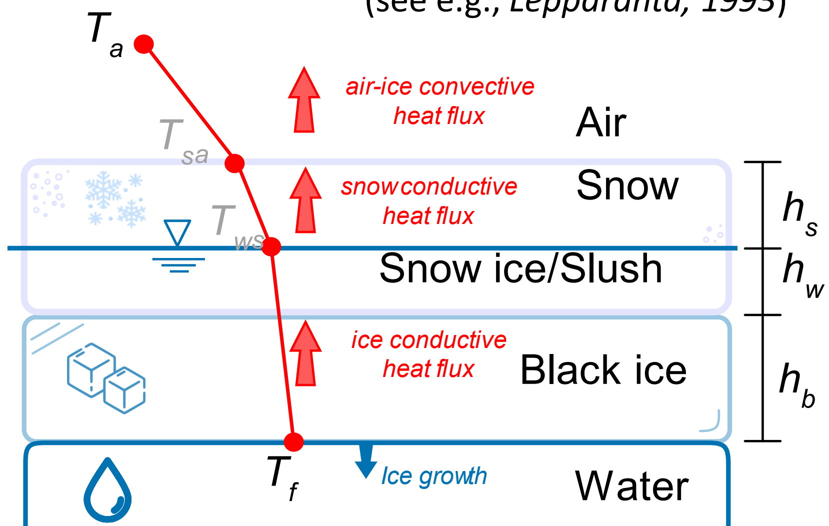
Under-ice ecology

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*)

$T_a < T_f + a_9$



Assumptions:
- no thermal inertia (linear *T* profile)
- no internal heat source
- no heat flux from the water
- heat flux cont. at the interfaces
- no snow ice/slush multiple layers

https://www.klikk.no/produkthjemmesider/villmarksliv/viltogvariert/stalis-3136455

Algorithm for flooding (buoyancy)

Observed/modelled precipitation (liquid and solid)

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

Known thermophysical properties of ice

a_9: to account for possible bias correction of the (only) forcing T_a

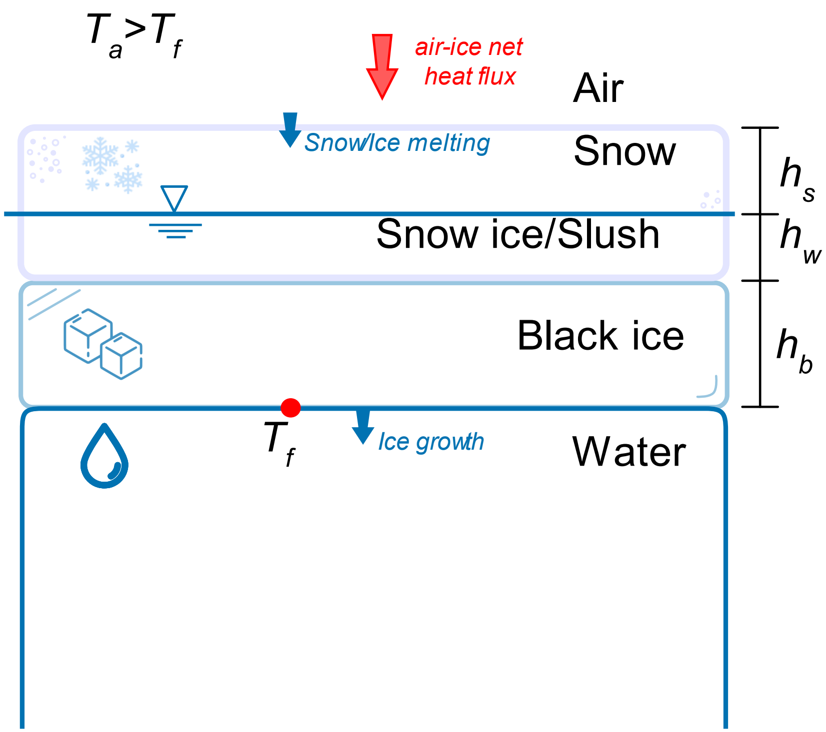
a_{10}: air convective heat transfer coefficient

The ice module

Melting equation

$T_a > T_f + a_9$

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



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

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

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

$$\delta = D_s / D_r$$

$$\phi_{net} = D_r \rho_w c_p \left\{a_1 + a_2 T_a - \cancel{a_3 T_w} + a_5 \cos\left[2\pi\left(\frac{t}{t_y} - a_6\right)\right]\right\}$$

$$T_w = T_f = 0°C$$

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

Known thermophysical properties of water/ice

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

The net surface heat flux determines the rate of melting.

(l = upper layer)

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

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

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

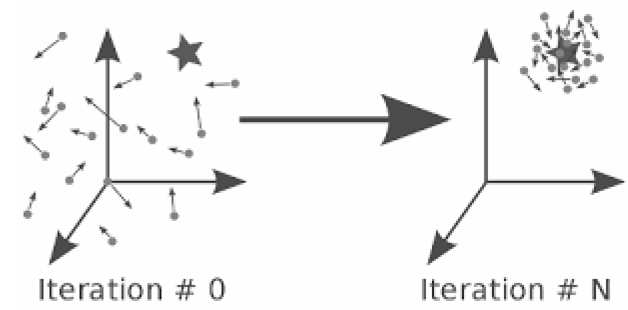
Model calibration and performance:

Multi-objective optimization problem:

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

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

PSO (Particle Swarm Optimization)

