RESPONSE OF LAKE ICE COVER TO WATER LEVEL AND AIR TEMPERATURE VARIATIONS IN TWO NORWEGIAN HYDROPOWER RESERVOIRS

***F. Hinegk**, A. Adeva Bustos, M. Toffolon*

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STUDY AREA & FRAMEWORK: HYDROCONNECT

HydroConnect Project:

Norwegian hydropower → balancing services for Europe
(= traditional Hydropower Plants to Pumped-Storage HP)

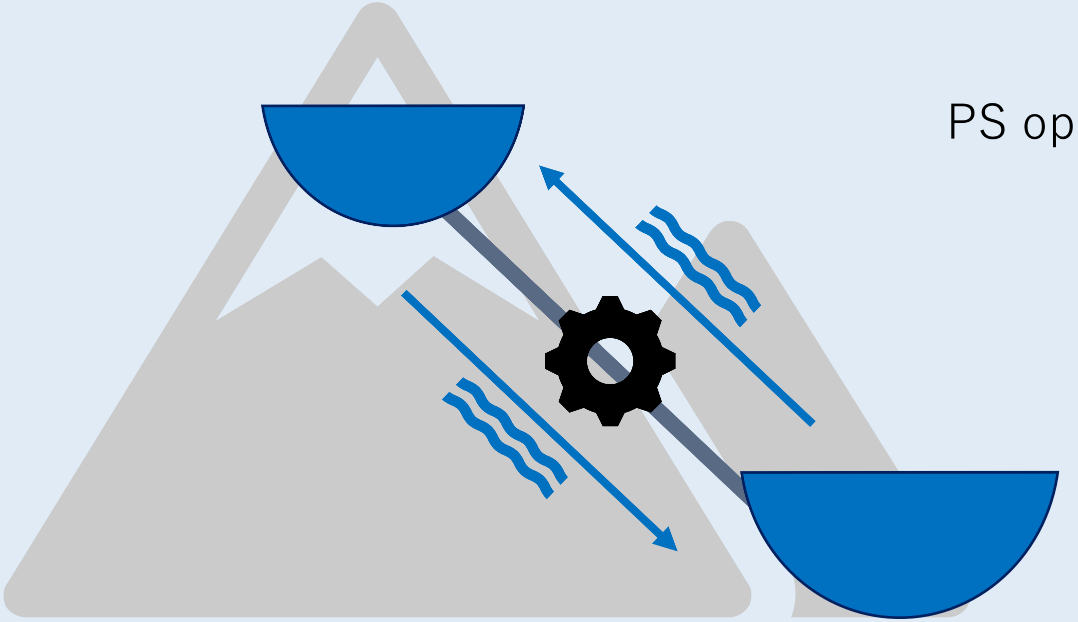
↓

potentiality & implications

	Roskreppfjorden	Øyarvatn
Area	29.75 km²	8.08 km²
Regulation levels	890-929 m a.s.l.	820-837 m a.s.l.
Regulation volume	695 millions m³	104 millions m³

PUMPED-STORAGE HYDROPOWER

PS hydropower plants = carbon-neutral **large-scale energy storage**



PS operations = large and frequent **exchange of water** between lower- and higher-altitude basins

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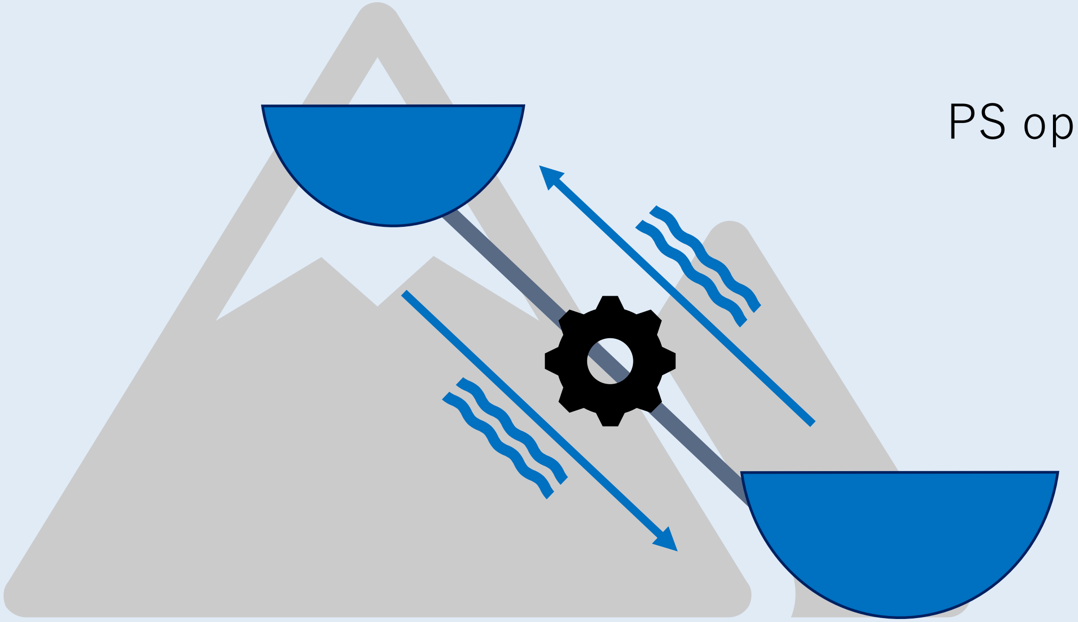

PS operations = large and frequent **exchange of water** between lower- and higher-altitude basins

Effects on reservoirs?

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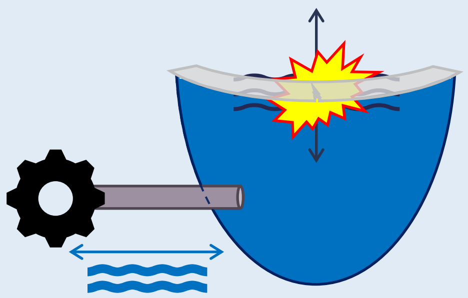
OBJECTIVE

Effects of PS operations on

Ice cover



OBJECTIVE

Effects of PS operations on

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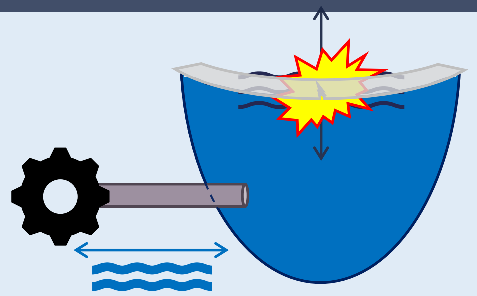
Effects of water level fluctuations on the ice cover?



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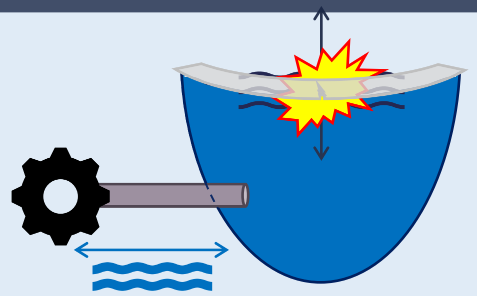
Why is integrity of ice cover relevant?

Effects of PS operations on

Ice cover

Effects of water level fluctuations on the ice cover?



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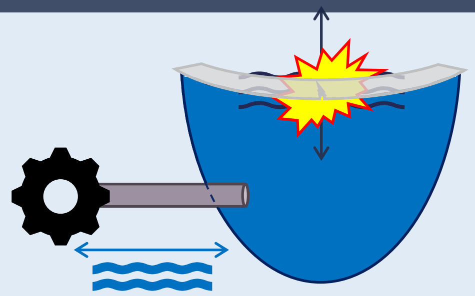

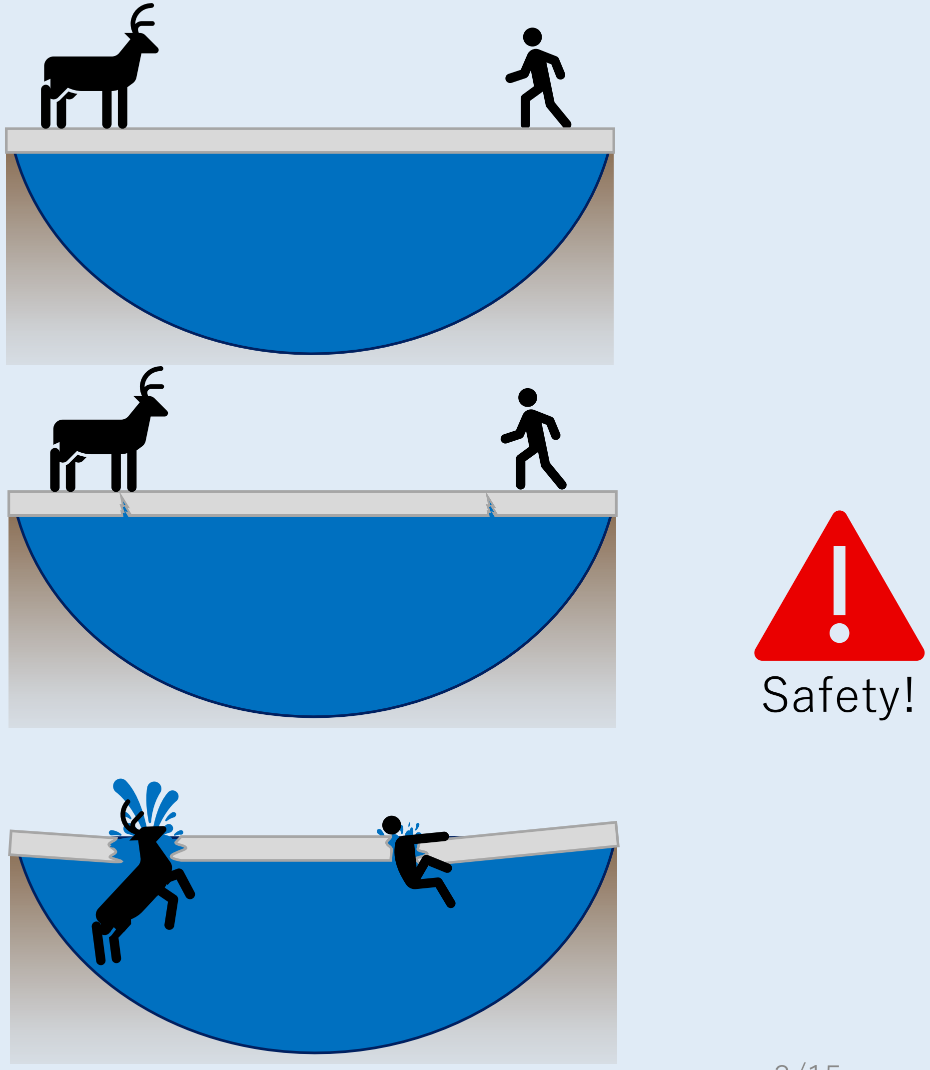

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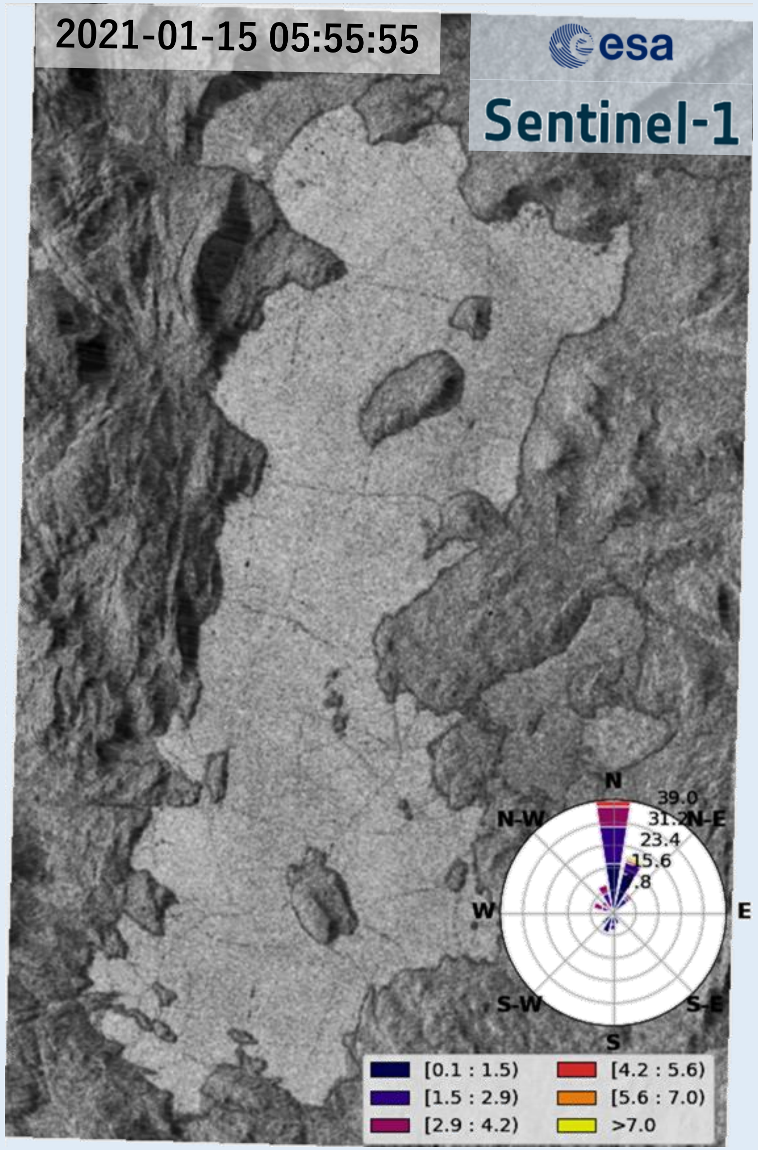
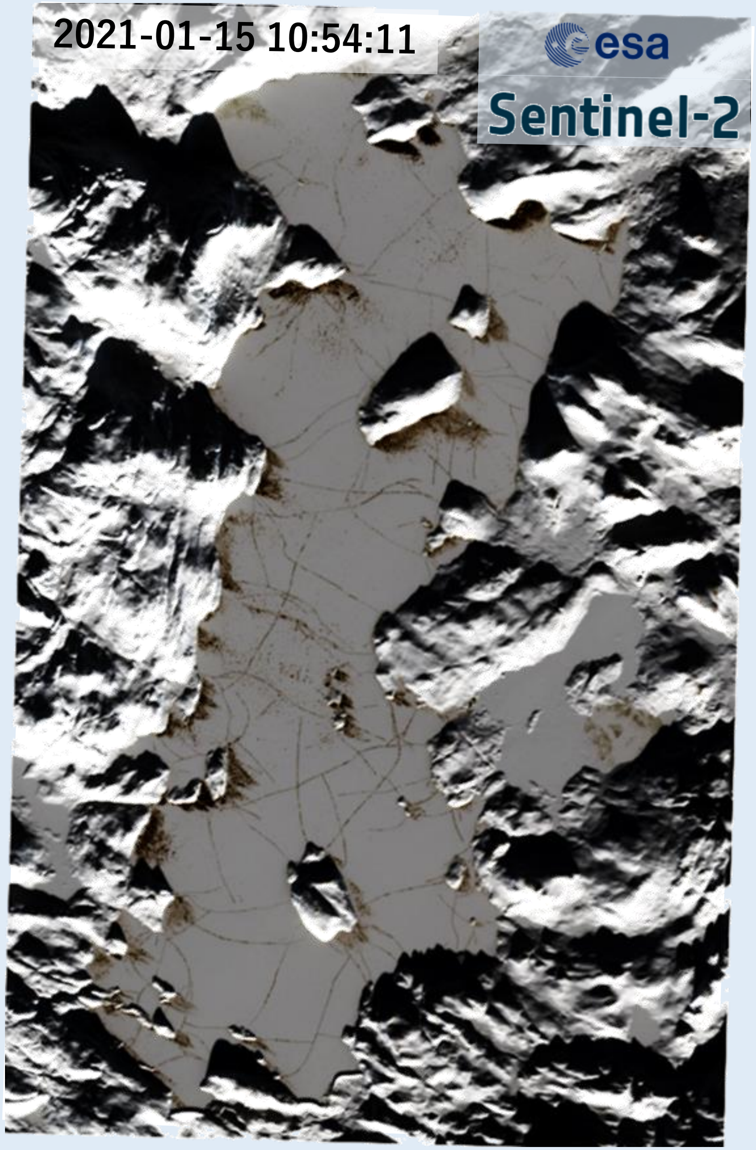
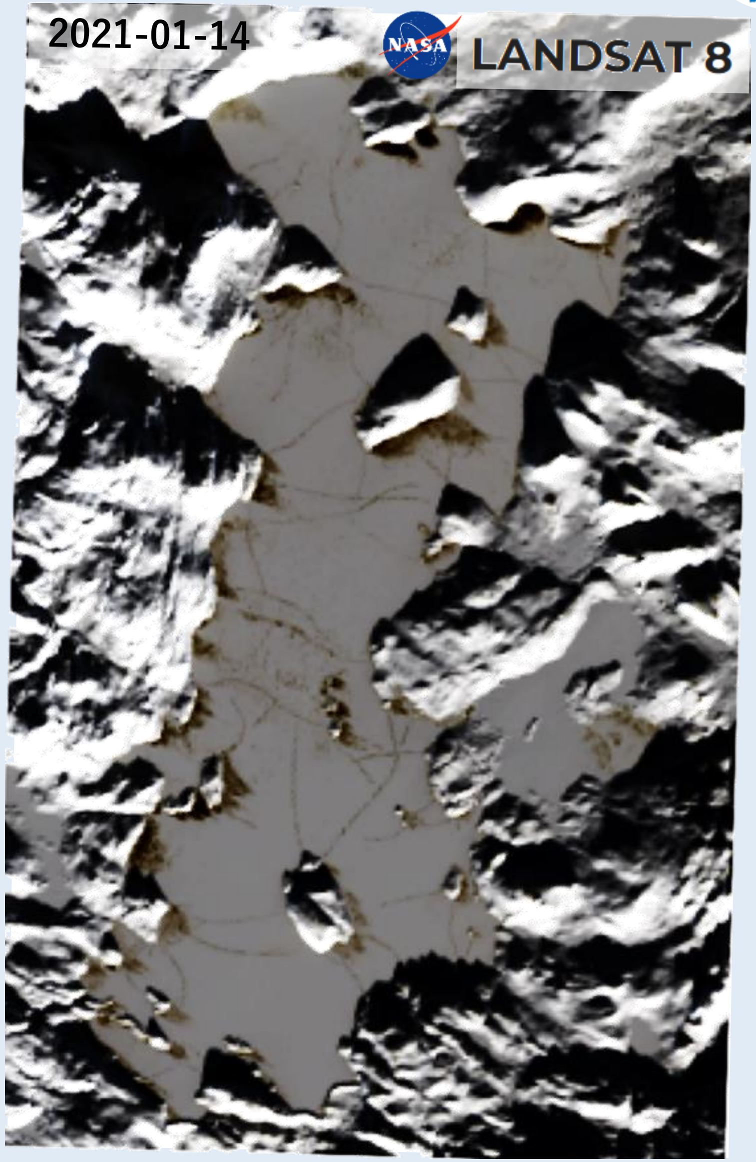
SATELLITE DATA — CRACK DETECTION