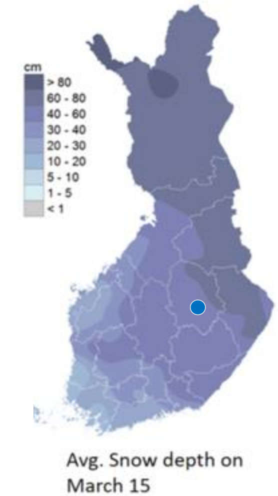


Results | Lake Kallavesi

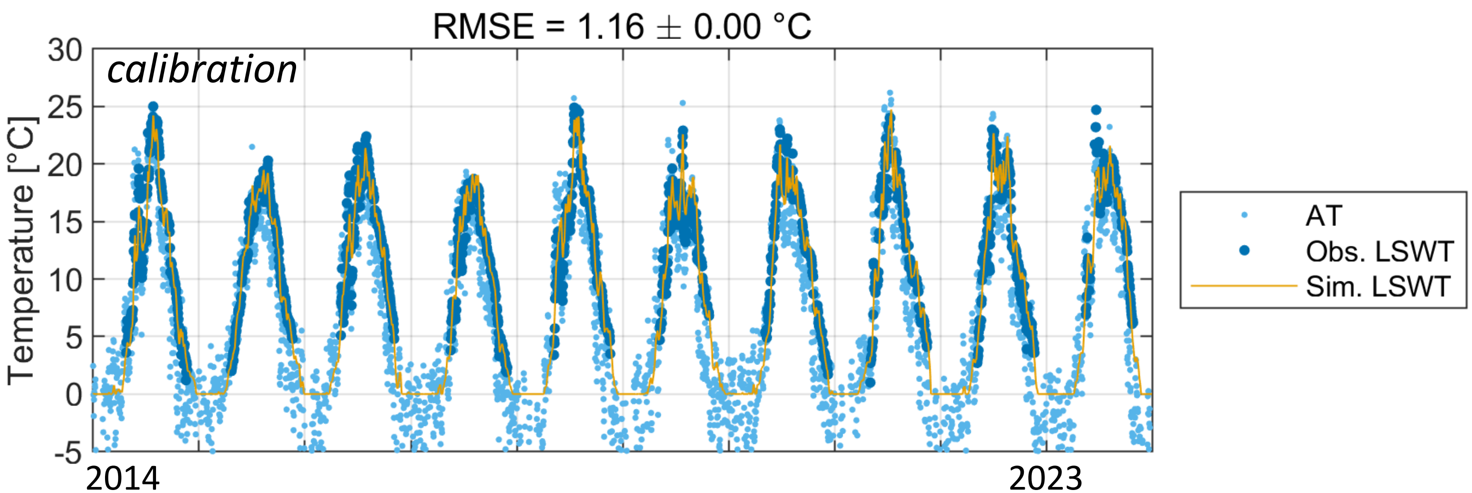
- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m

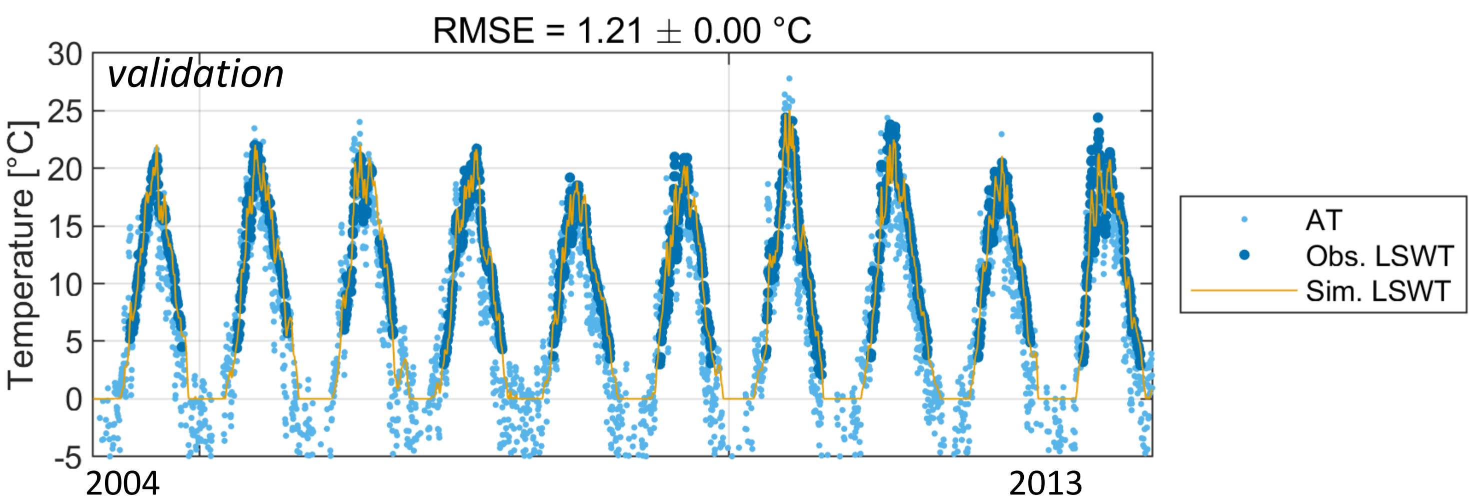
$$NSE_{tot} = NSE_{LSWT}$$

air2water model with 6 parameters



Neuenschwander et al. (2020)





Results | Lake Kallavesi

- Boreal oligotrophic lake
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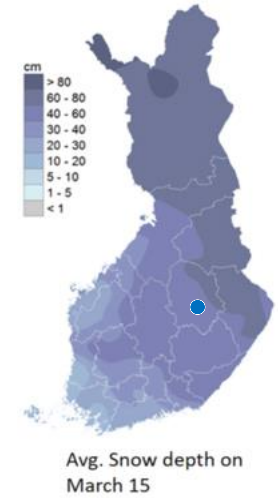
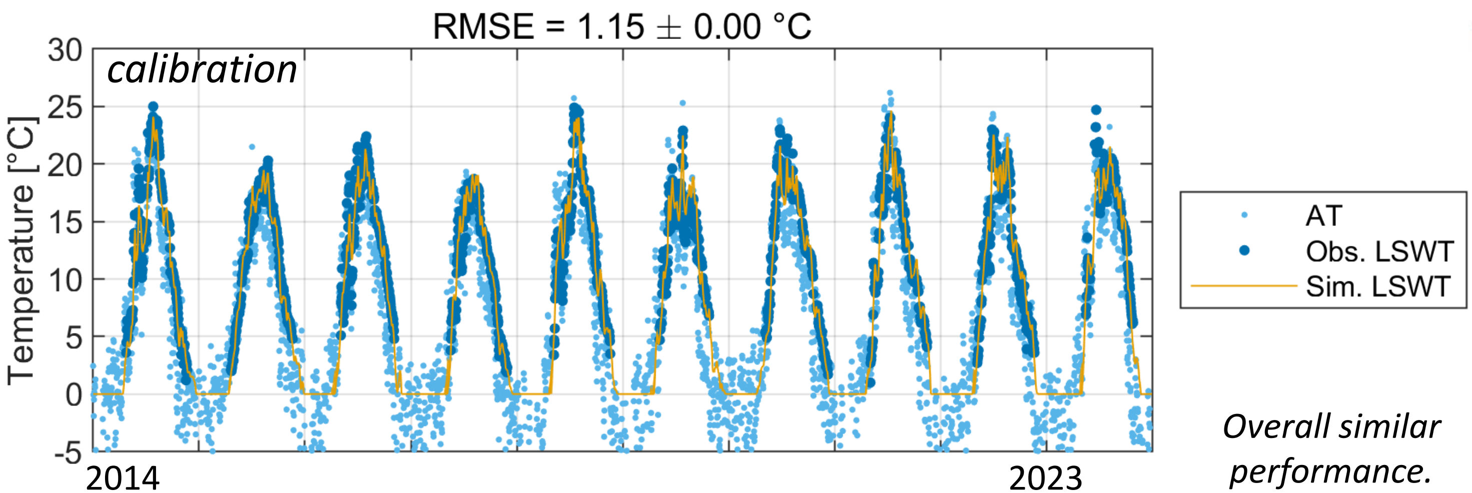
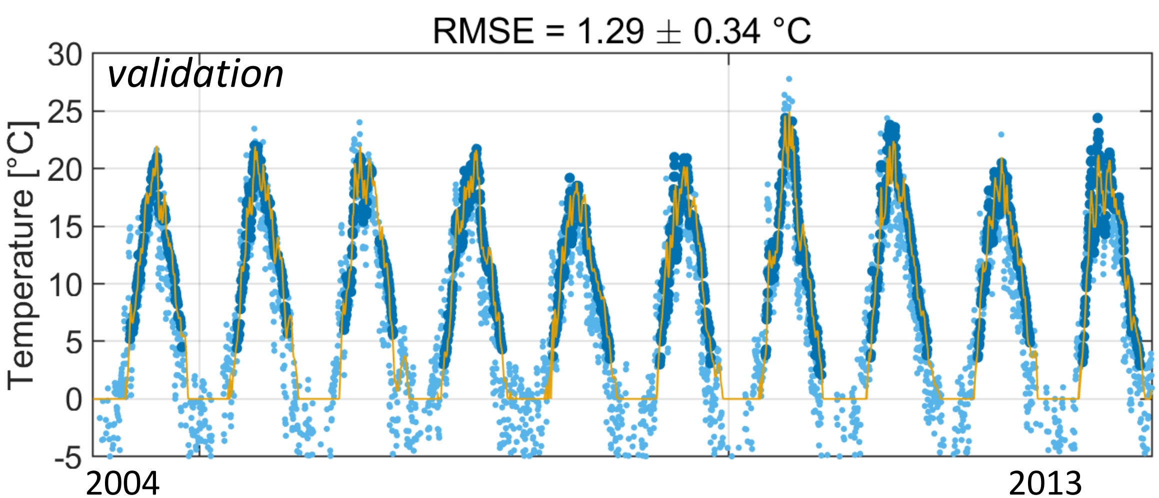
$$NSE_{tot} = \beta NSE_{LSWT} + \cancel{(1-\beta) NSE_{Ice}}$$