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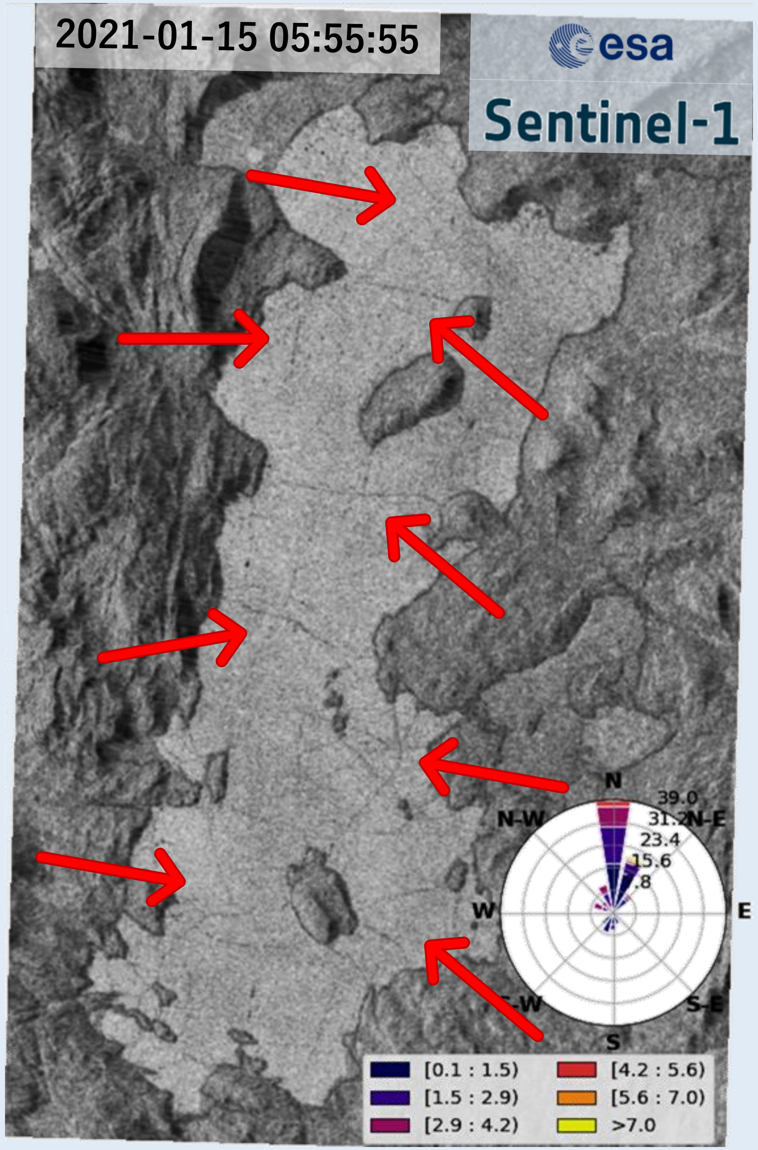

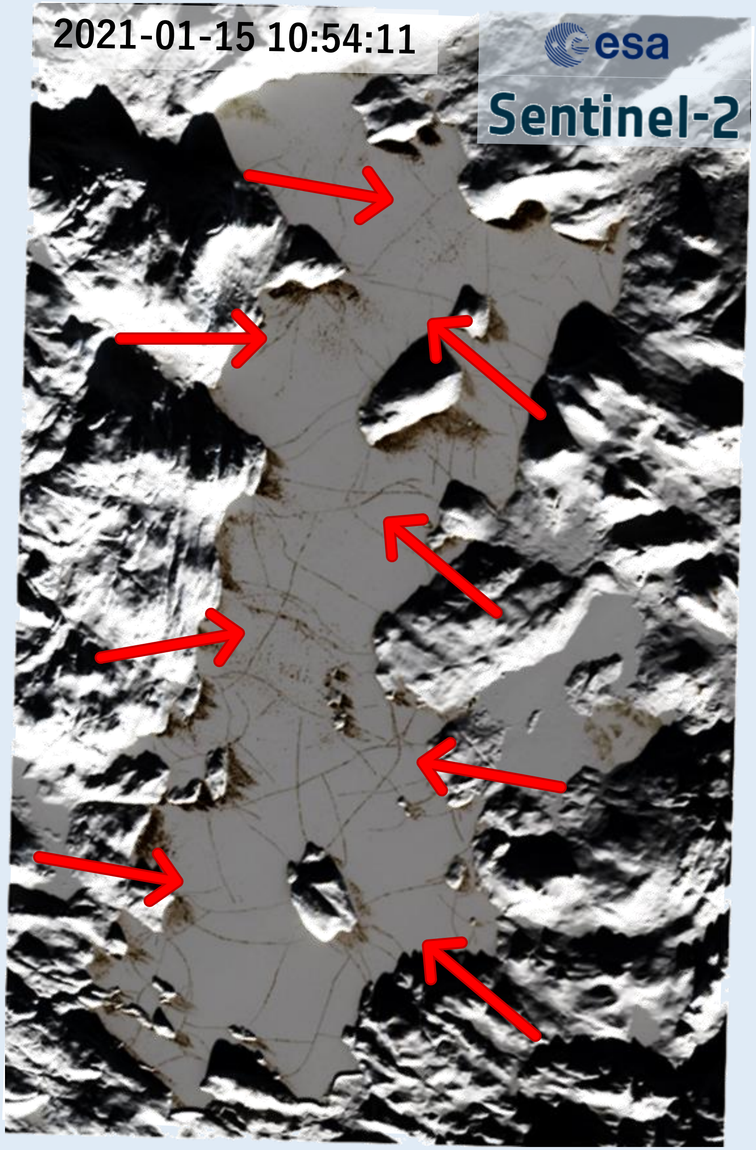

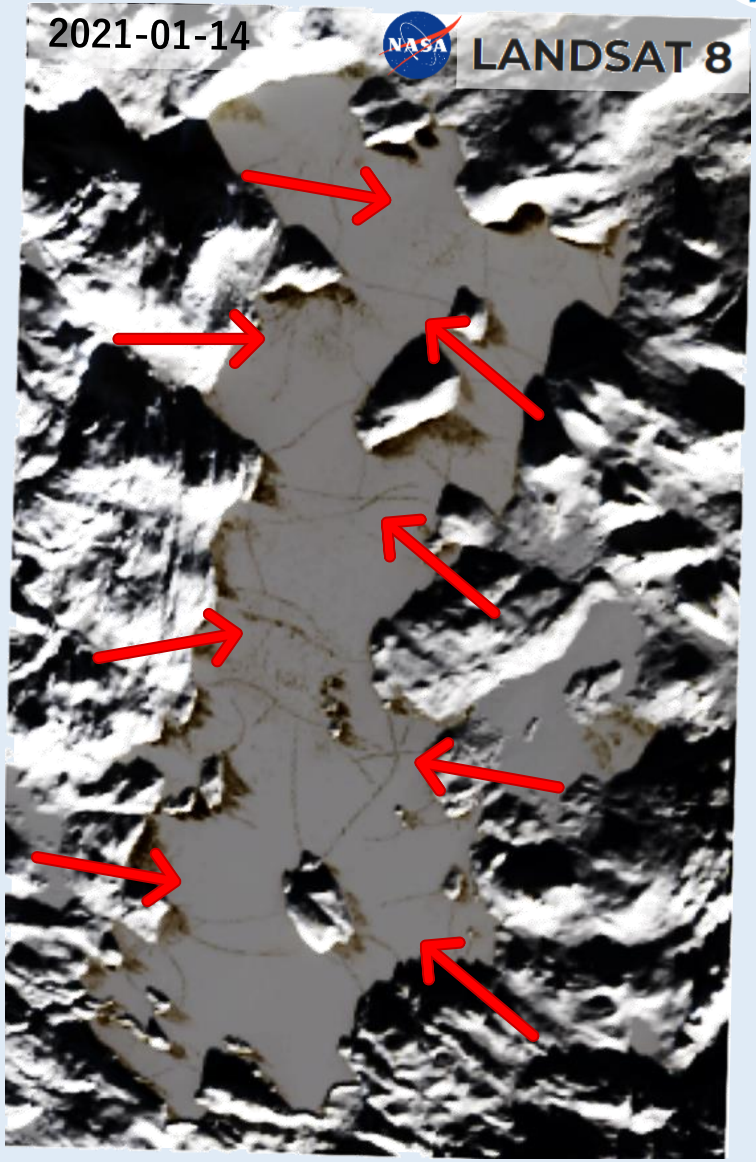

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SATELLITE DATA — CRACK PATTERN ANALYSIS

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Sentinel-2
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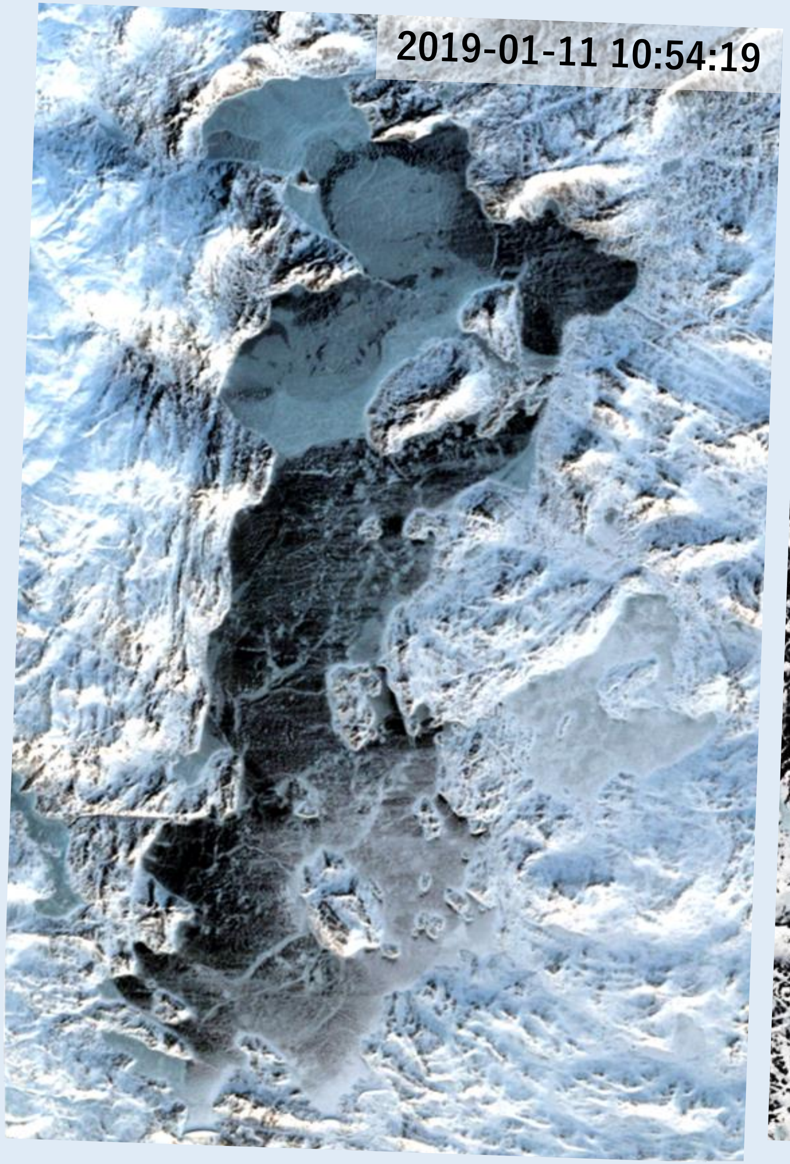
LANDSAT 8
LANDSAT 9
NASA

Visual analysis of multispectral and SAR imagery

↓

Cracks in the ice cover detected in **early winter** and **persisted** for the **whole ice season**



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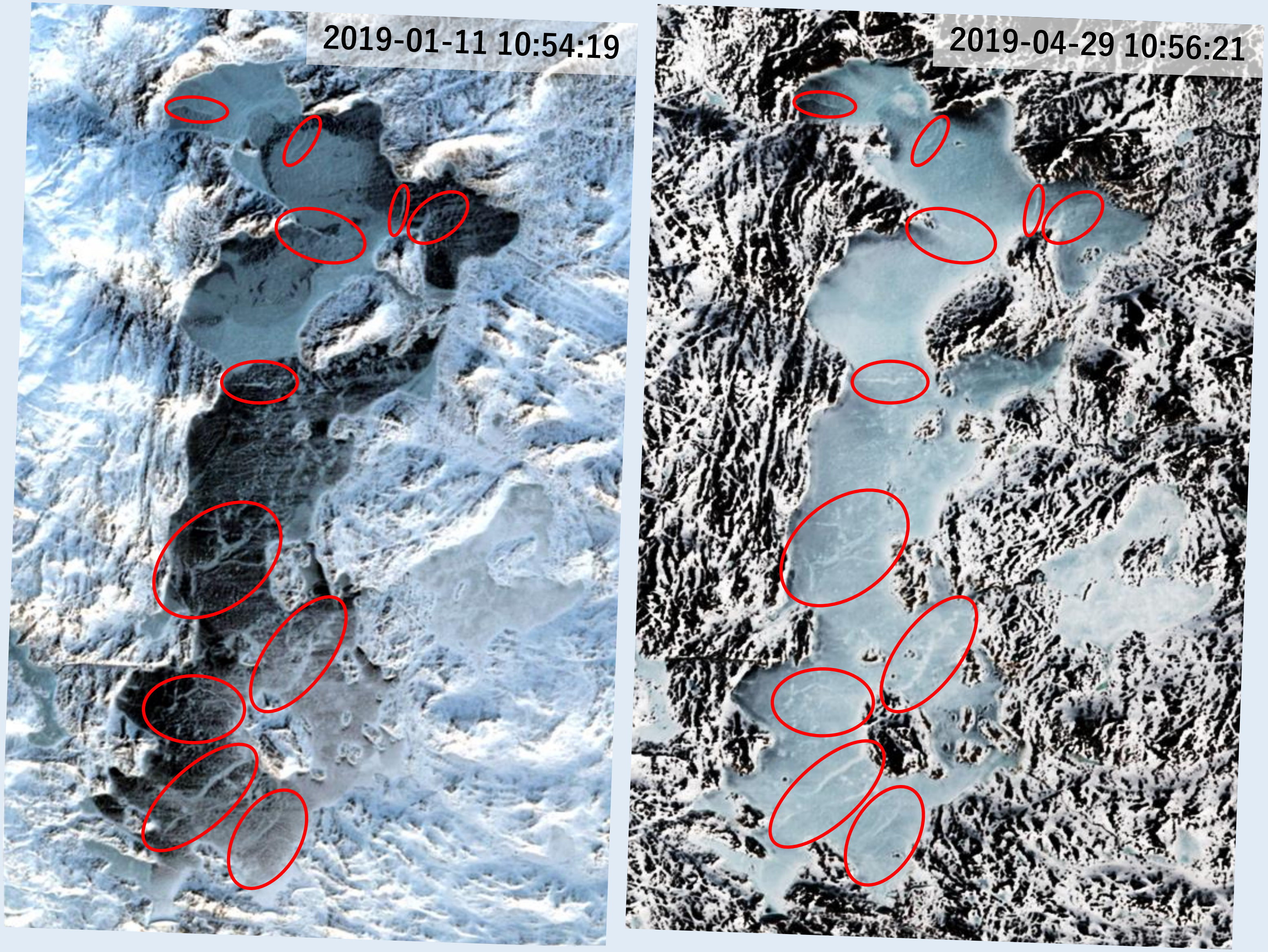