Case when $\beta = 1$



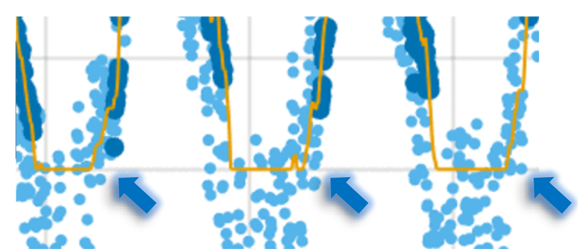
Neuenschwander et al. (2020)





Overall similar performance. Slight worsening in validation but …

air2water



Results | Lake Kallavesi

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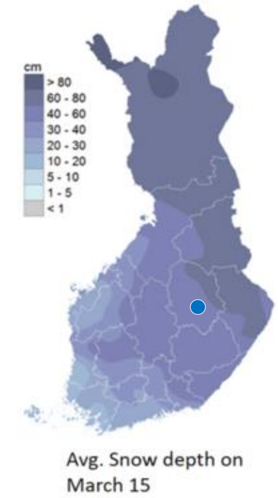
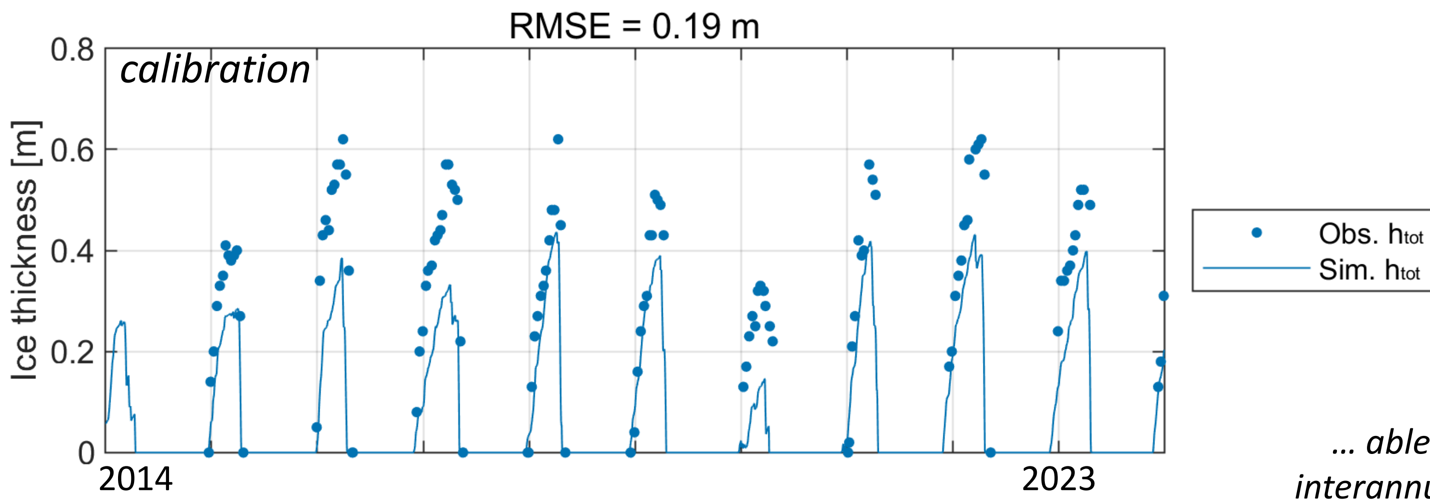
- Central Finland
- Mean depth 8.9 m

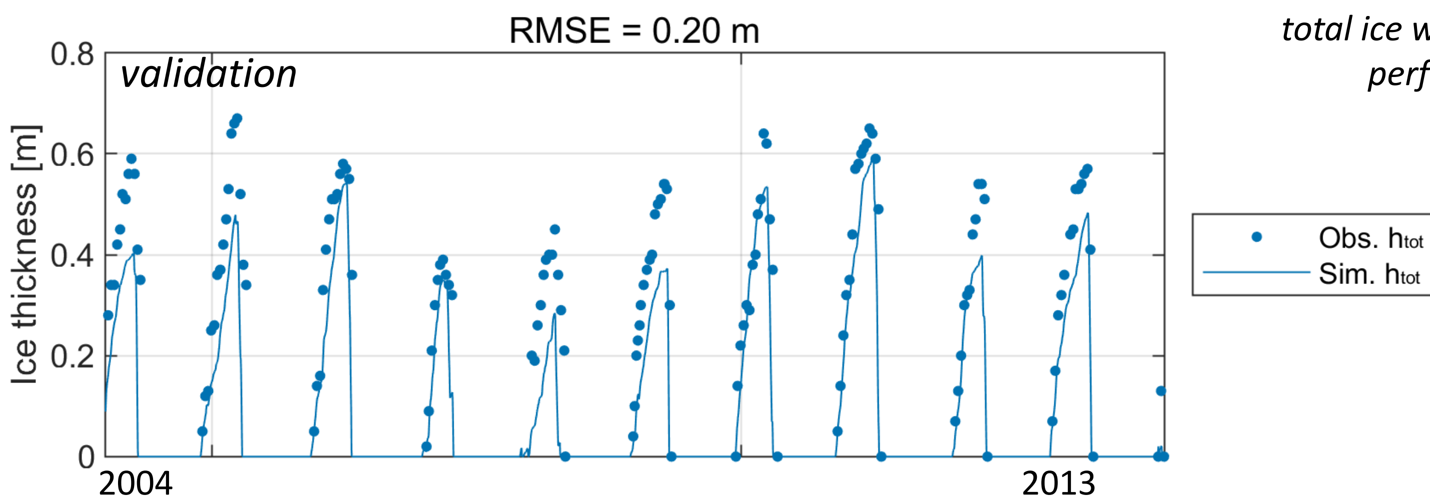
$$NSE_{tot} = \beta NSE_{LSWT} + (1-\beta) NSE_{Ice}$$