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Visual analysis of multispectral and SAR imagery

Focus: **crack pattern** in ice cover

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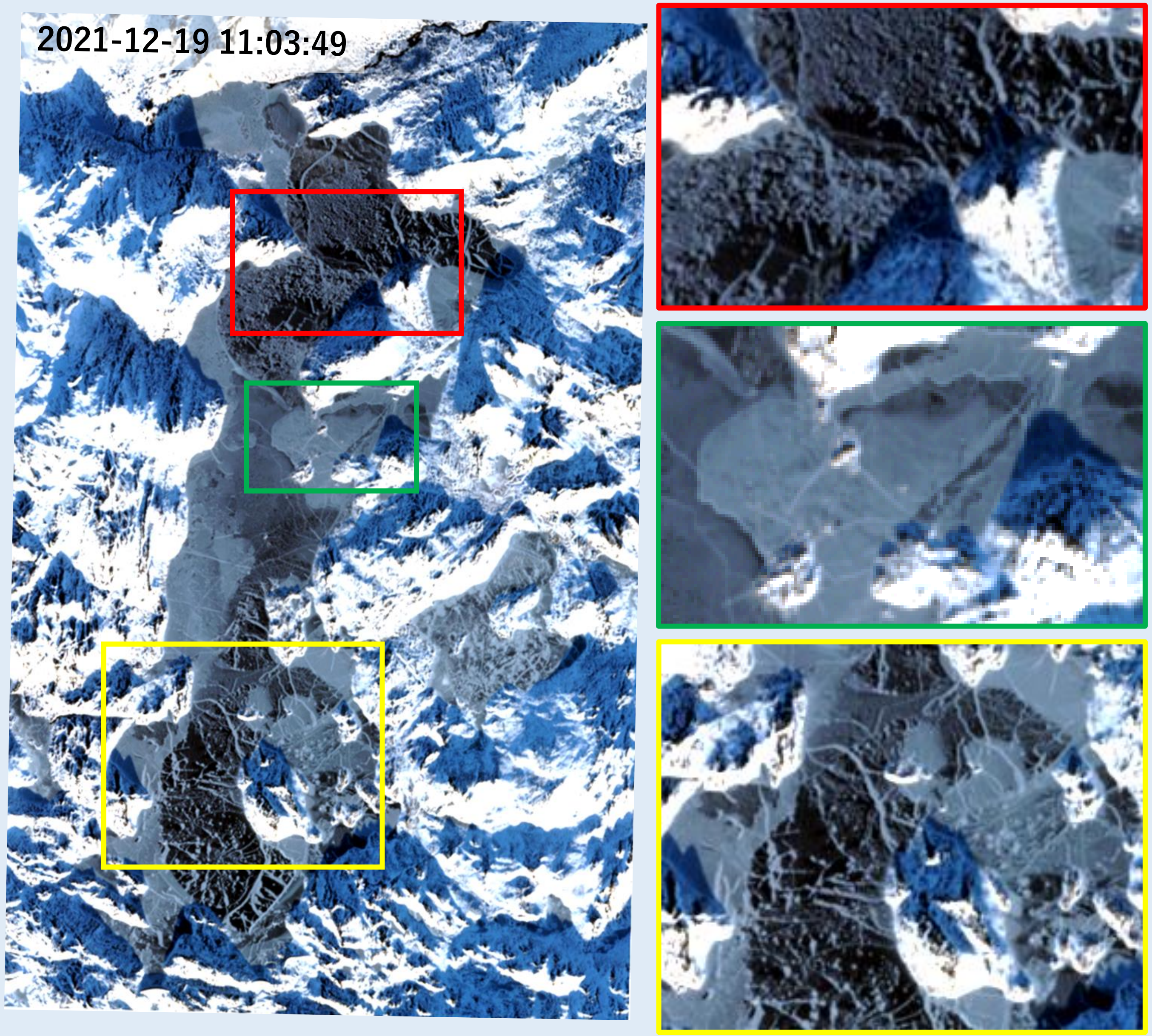

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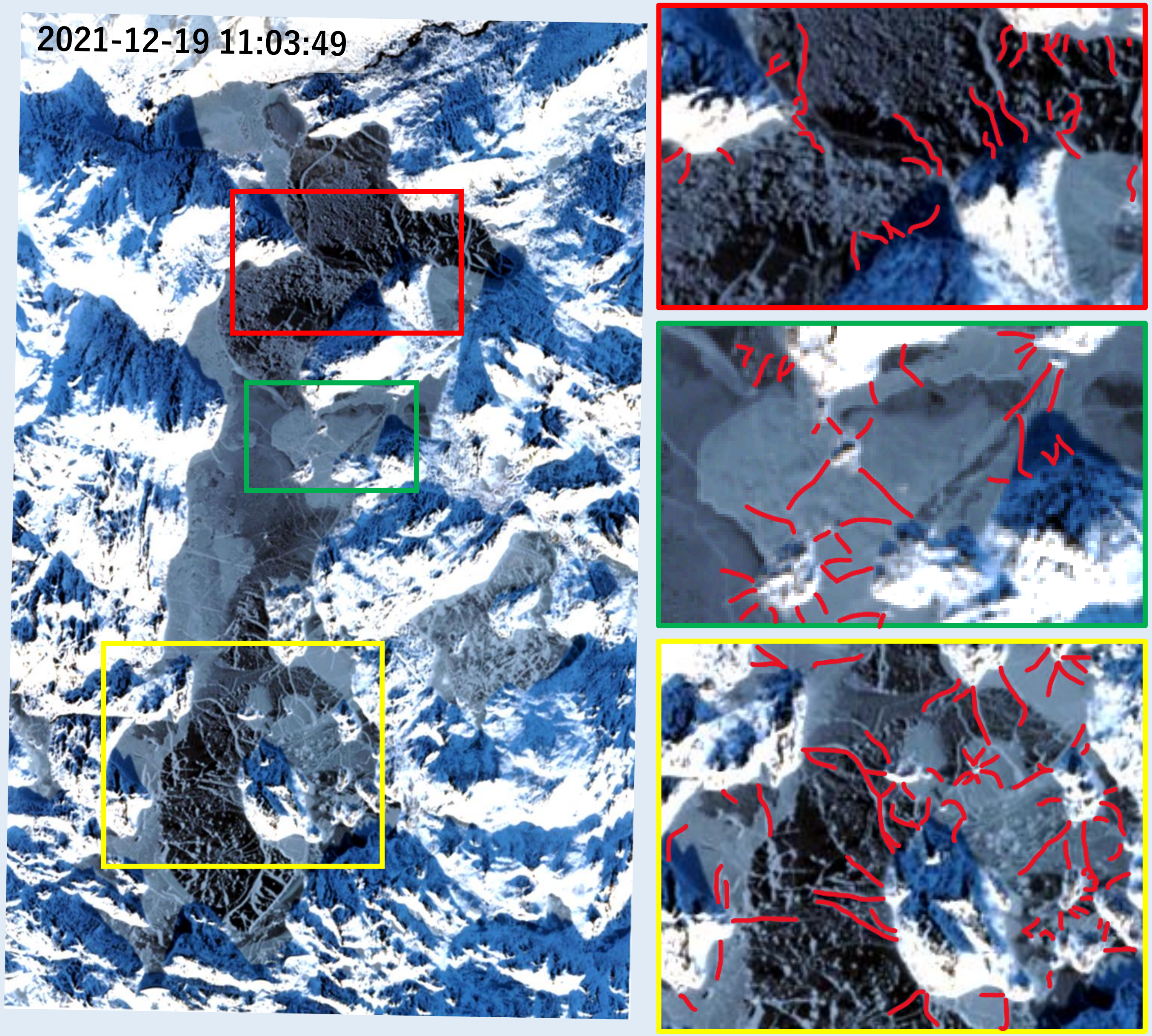
Visual analysis of multispectral and SAR imagery

Focus: **crack pattern** in ice cover

Most cracks propagate from **bathymetric obstacles**



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DATA ANALYSIS

Origin of the cracks?

Pressure variation due to water level change
(Bearing capacity problem)

↓

water level data

Sira·Kvina KRAFTSELSKAP

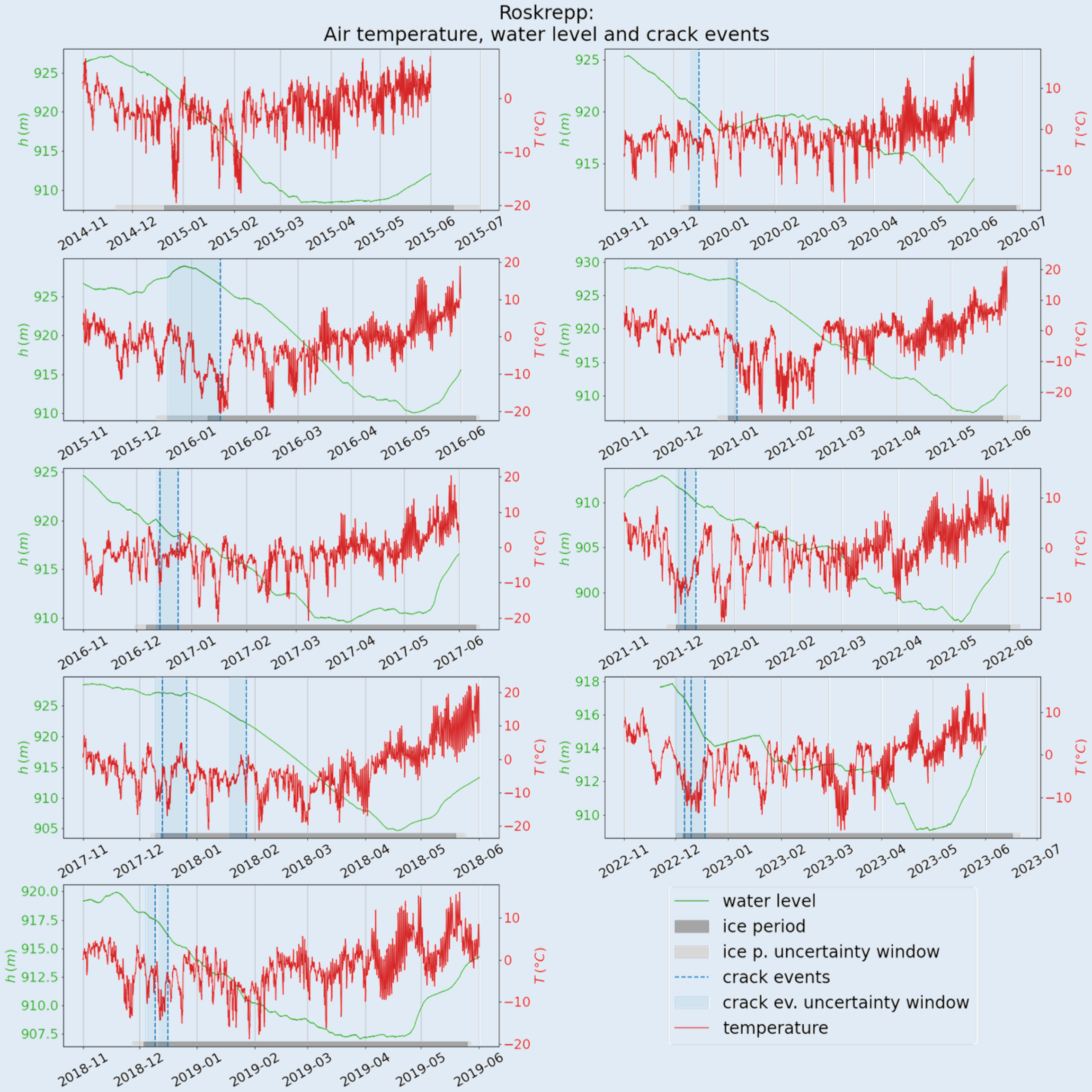
Steep temperature variations
(Thermal expansion problem)

↓

air temperature data
(no ice temperature data available)

OpenWeather

DATA ANALYSIS



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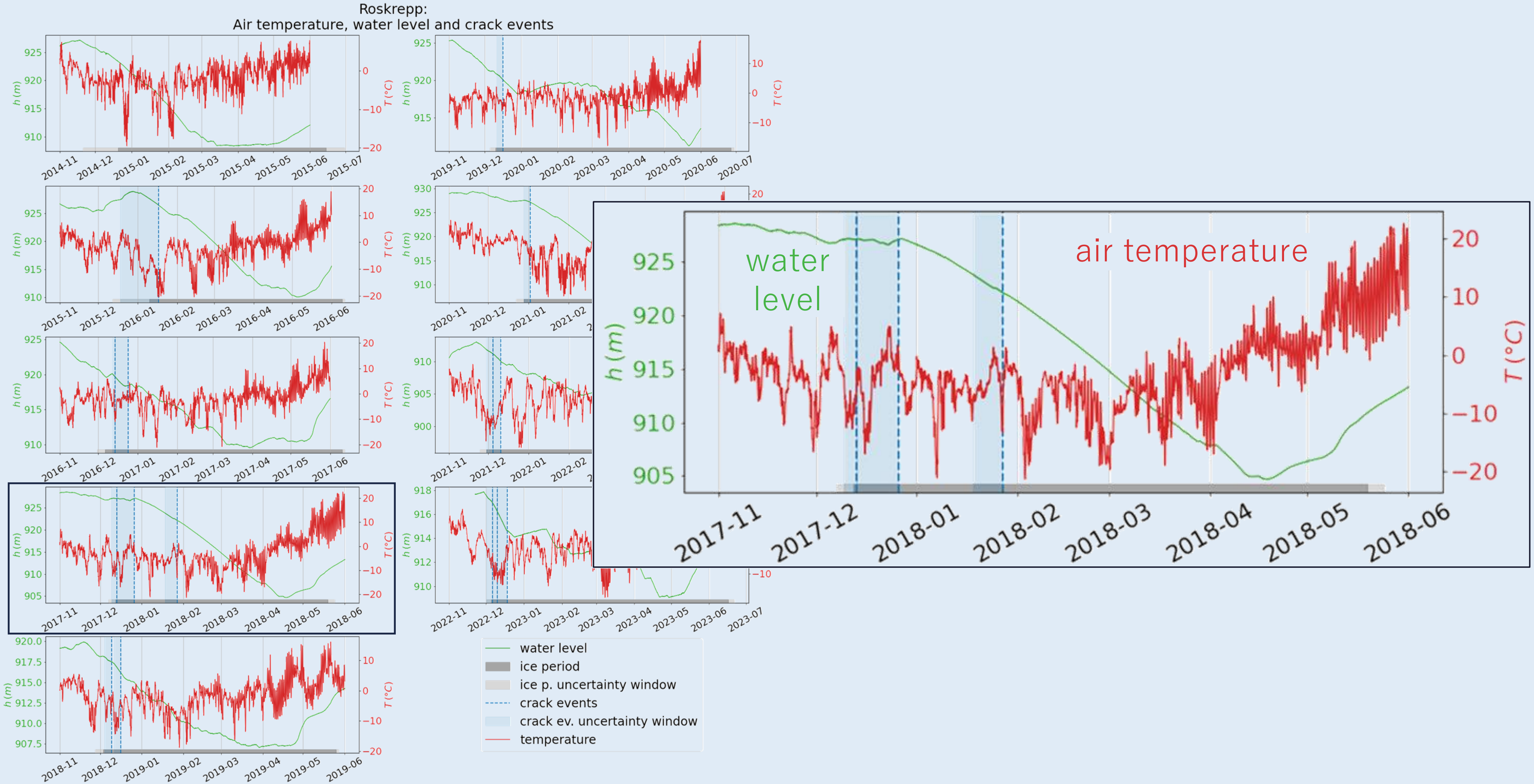
DATA ANALYSIS