Case when $\beta = 1$



Neuenschwander et al. (2020)





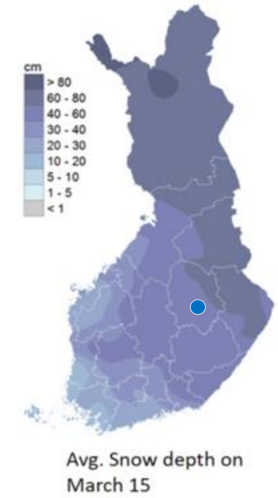
… able to reproduce interannual variability of total ice with a reasonable performance …

Results | Lake Kallavesi

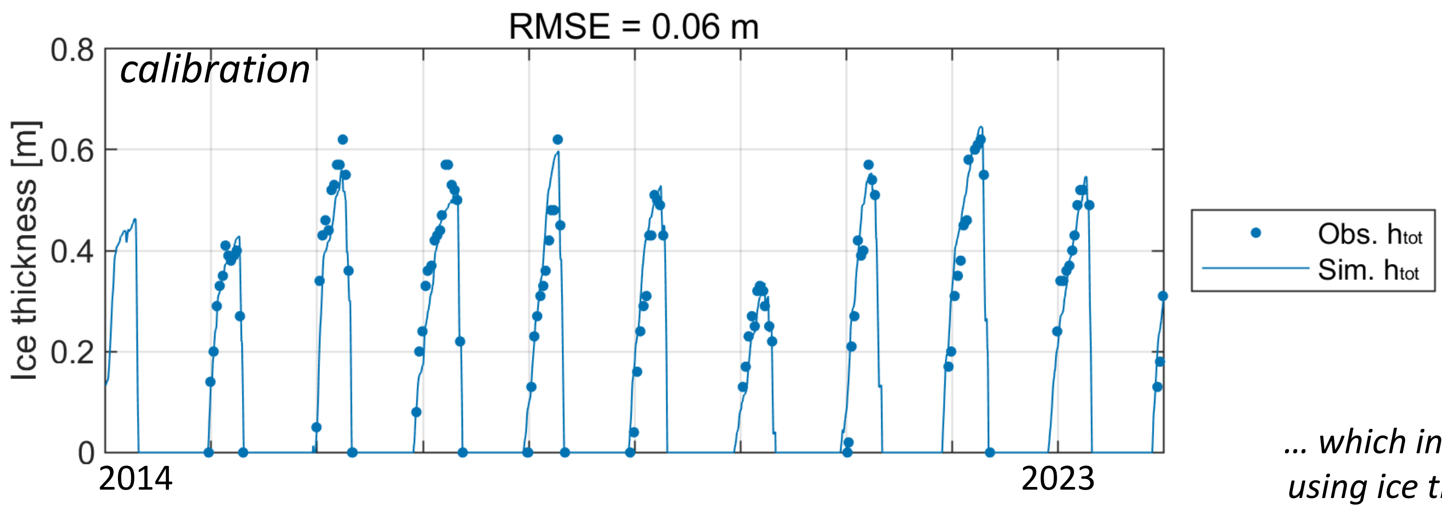
- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m

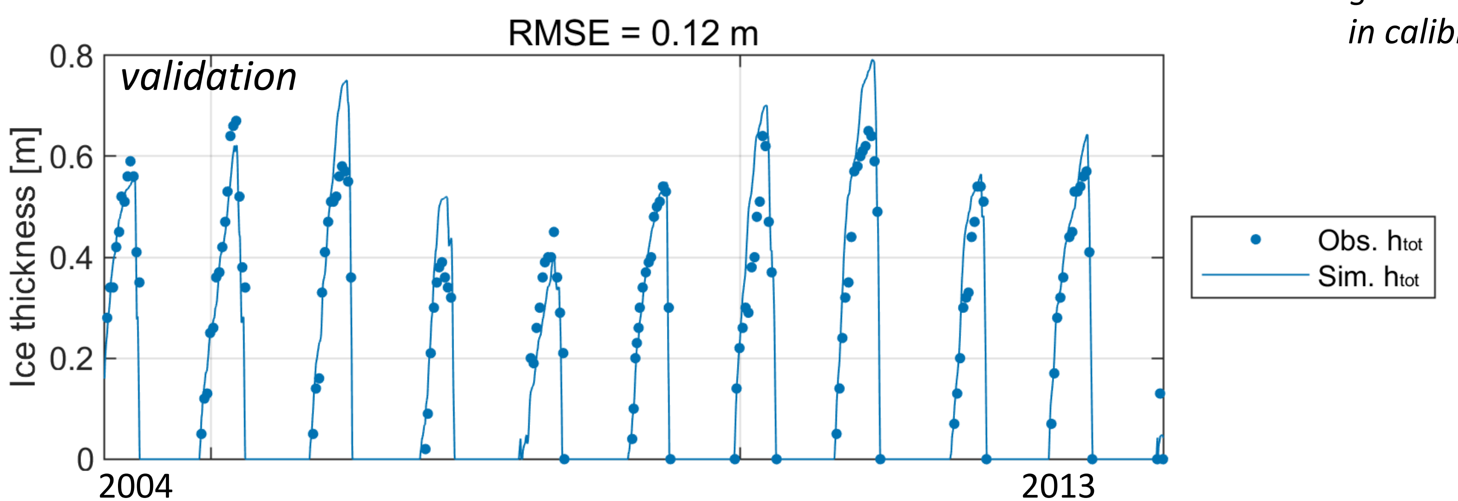
$$NSE_{tot} = \beta NSE_{LSWT} + (1-\beta)\, NSE_{Ice}$$

Case when $\beta = 0.5$



Neuenschwander et al. (2020)





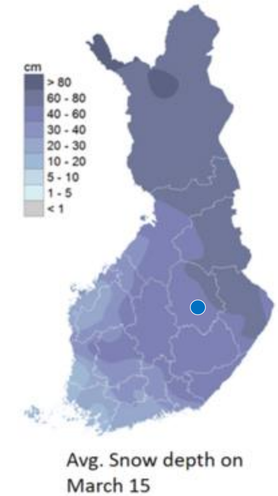
... which increases when using ice thickness data in calibration ...

Results | Lake Kallavesi

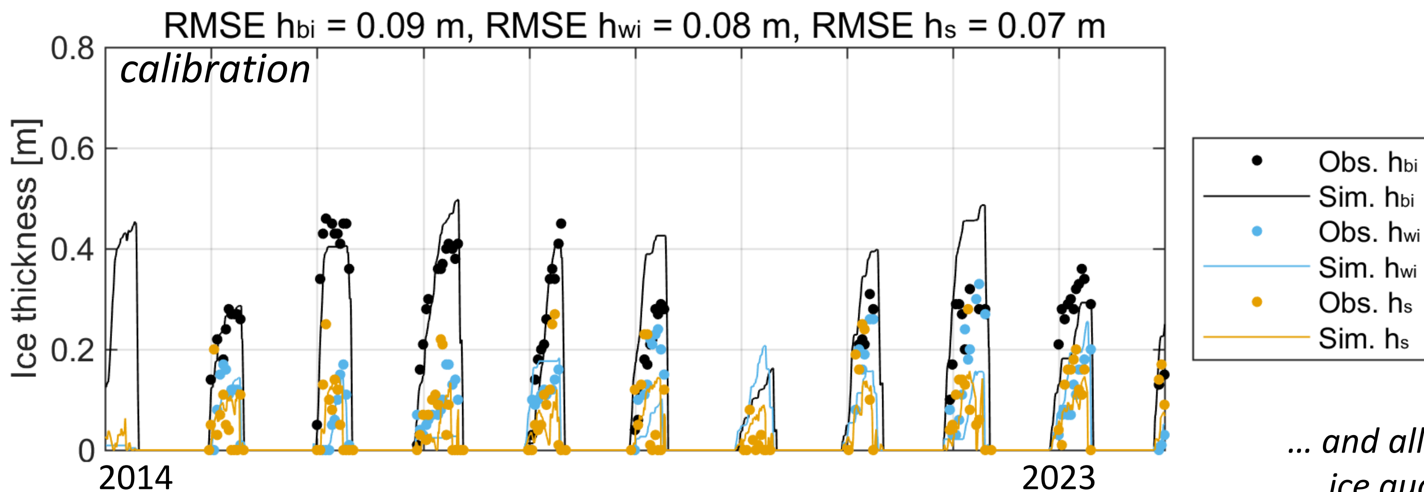
- Boreal oligotrophic lake
- Central Finland
- Mean depth 8.9 m

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

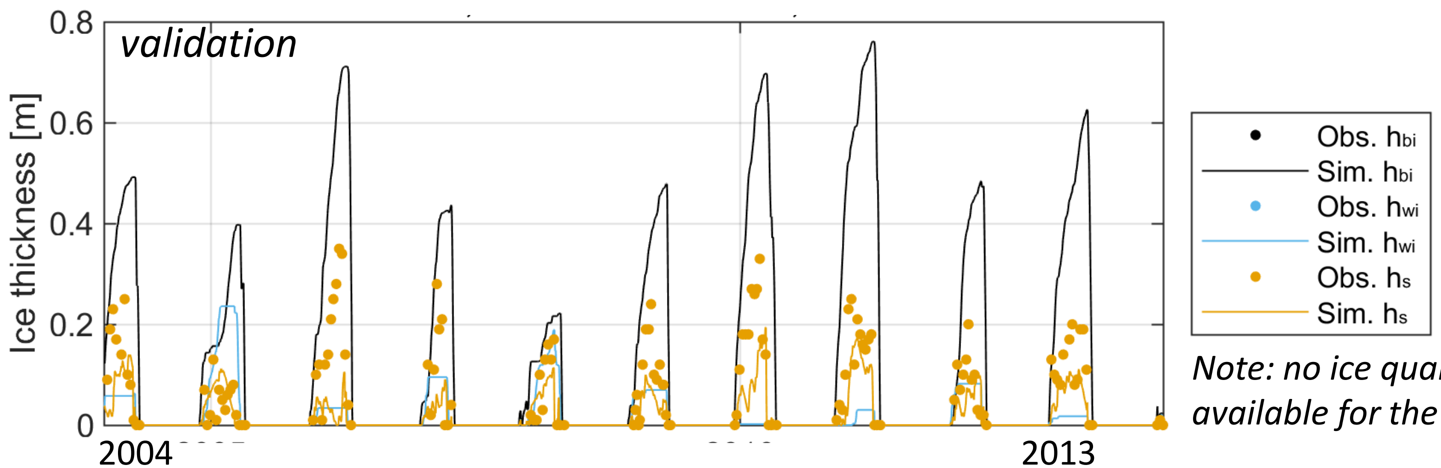
Case when $\beta = 0.5$



Neuenschwander et al. (2020)



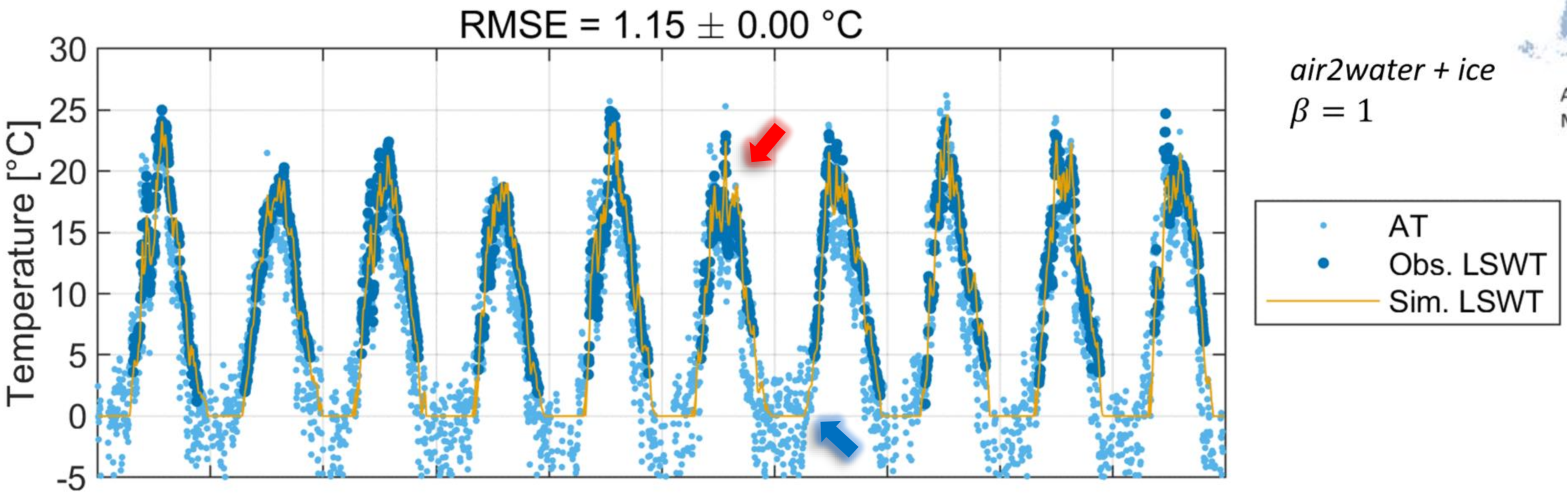
... and allows predicting ice quality as well.