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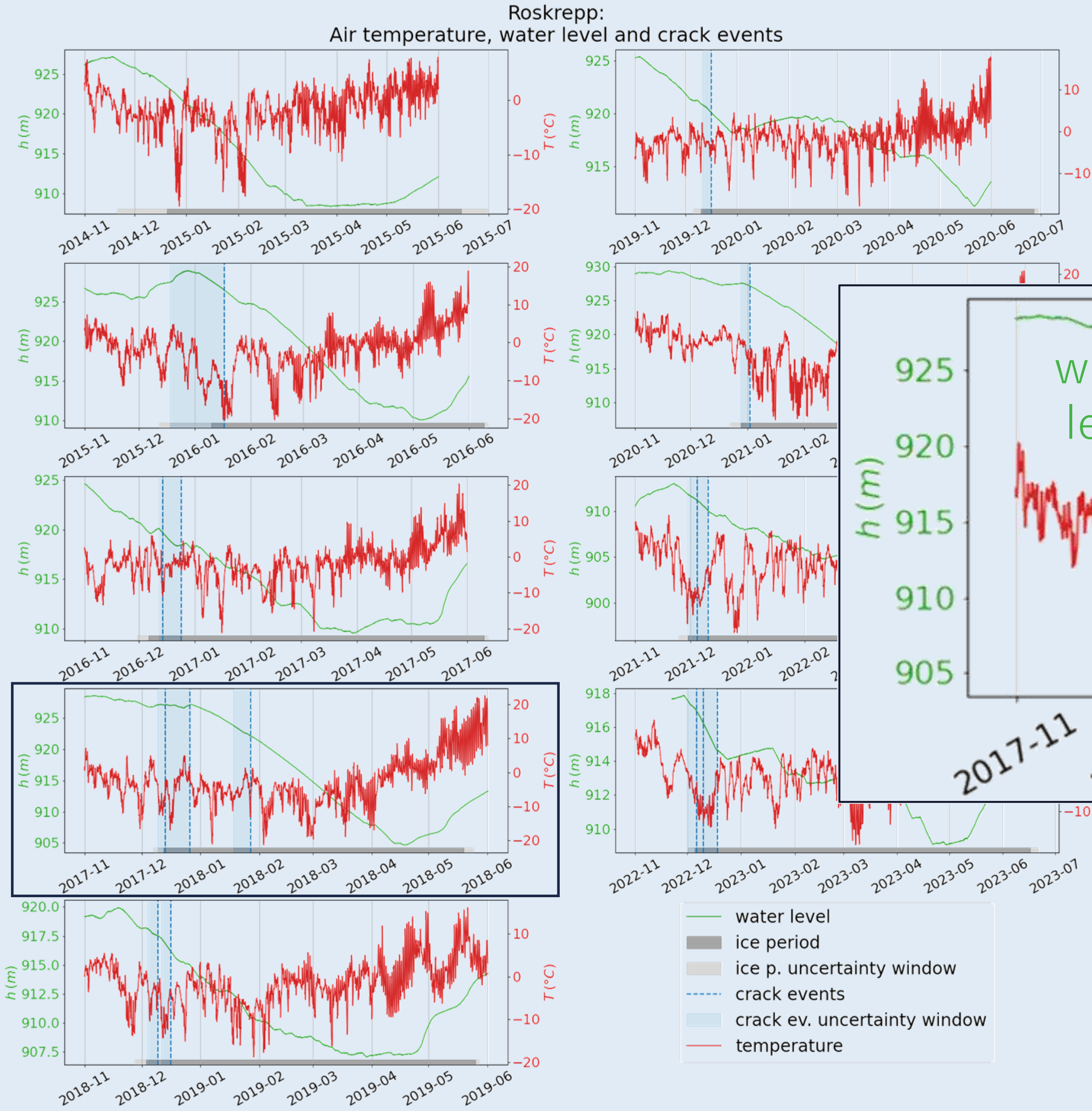

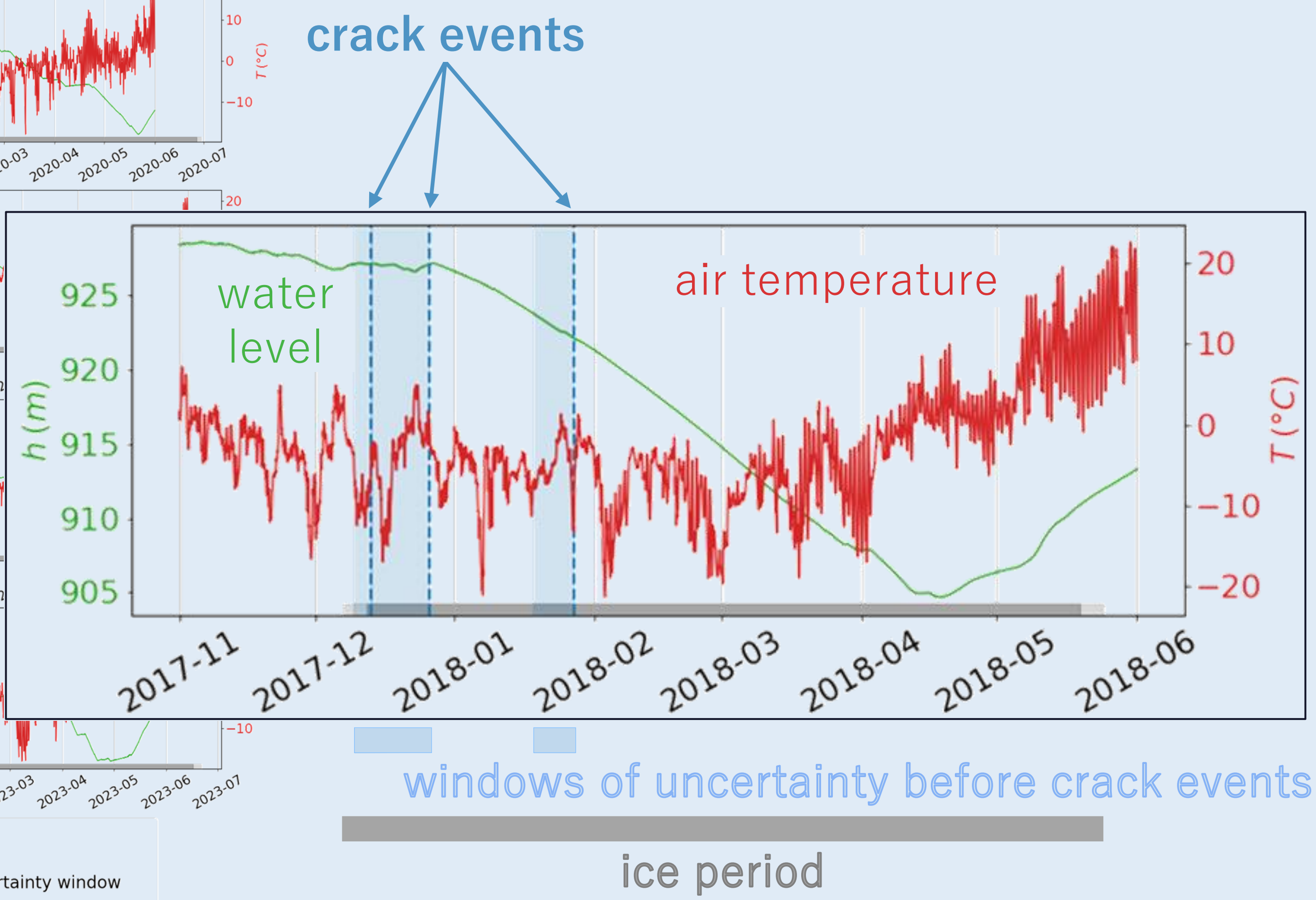

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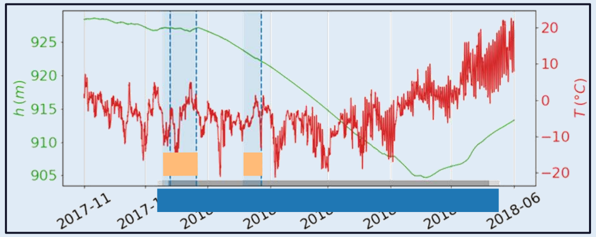