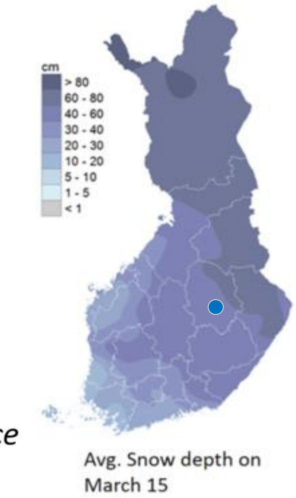
Note: no ice quality data were available for the validation period.

Results | Lake Kallavesi

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



air2water + ice
$\beta = 1$



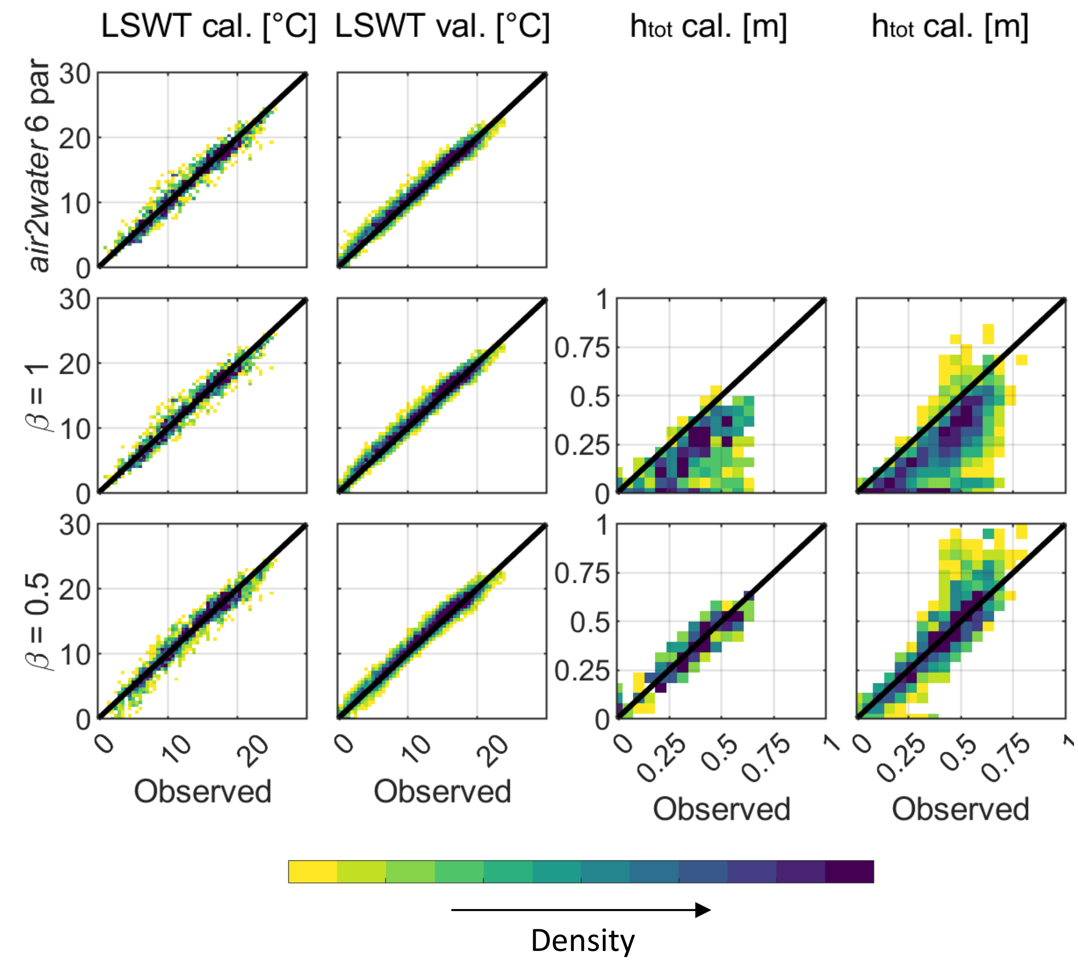
Neuenschwander et al. (2020)

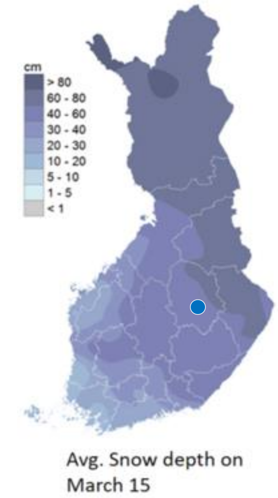
There is no free lunch:

- *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

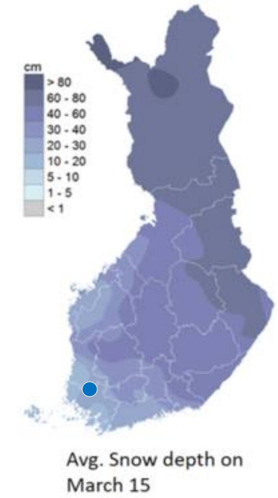




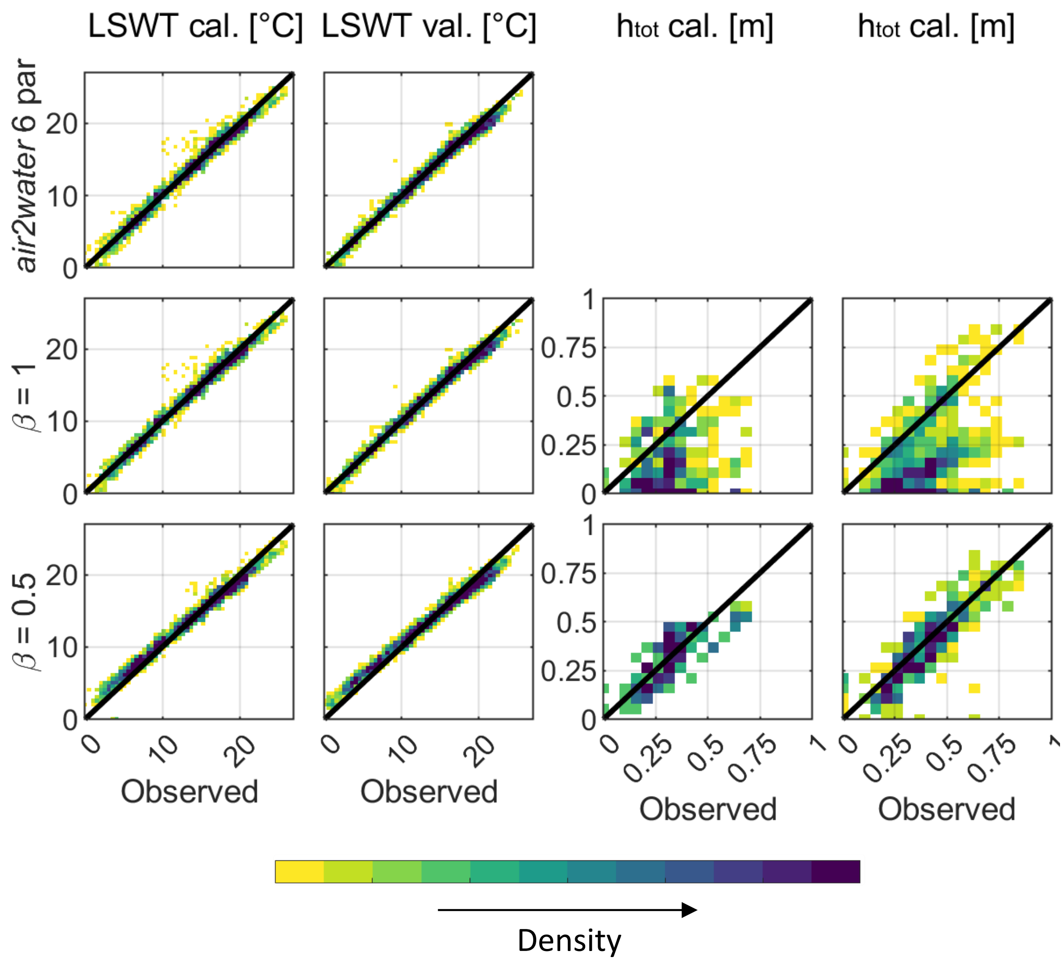
Neuenschwander et al. (2020)