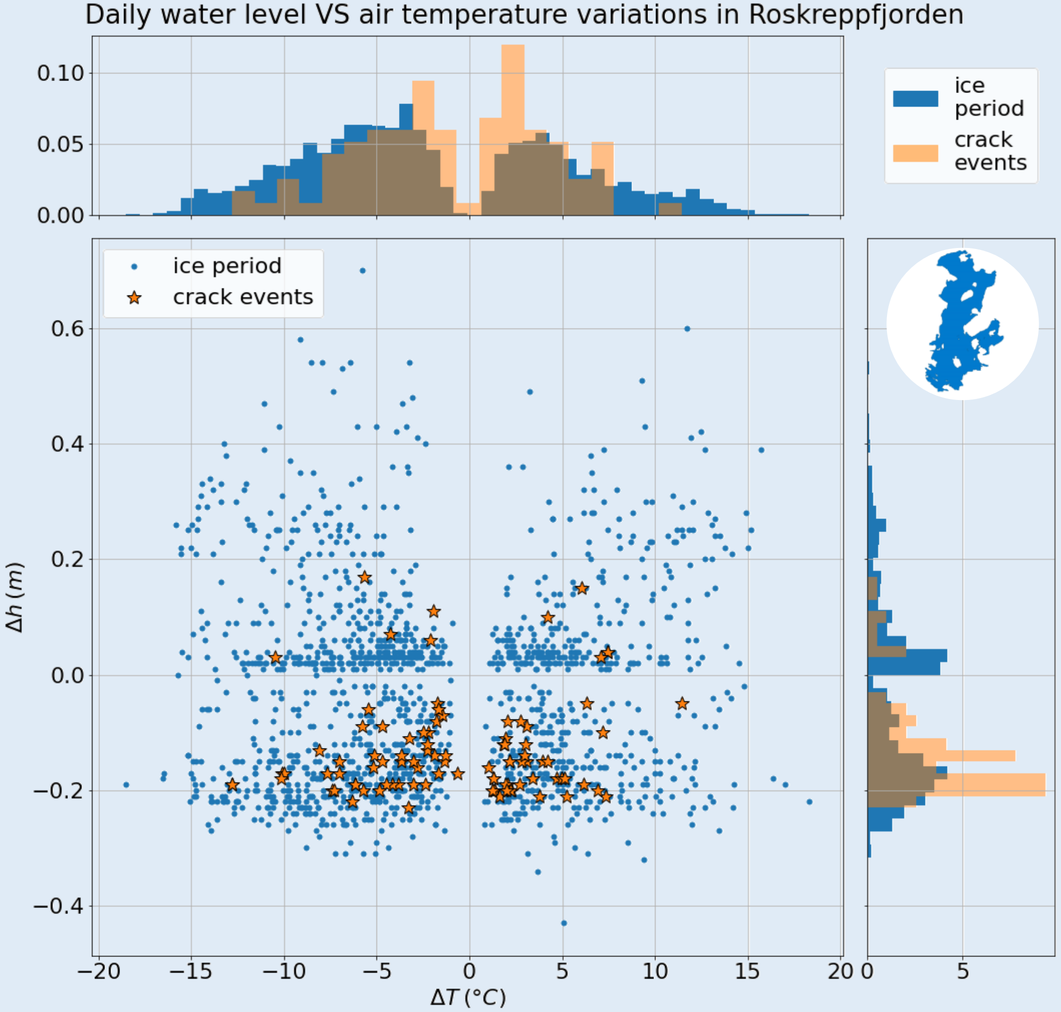

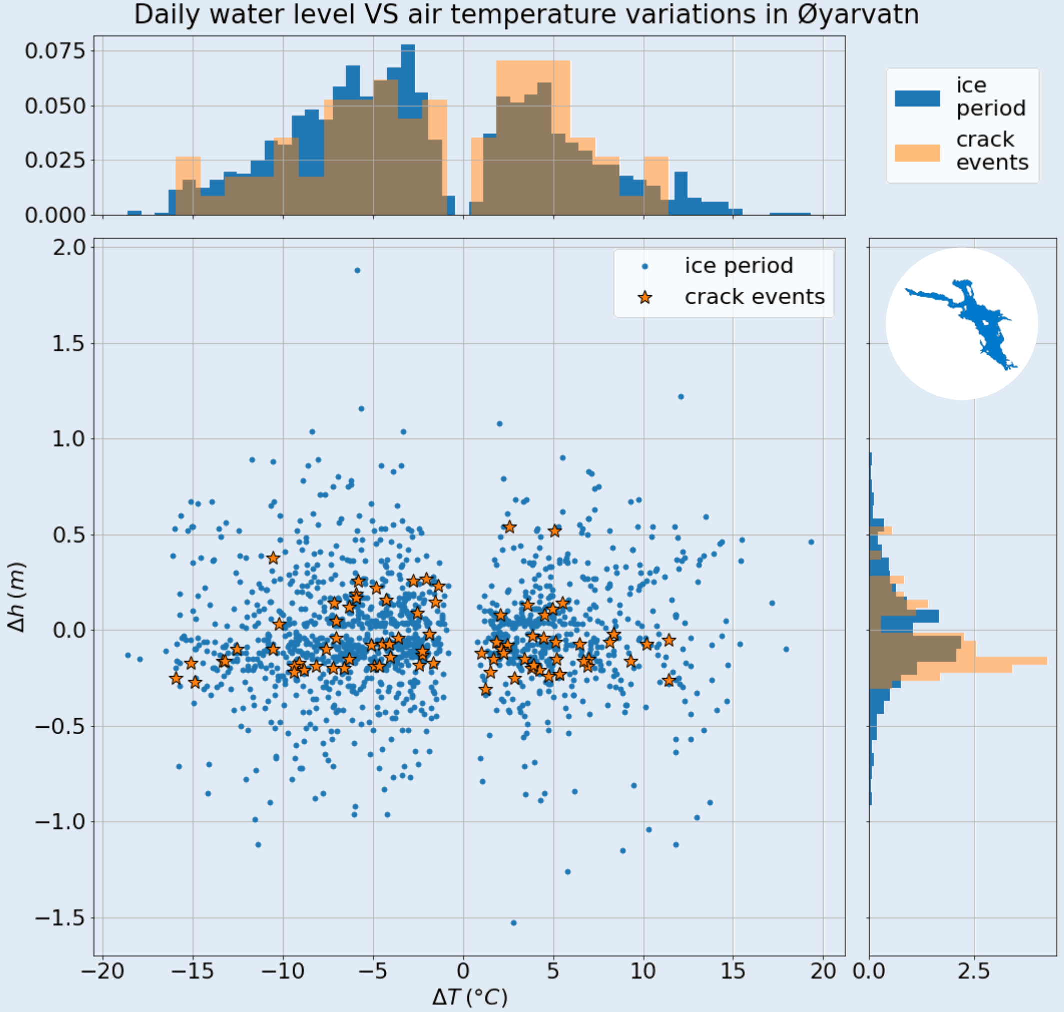

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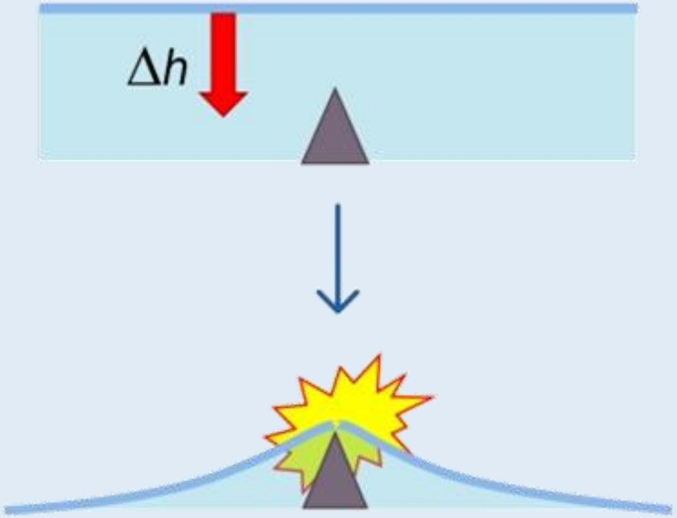
HYPOTHESIS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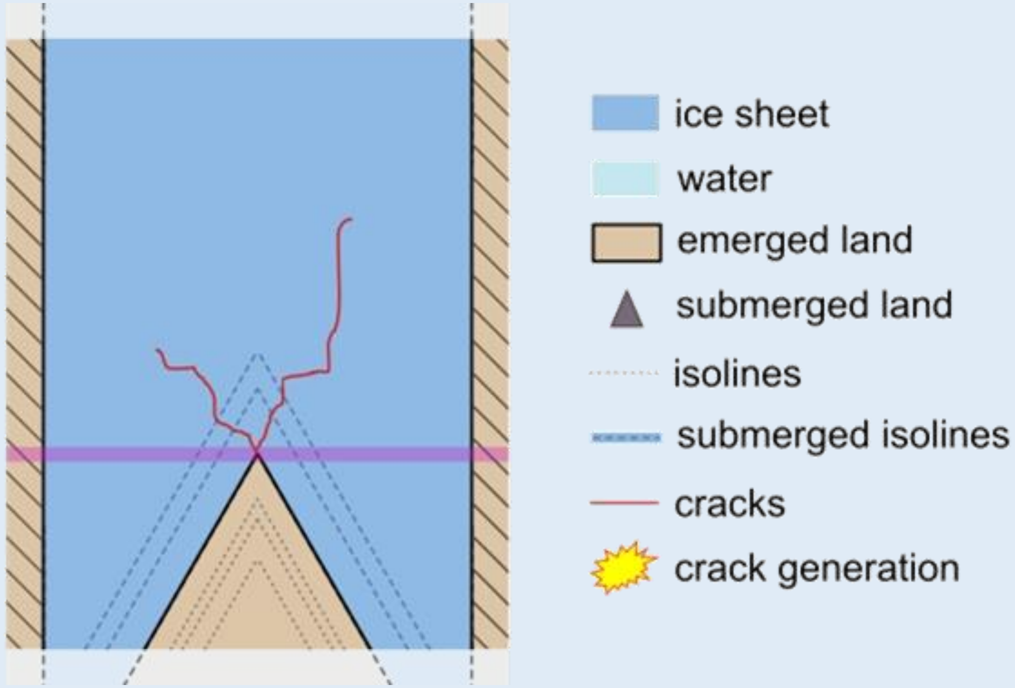
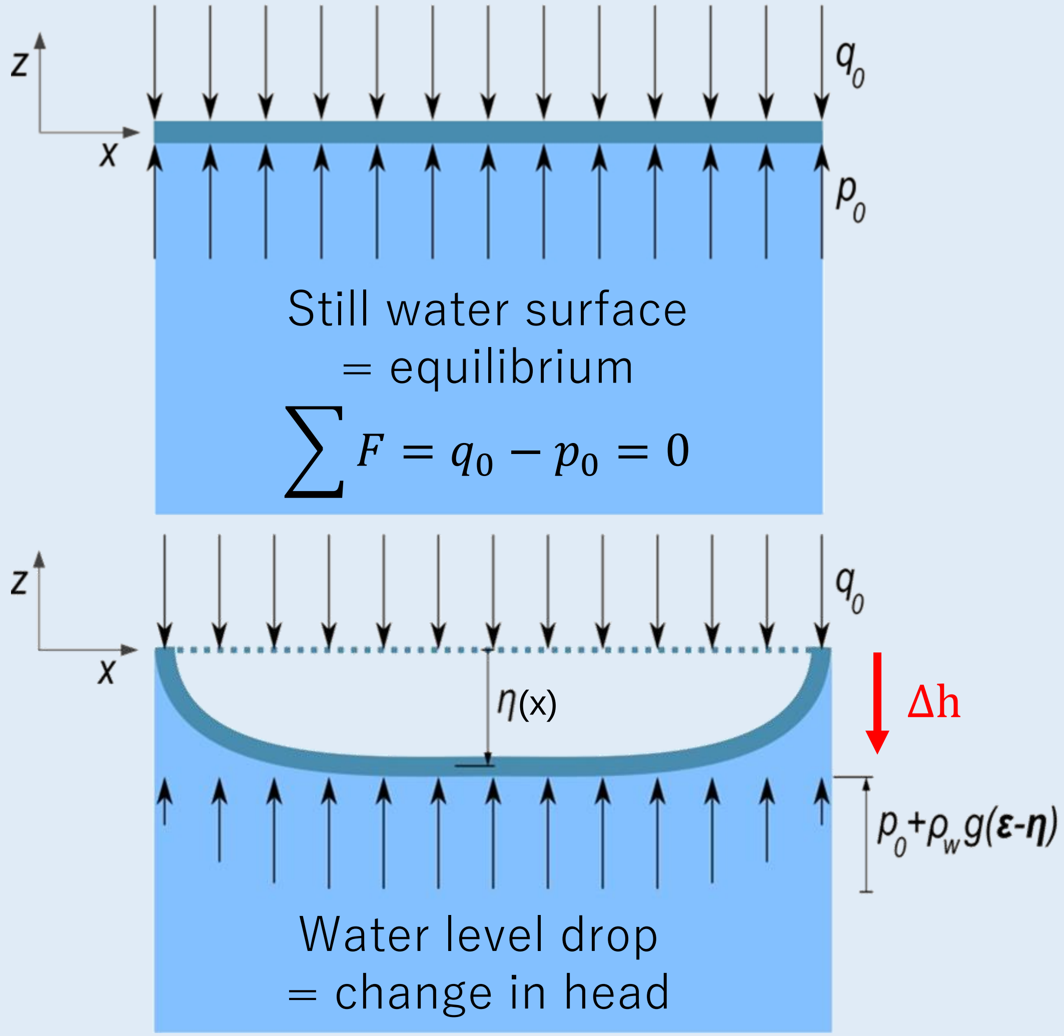

ice sheet
water
emerged land
submerged land
isolines
submerged isolines
cracks
crack generation

MECHANICAL MODEL



Elastic line equation

ice beam deflection

variation of piezometric head

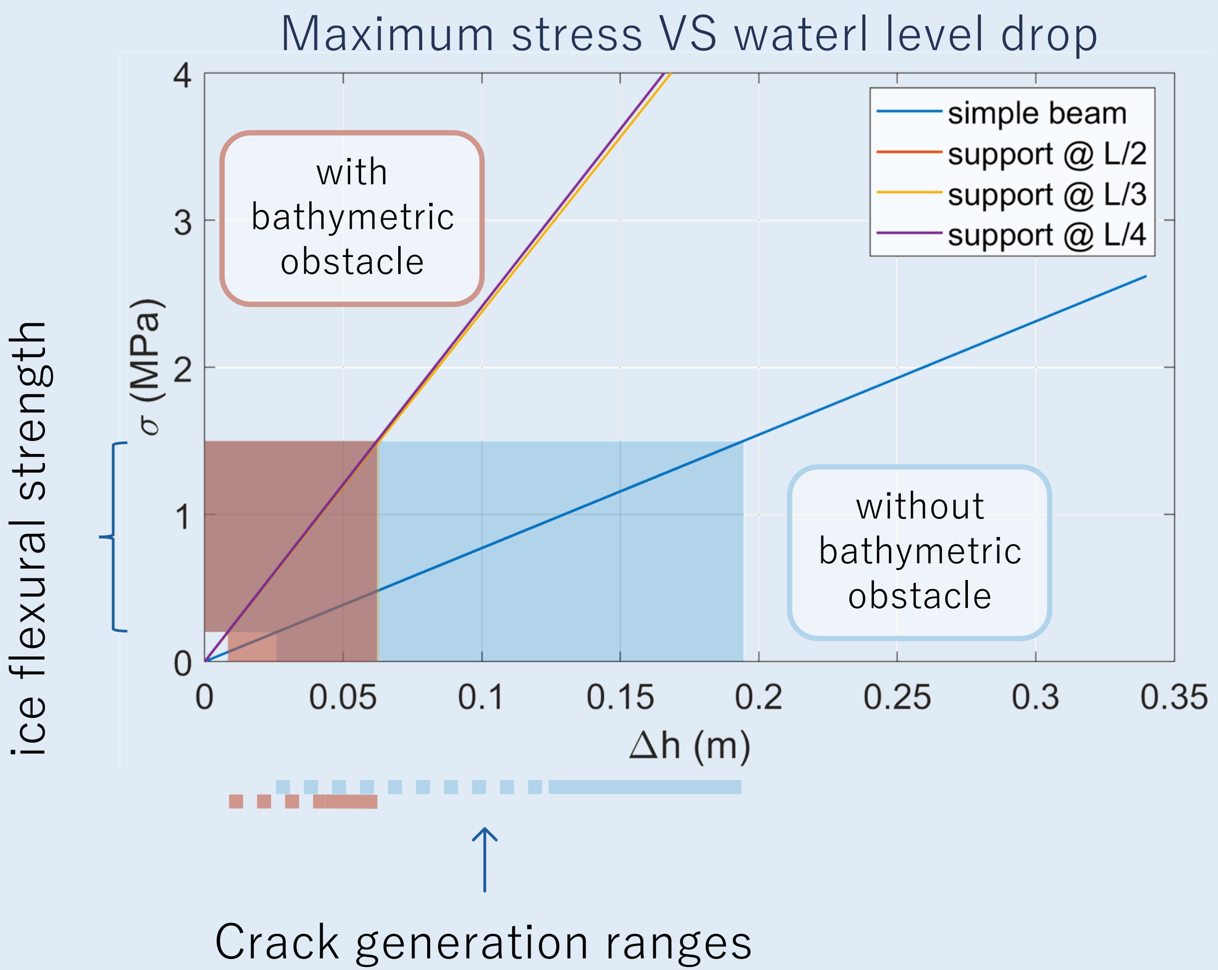
$$EI \frac{d^4\eta}{dx^4} = \rho_w g(\varepsilon - \eta)$$

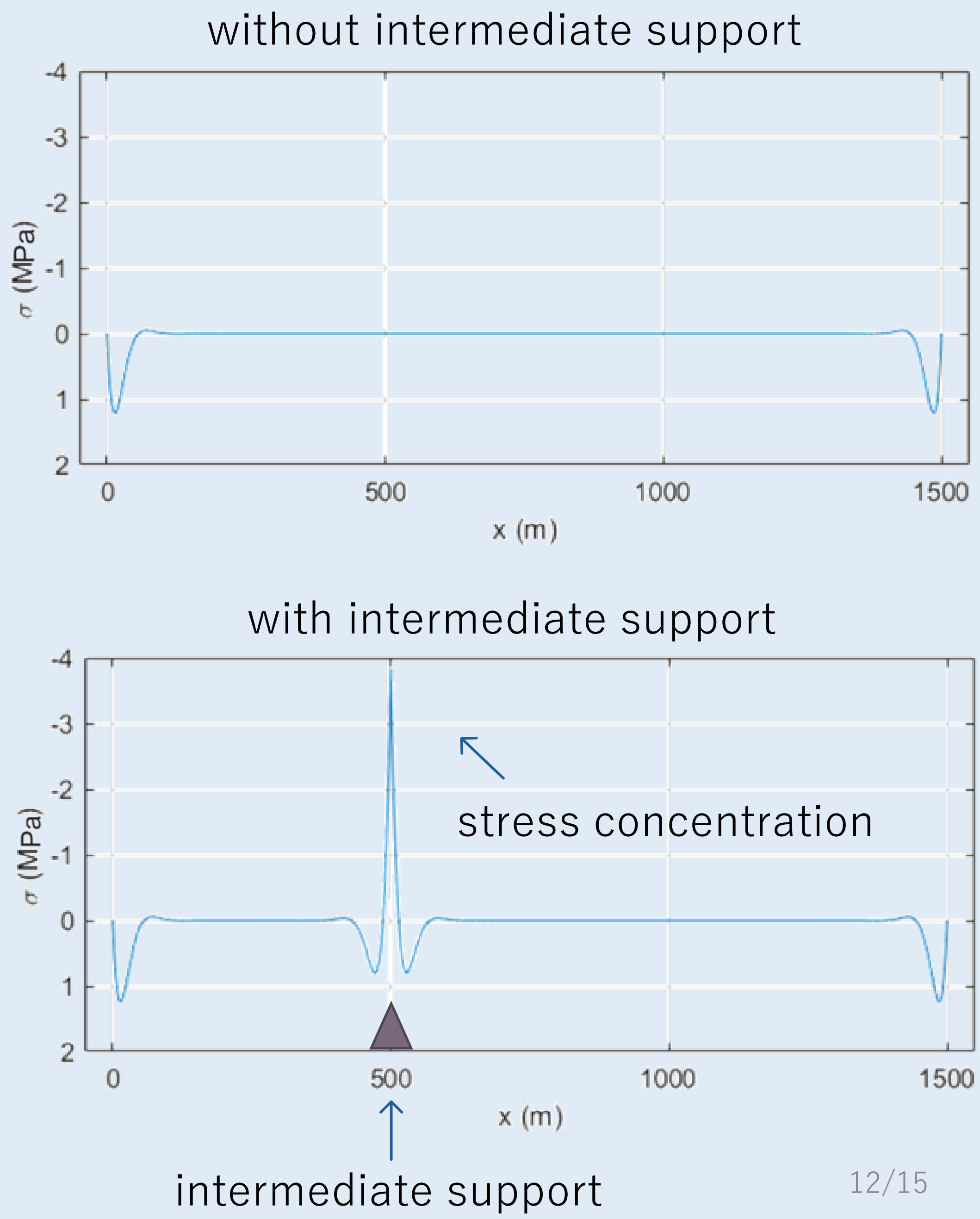
flexural rigidity of the ice beam

response of the water foundation

intermediate support introduced to simulate presence of **bathymetric obstacle**

MECHANICAL MODEL





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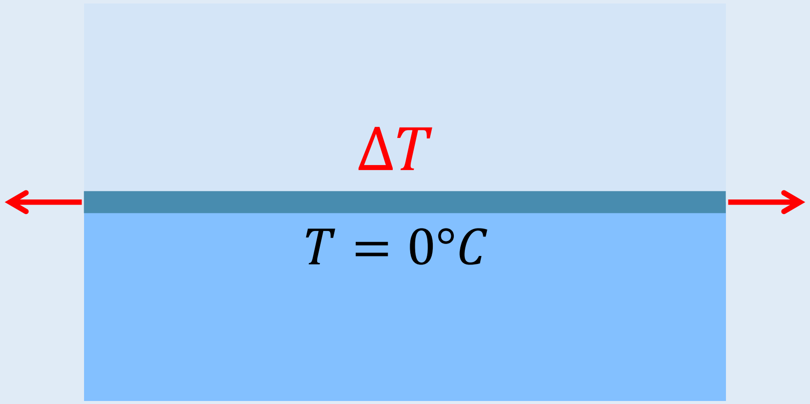
THERMAL EXPANSION MODEL



Critical thermal stress

Infinite beam approximation

ice beam elastic modulus

$$\sigma_c = E\,\alpha\,\frac{\Delta T}{2}$$

coefficient of thermal expansion

Free floating beam – plane stress and strain

ice thickness

$$\sigma_c = max\left(\frac{E\,H}{2}\,\frac{d^2 w_D}{dx^2}\right)$$

$$w_D = f(x, \alpha\,\Delta T, L, H, E, \rho_w, \rho_I)$$

ice density

ice beam deflection

ice beam length

water density

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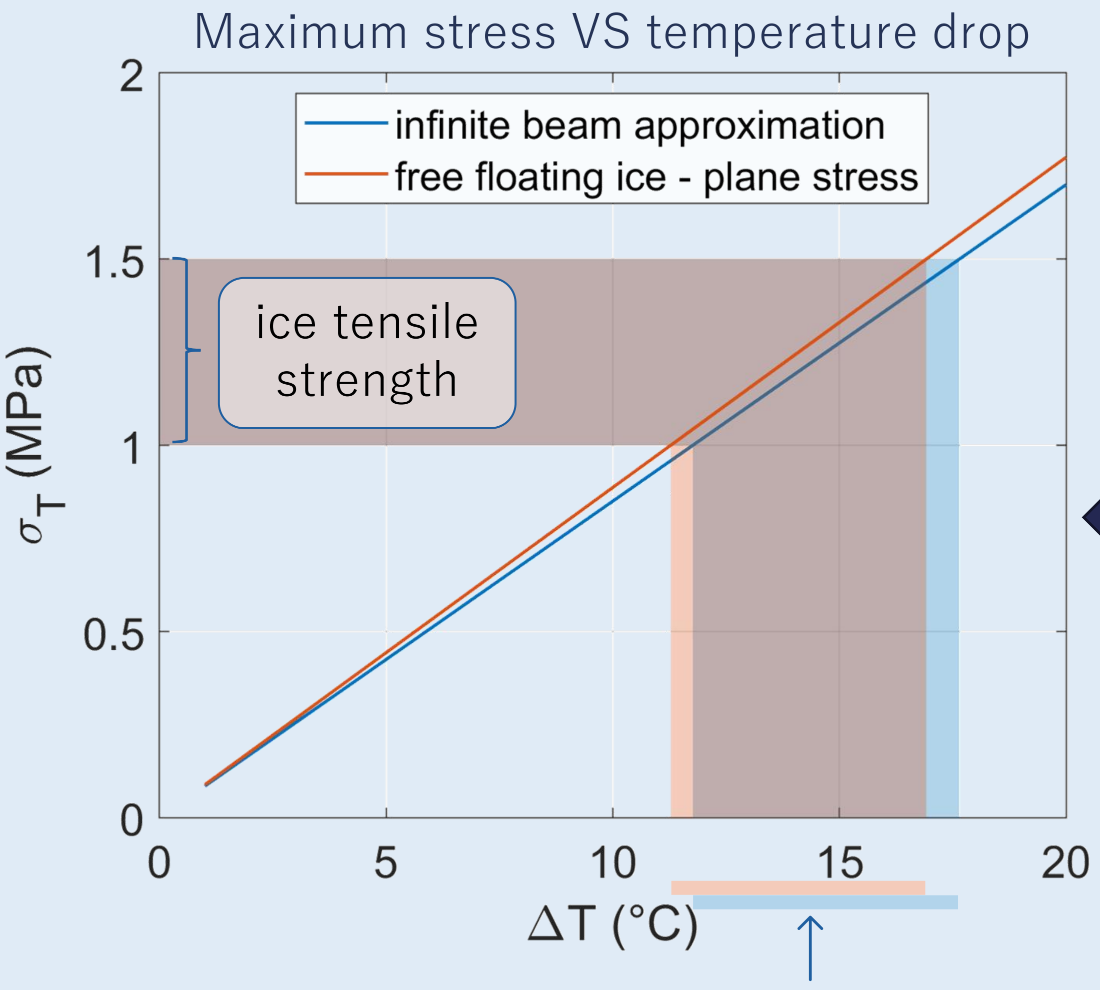
THERMAL EXPANSION MODEL



Crack generation ranges

Critical thermal stress

Infinite beam approximation

$$\sigma_c = E \alpha \frac{\Delta T}{2}$$

- E: ice beam elastic modulus
- α: coefficient of thermal expansion

Free floating beam – plane stress and strain

$$\sigma_c = max\left(\frac{E H}{2} \frac{d^2 w_D}{dx^2}\right)$$

$$w_D = f(x, \alpha\, \Delta T, L, H, E, \rho_w, \rho_I)$$

- H: ice thickness
- w_D: ice beam deflection
- L: ice beam length
- ρ_w: water density
- ρ_I: ice density

CONCLUDING REMARKS

There is a **critical period** (early winter) for crack formation in the study sites

Negative **water level** variations: likely **leading cause** of ice cover cracking in the study reservoirs

Role of modulation of HP operations on ice cover integrity during the critical period for crack formation **should be investigated** in depth.

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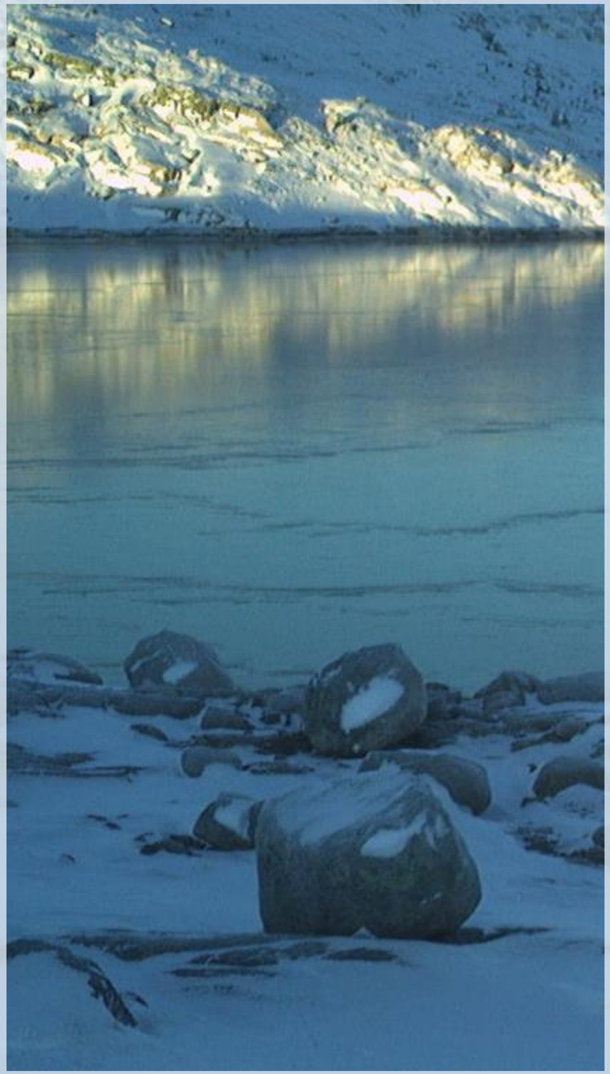
AKNOWLEDGEMENTS



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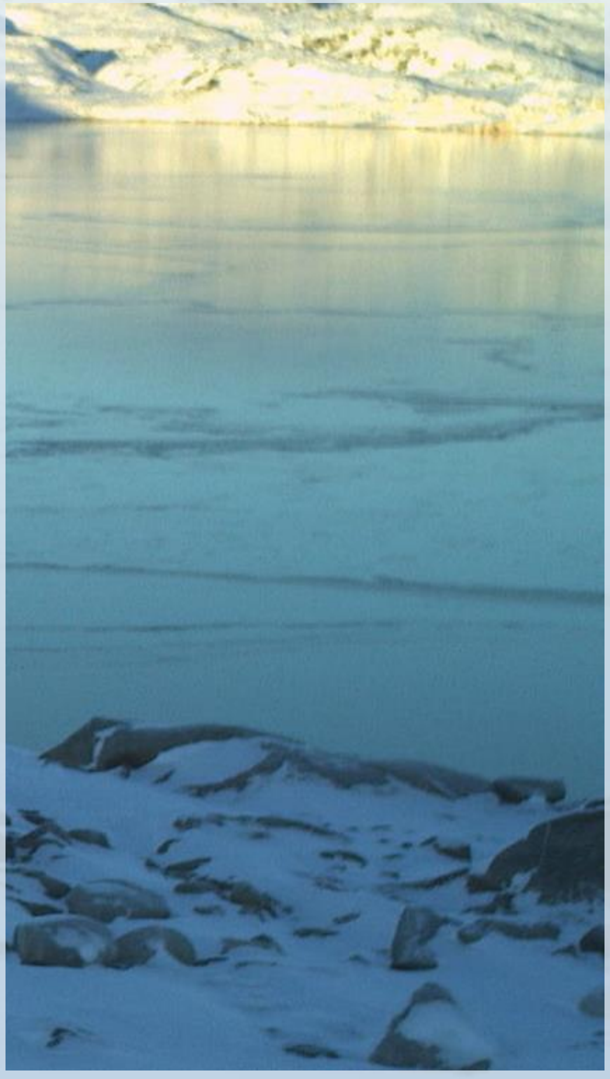

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❯ THANK YOU FOR YOUR ATTENTION!

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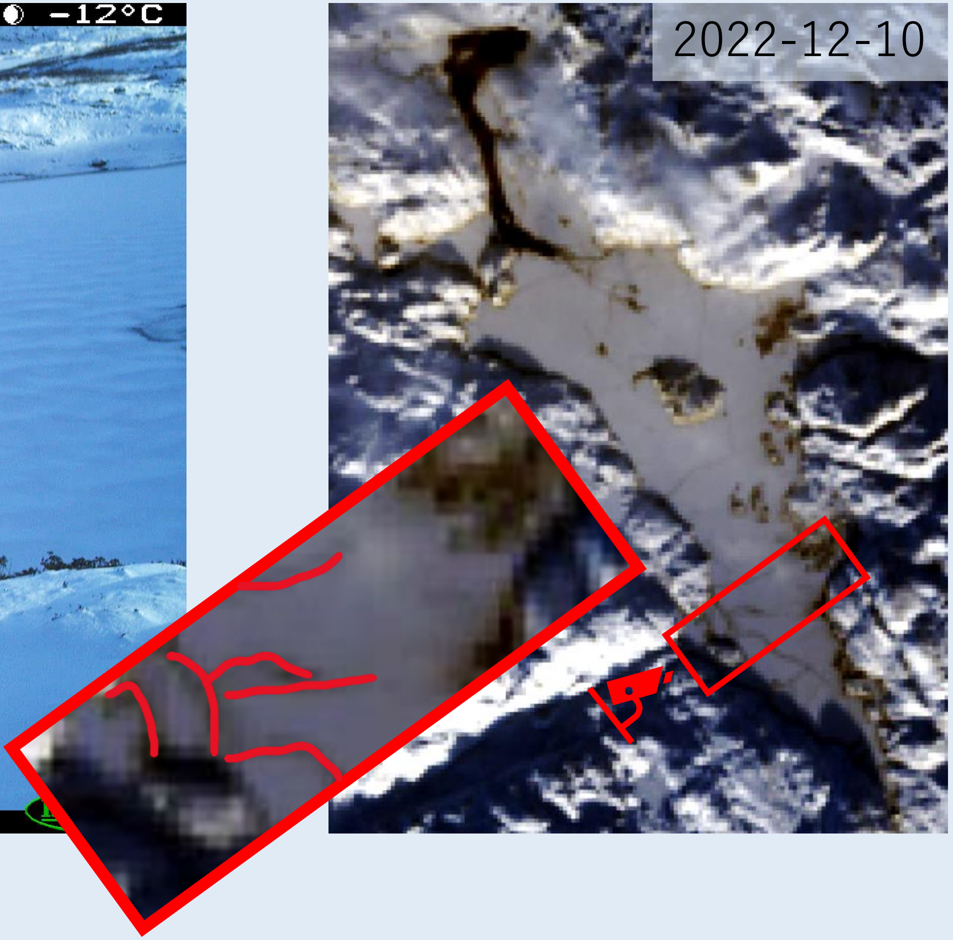
CRACK DETECTION



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RELEVANCE OF ICE INTEGRITY

STUDY AREA: AVAILABLE DATA

AVAILABLE

- Meteorological data
- Water level & hydropower discharge
- Water temperature profiles*
- Imagery from in-situ cameras

NON-EXISTENT

- Ice cover-related data (thickness, temperature, coverage...)
- Natural inflows discharges

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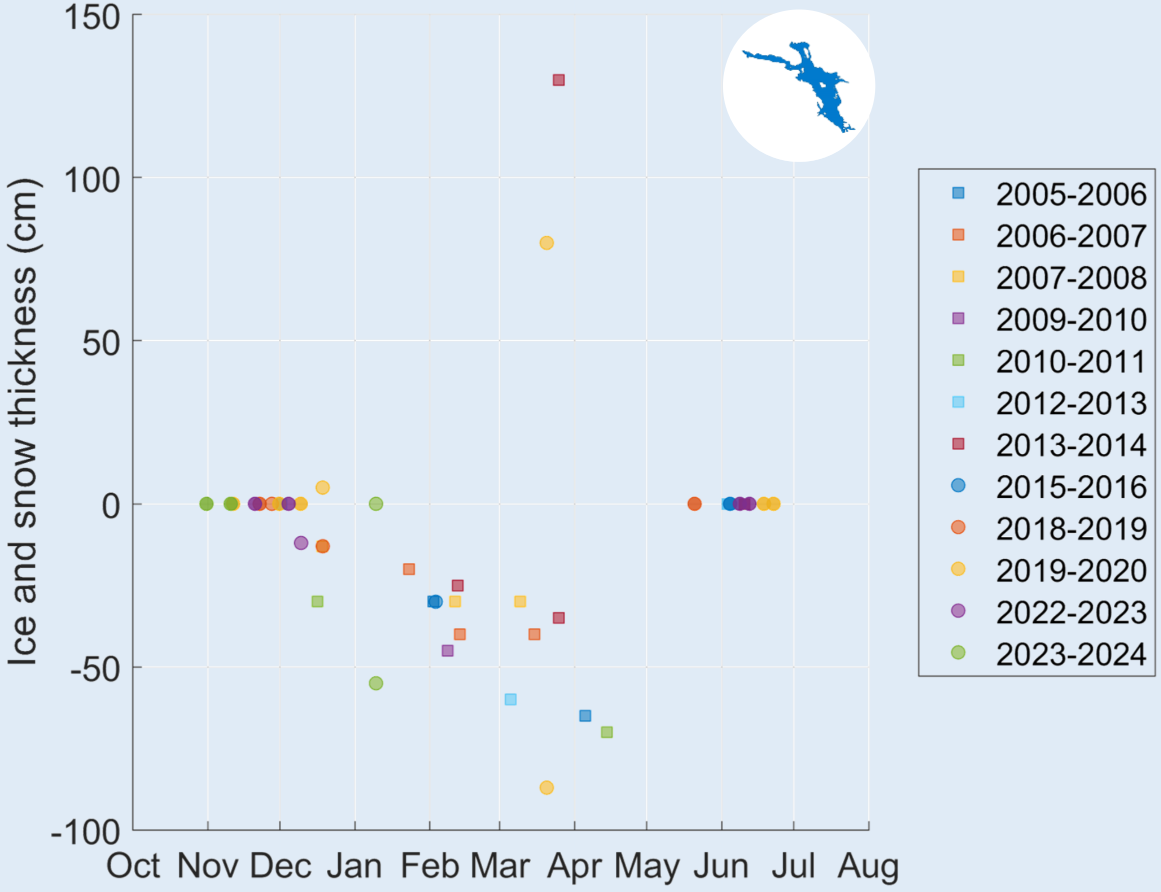
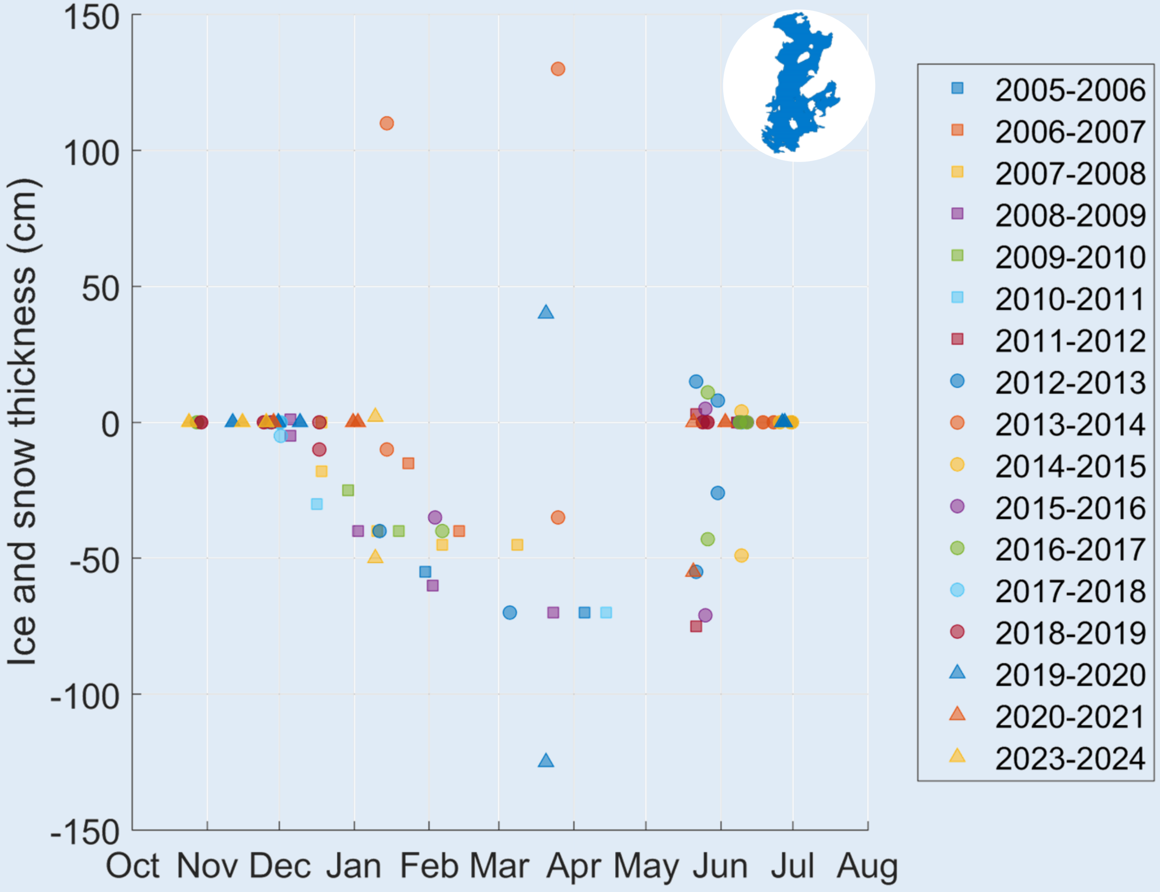
STUDY AREA: ICE THICKNESS





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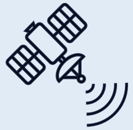