Results | Lake Pyhajarvi

- Eutrophic lake
- Southern Finland
- Mean depth 5.4 m

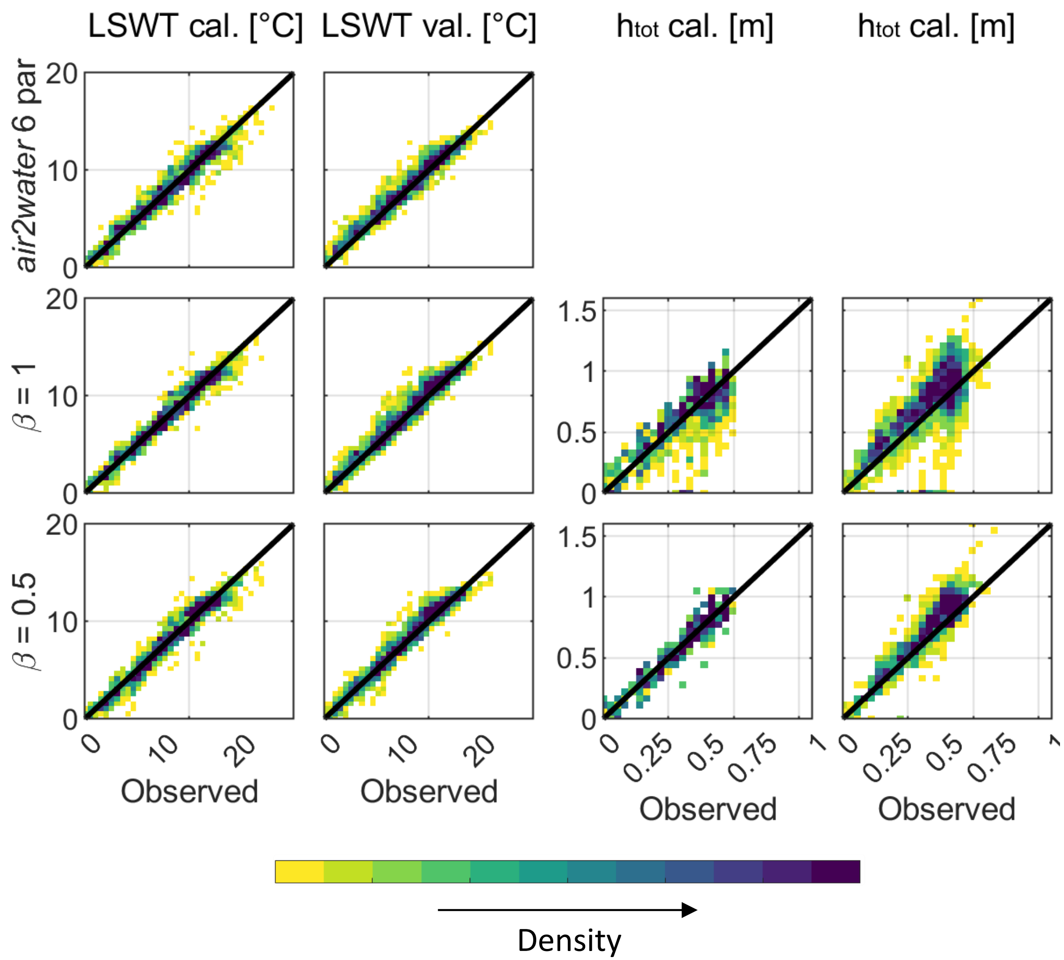


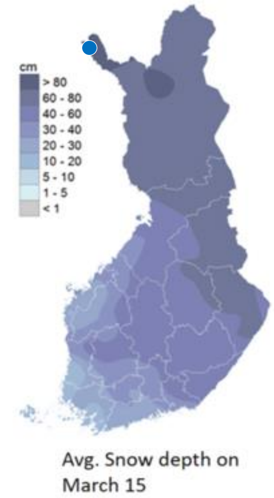
Neuenschwander et al. (2020)



Results | Lake Kilpisjarvi

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

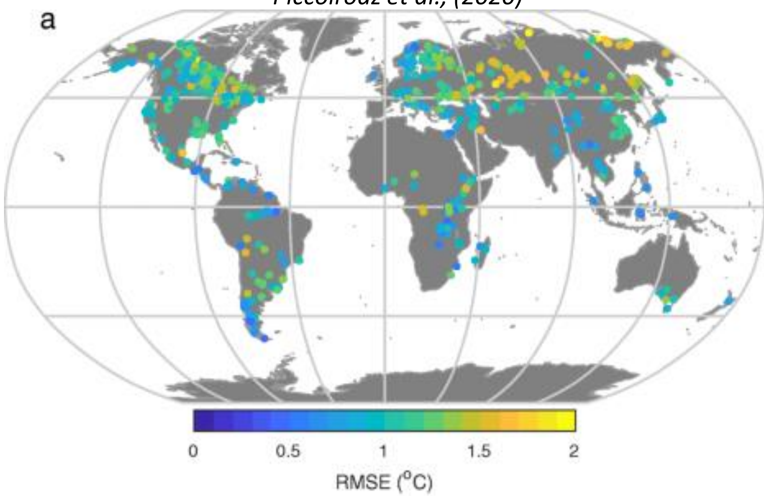


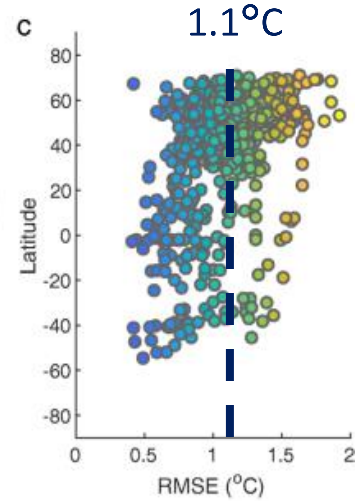


Neuenschwander et al. (2020)