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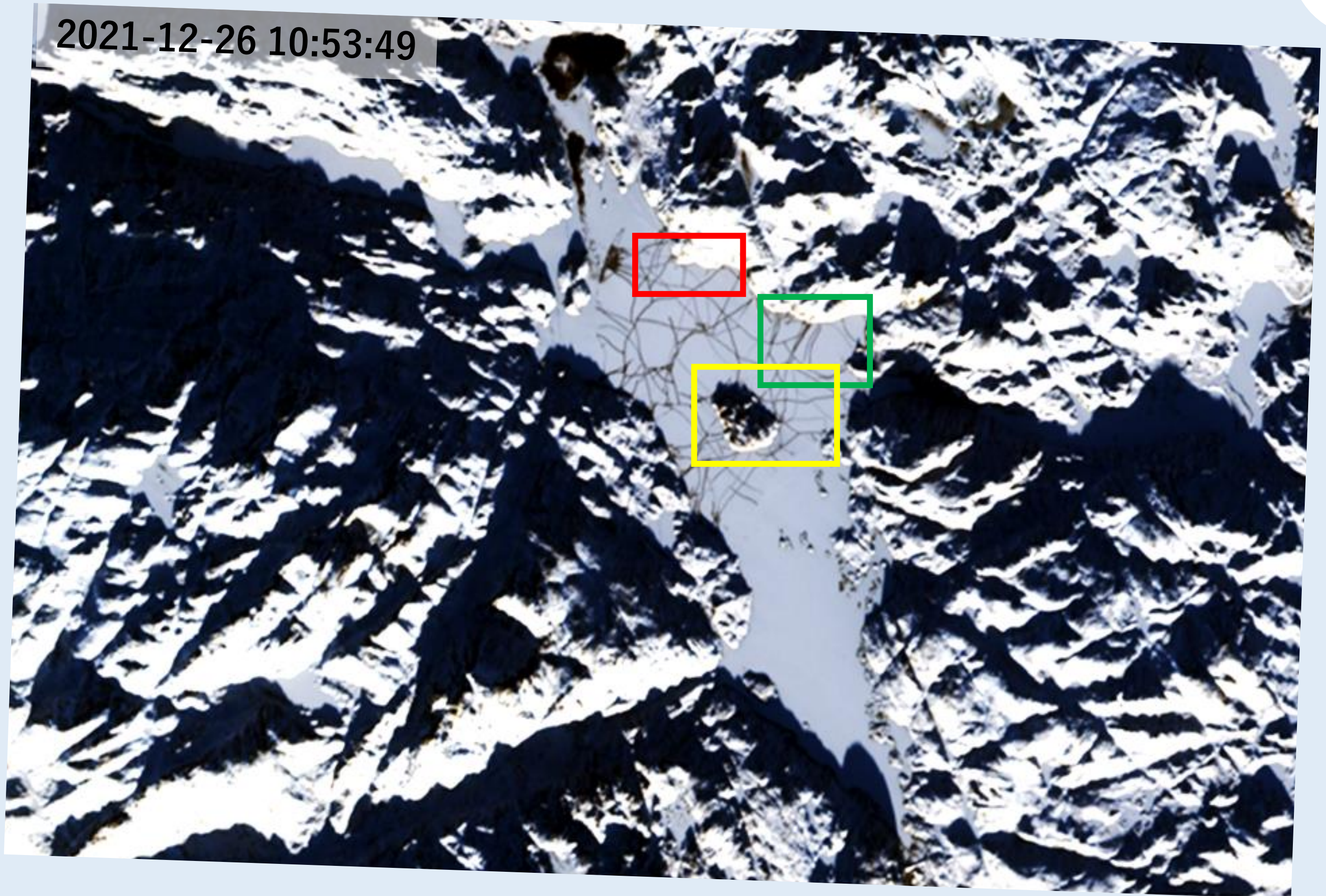

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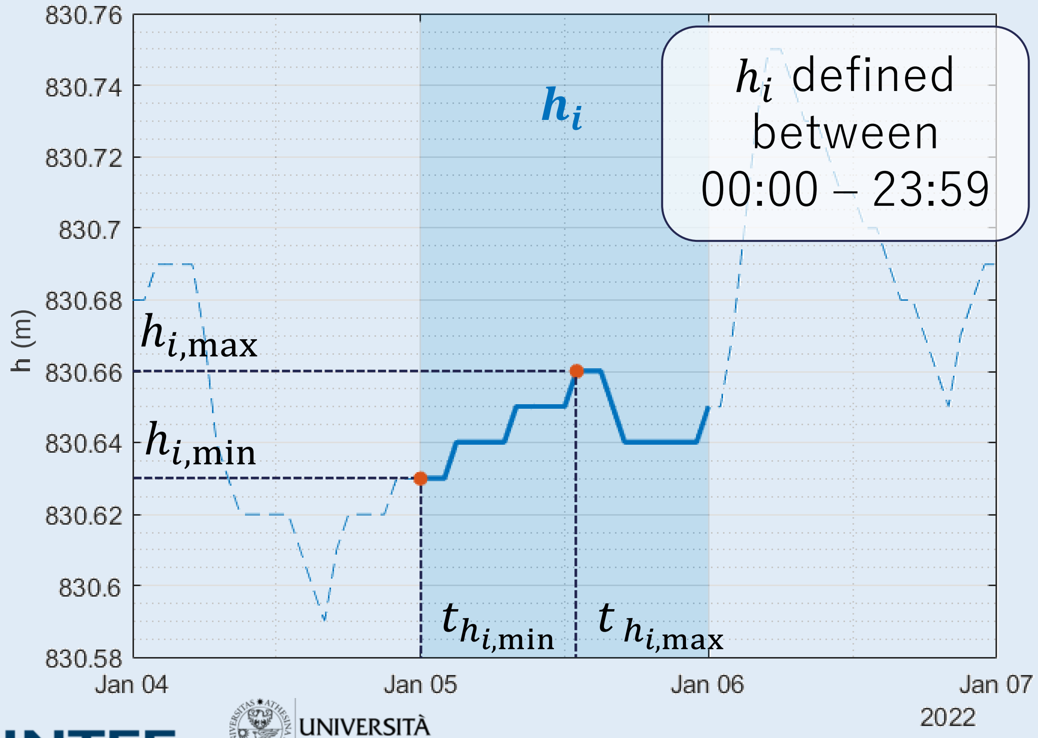
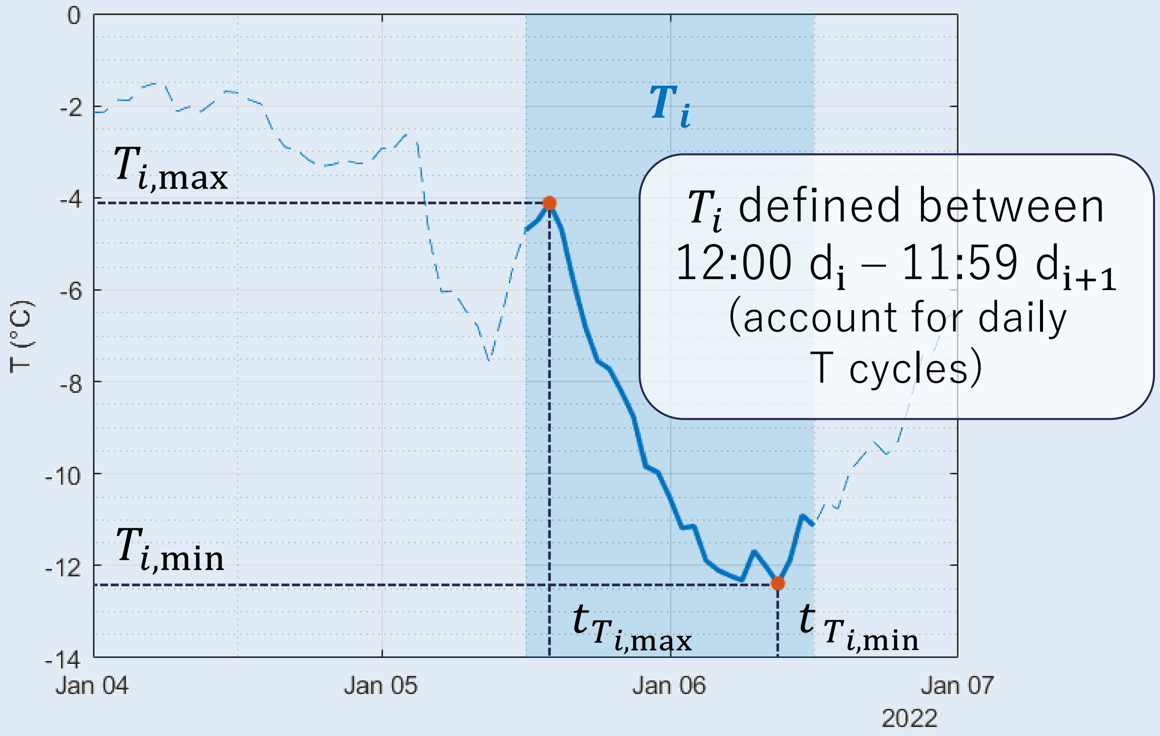
DATA ANALYSIS

Maximum daily variations: $(\max(x_i) - \min(x_i)) \cdot \mathrm{sign}(t_{x_{i,\max}} - t_{x_{i,\min}})$





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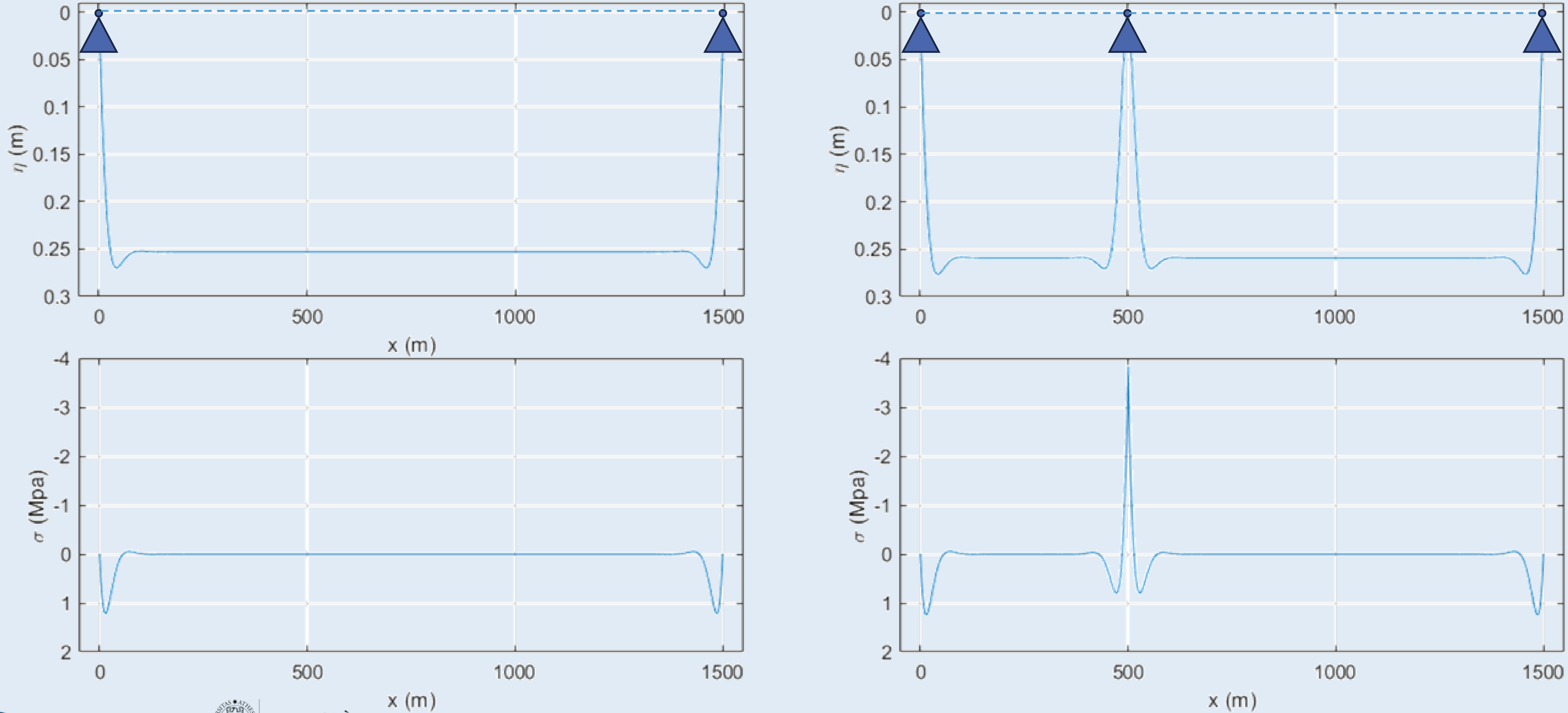
SIMPLIFIED MECHANICAL MODEL

Simple ice beam

Beam with intermediate support

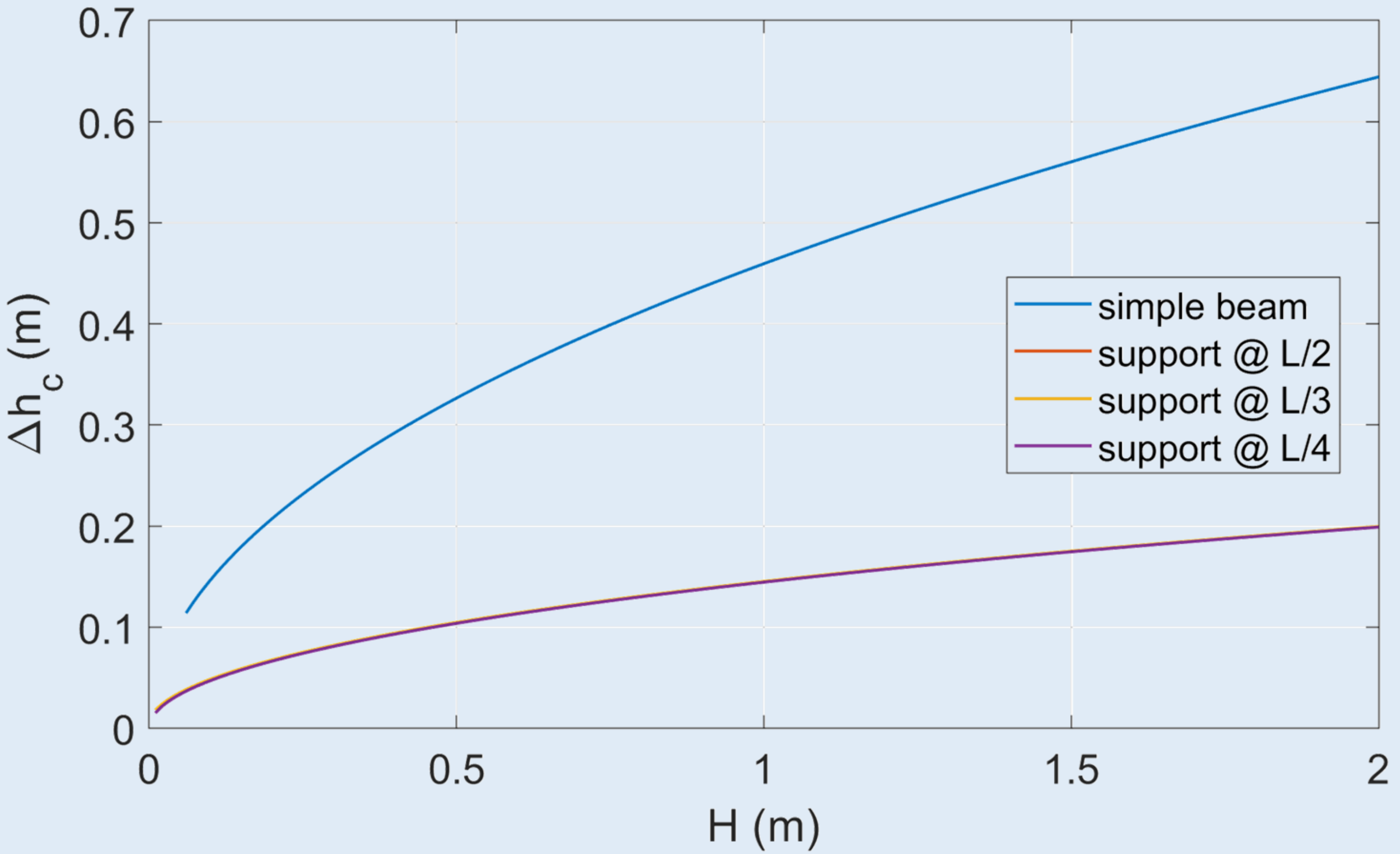
$\Delta h = 0.25$ m, E = 6 Mpa, H = 80 cm