Current developments

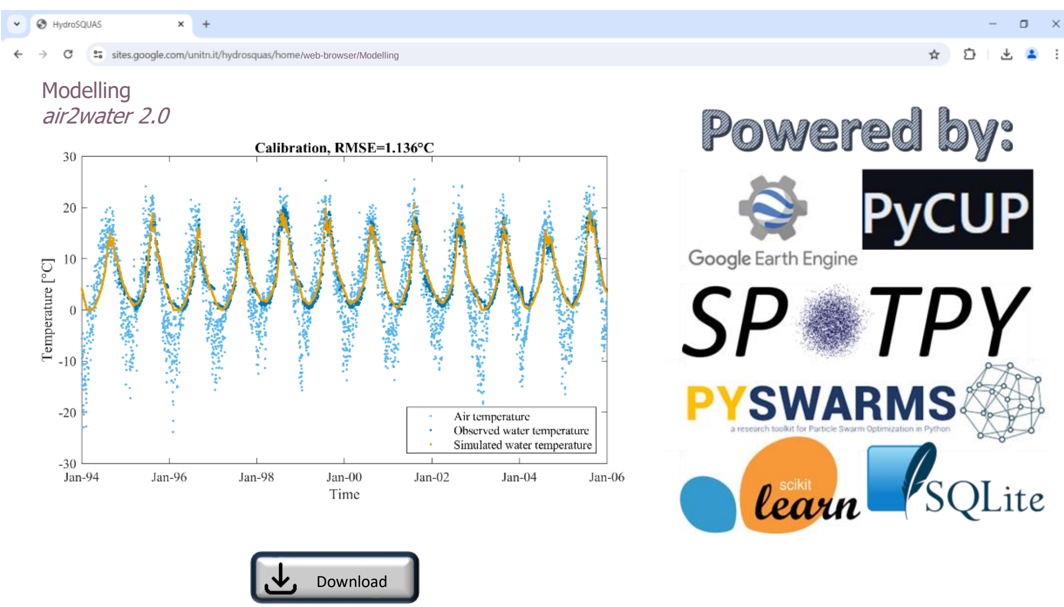
Piccolroaz et al., (2020)





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:

$RMSE_{LSWT} \sim 1\,^{\circ}C$
$RMSE_{Ice} \sim 0.1\ m$

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

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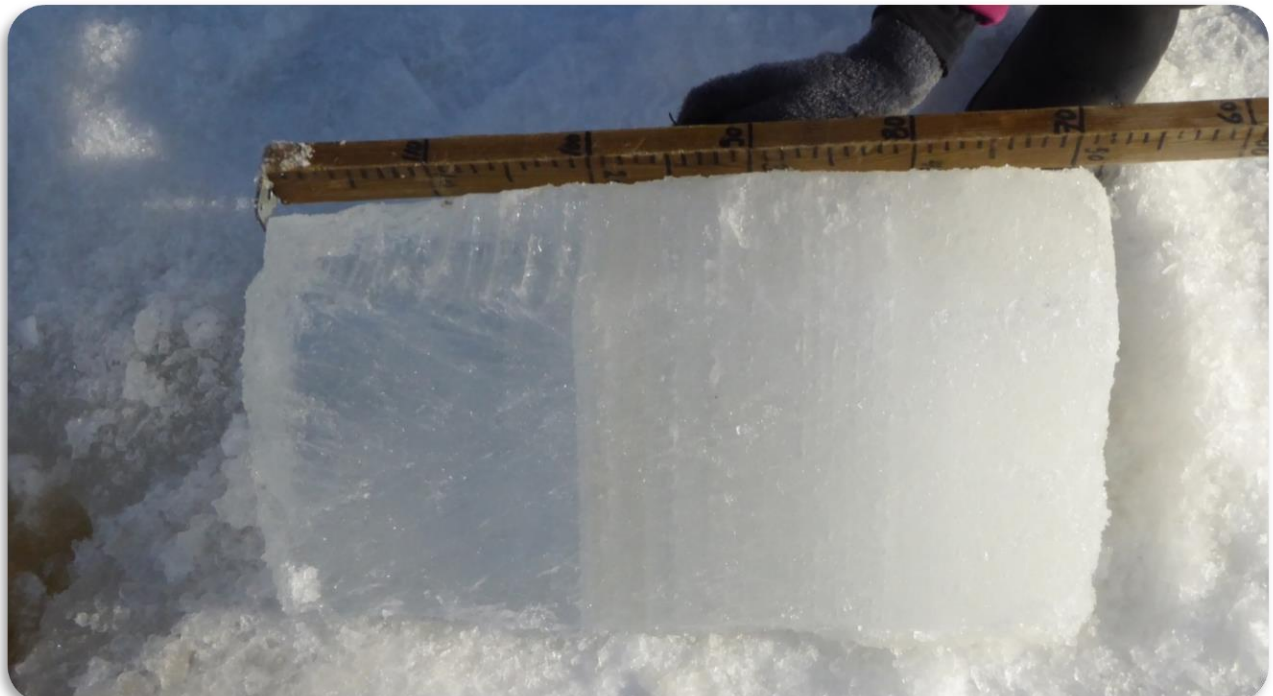

UNIVERSITÀ DI TRENTO
INAR Institute for Atmospheric and Earth System Research
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s.piccolroaz@unitn.it
https://www.linkedin.com/in/sebastianopiccolroaz/

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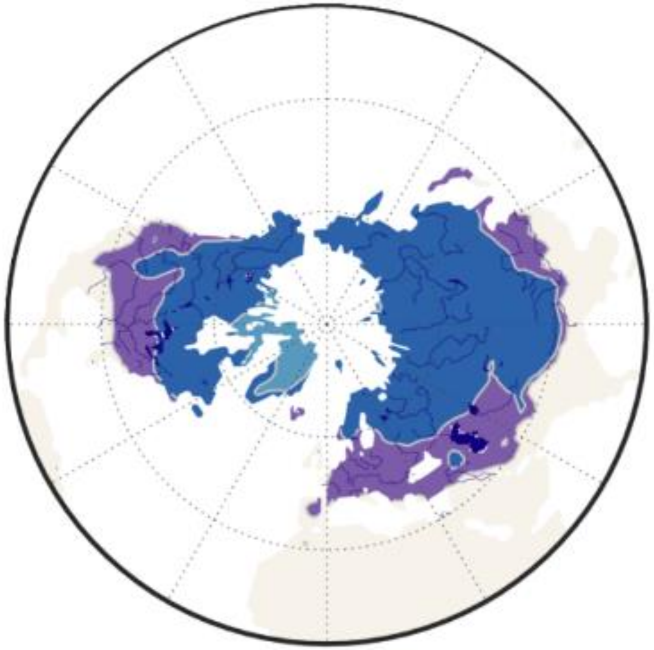

SPECIAL COLLECTION ORGANIZERS:

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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