MODEL PARAMETERS: LITERATURE REVIEW

Name	Symbol	Value	Unit	Sources
Elastic modulus	E	1.2-10	GPa	[12, 9, 11, 31]
Flexural strength	σ_c	0.2-1.5	MPa	[10, 11, 1, 31]
Tensile strength	$\sigma_{c,T}$	1-1.5	MPa	[9, 12]
Coefficient of thermal expansion	α_T	$5\text{-}11{\times}10^{-5}$	$^\circ C^{-1}$	[9, 12, 13, 20]
Thermal diffusivity	κ	1.3×10^{-7}	$m^2\,s^{-1}$	[20]
Freshwater density	ρ_w	1000	$kg\,m^{-3}$	

MECHANICAL MODEL: ROLE OF ICE THICKNESS



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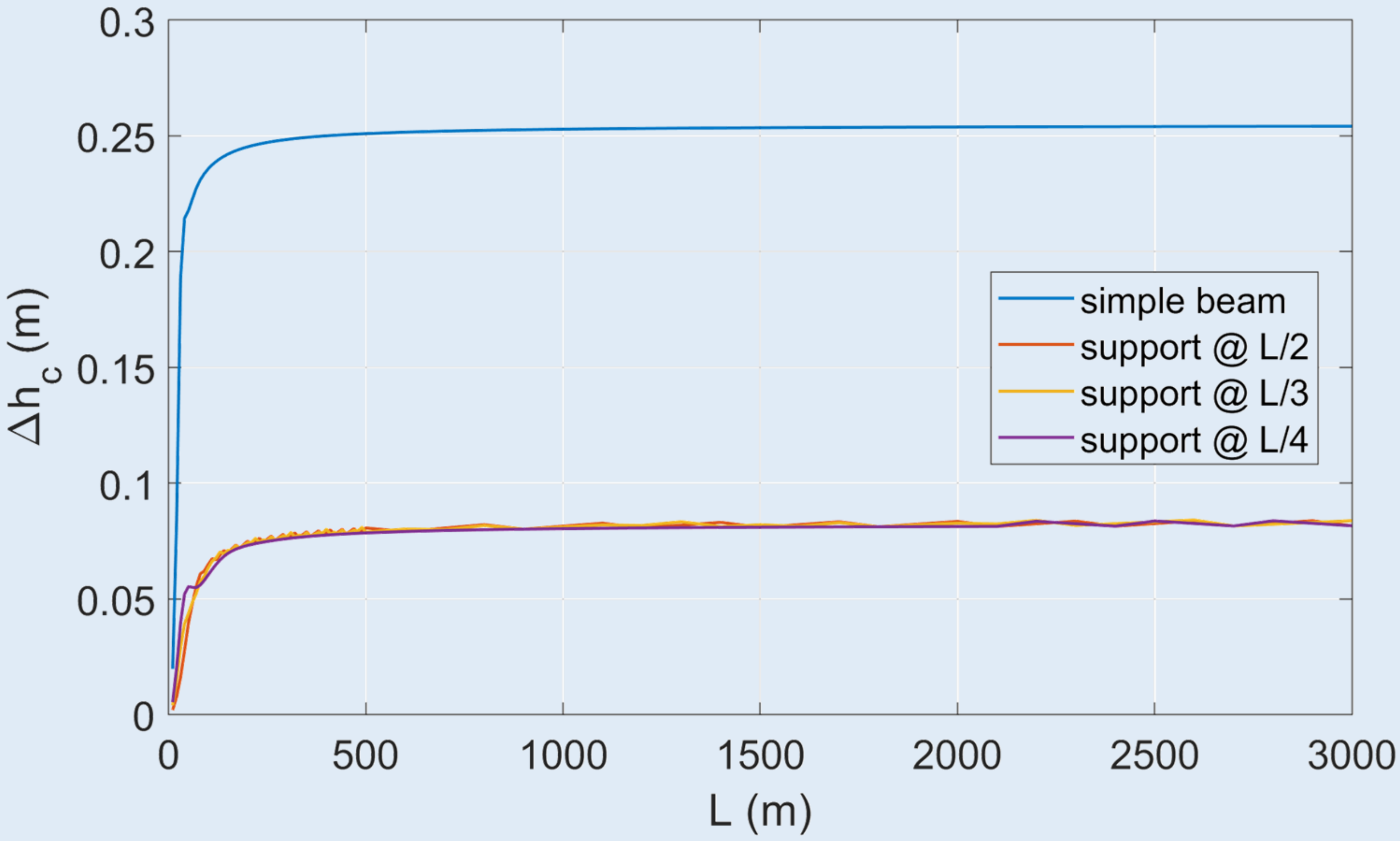
MECHANICAL MODEL: ROLE OF ICE BEAM LENGTH



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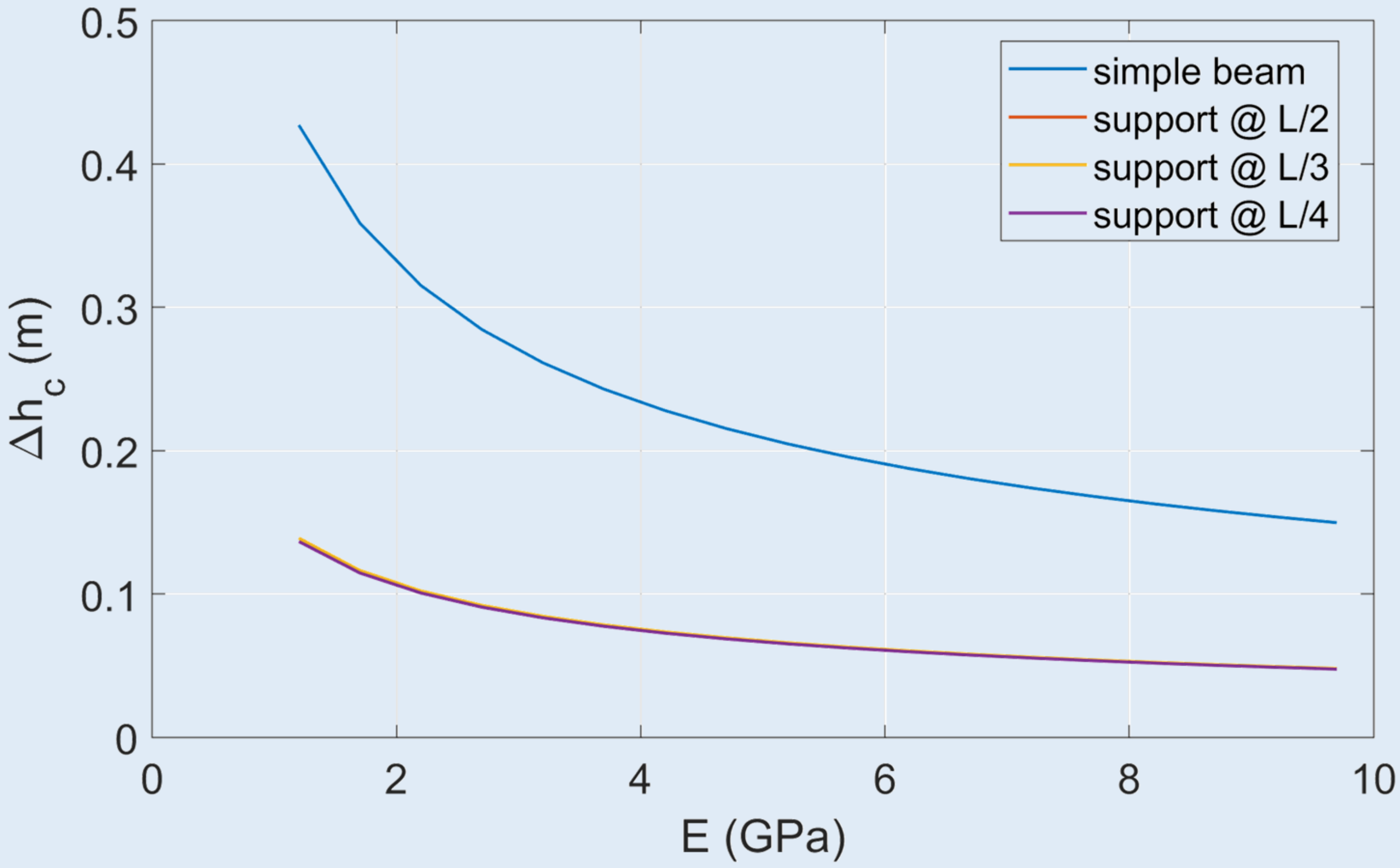
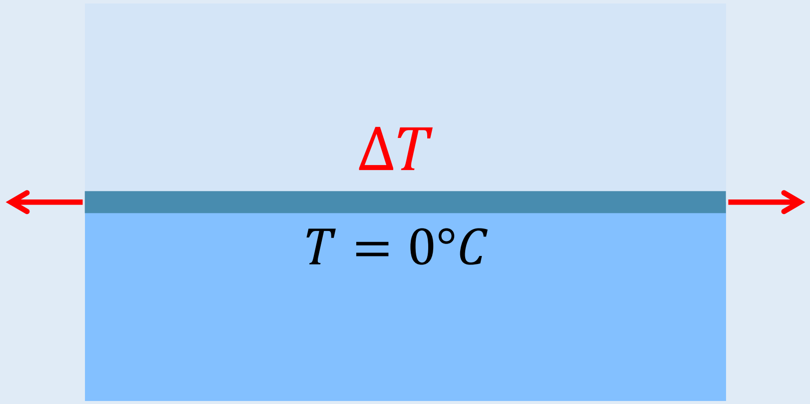
MECHANICAL MODEL: ROLE OF ICE ELASTIC MODULUS



THERMAL EXPANSION MODEL



Critical thermal stress

Free floating beam – plane stress and strain

$$\sigma_c = max\left(\frac{E\,H}{2}\,\frac{d^2 w_D}{dx^2}\right)$$

$$w_D = f(x, \alpha\,\Delta T, L, H, E, \rho_w, \rho_I)$$

ice thickness (H); ice density (ρ_I); ice beam deflection (w_D); ice beam length (L); water density (ρ_w)

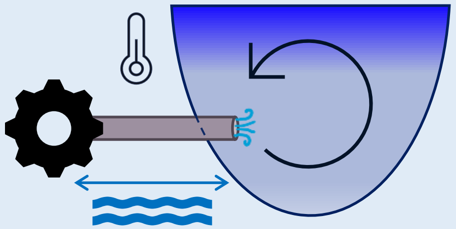
$$l = L/2$$

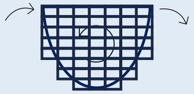
$$w_D = \frac{K}{2\lambda 6\,(sinh\,\lambda l + sin\,\lambda l)}\left\{\begin{array}{c}(-\,cosh\,\lambda l sin\,\lambda l - sinh\,\lambda l\,cos\,\lambda l)\,sinh\,\lambda x\,sin\,\lambda x \\ + \\ (-\,sinh\,\lambda l\,cos\,\lambda l + cosh\,\lambda l sin\,\lambda l)\,cosh\,\lambda x\,cos\,\lambda x\end{array}\right\} + H\left(\frac{\rho_i}{\rho_w} - \frac{1}{2}\right) + \frac{K}{4\lambda^4}x^2$$

$$K = 6\frac{\rho_w g}{E H^4}\alpha_T\,(T_s - T_b)$$

NEXT STEPS

Thermal stratification





2D hydro-thermodynamic modelling

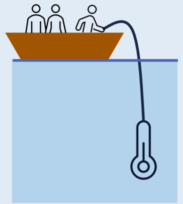
Water Quality Research Group
CE-QUAL-W2 Hydrodynamic and Water Quality Model

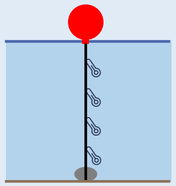
air2water

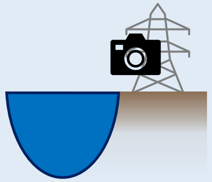
OpenWeather

Sira-Kvina KRAFTSELSKAP

Calibration & validation with in-situ data







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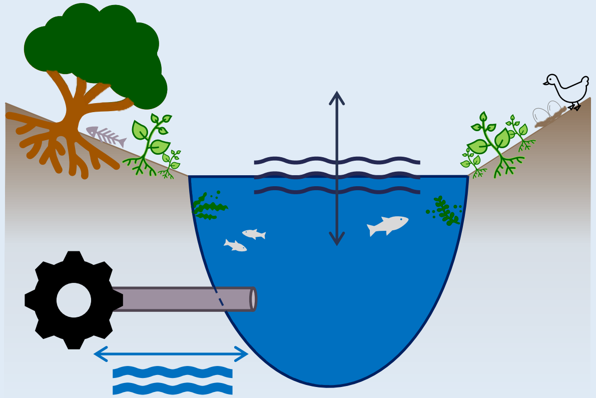
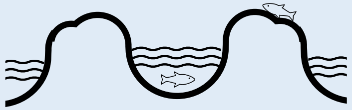
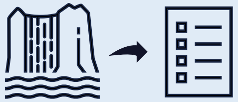
NEXT STEPS

Littoral zone





Identify environmental impacts



Quantify impacts with environmental indexes

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Report

Testing and evaluation of a HYMO classification system for lakes and reservoirs

SINTEF Energy Research

No	Parameter	Near-natural	Slightly modified	Moderately modified	Extensively modified	Severely modified
100	Change in annual inflow	<5 % regulation upstream	5-20 % regulation upstream	20-50% regulation upstream	50-90% regulation upstream	>90% regulation upstream
101	Upstream barriers affecting sediment processes	<5 % reduction in distance to natural upstream barrier	5-10 % reduction in distance to natural upstream barrier	10-50 % reduction in distance to natural upstream barrier	50-90 % reduction in distance to natural upstream barrier	>90 % reduction in distance to natural upstream barrier
200	Water level changes	<2 meters	2-3 meters	3-10 meters	10-50 meters	>50 meters
201	Total volume change	<5 % change from natural volume	5-10 % change from natural volume	10-30 % change from natural volume	30-70 % change from natural volume	>70 % change from natural volume
202	Change in retention time	<5 % change in retention time	5-20 % change in retention time	20-50 % change in retention time	50-100 % change in retention time	>100 % change in retention time
203	Change in date of filling	<3 days change compared to filling by starting date	3-10 days change compared to filling by starting date	10-20 days change compared to filling by starting date	20-70 days change compared to filling by starting date	>70 days change compared to filling by starting date
204	Change in date of emptying	<3 days change compared to emptying by starting date	3-10 days change compared to emptying by starting date	10-20 days change compared to emptying by starting date	20-70 days change compared to emptying by starting date	>70 days change compared to emptying by starting date
205	Water level change at filling date	<5 % relative deviation from natural water level	5-10 % relative deviation from natural water level	10 – 30 % relative deviation from natural water level	30-70 % relative deviation from natural water level	>70 % relative deviation from natural water level
206	Water level change at emptying date	<5 % relative deviation from natural water level	5-10 % relative deviation from natural water level	10 – 30 % relative deviation from natural water level	30-70 % relative deviation from natural water level	>70 % relative deviation from natural water level
207	Short term water level variations (days)	<0.1 meters change during one day (90-percentile day during a year)	0.1-0.5 meters change during one day (90-percentile day during a year)	0.5-1 meter during one day (90-percentile day during a year)	1-2 meters during one day (90-percentile day during a year)	>2 meters during one day (90-percentile day during a year)
208	Short term water level variations (weeks)	<0.3 meter within a week (90-percentile of a week during a year)	0.3-1 meter within a week (90-percentile of a week during a year)	1-3 meters in a week (90-percentile of a week during a year)	3-5 meters during one week (90-percentile week during a year)	>5 meters during one week (90-percentile week during a year)
210	Dewatered areas	<5 % dewatered compared to natural surface area	5-10 % dewatered compared to natural surface area	10-40 % dewatered compared to natural surface area	40-90 % dewatered compared to natural surface area	>90 % dewatered compared to natural surface area
211	Relative lake level fluctuation	<5 % in relative lake level fluctuations	5-50 % in relative lake level fluctuations	50-100 % in relative lake level fluctuations	100-150 % in relative lake level fluctuations	>150 % in relative lake level fluctuations
212	Dewatered littoral zone versus total littoral zone (ratio)	<5 % affected by dewatering	5-10 % affected by dewatering	10-40 % affected by dewatering	40-90 % affected by dewatering	>90 % affected by dewatering
213	Loss in lateral connectivity along the shoreline	<5 % of shoreline affected	5-20 % of shoreline affected	20-50 % of shoreline affected	50-90 % of shoreline affected	>90 % of shoreline affected
214	Riparian zone changes	<5 % of riparian vegetation affected (measured as % of shoreline)	5-20 % of riparian vegetation affected (measured as % of shoreline)	20-50 % of riparian vegetation affected (measured as % of shoreline)	50-90 % of riparian vegetation affected (measured as % of shoreline)	>90 % of riparian vegetation affected (measured as % of shoreline)
220	Change in substrate qualities	<5 % spawning substrate lost	5-10 % spawning substrate lost	10-40 % spawning substrate lost	30-90 % spawning substrate lost	>90 % spawning substrate lost

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