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Bathymetry of sea ice melt ponds reconstructed from aerial photographs using shallow water photogrammetry

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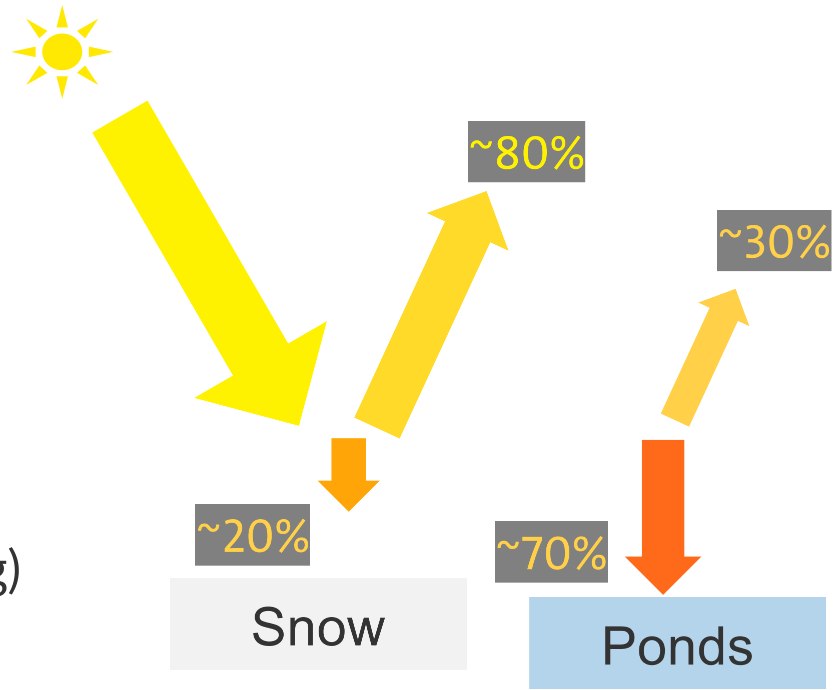
05 Nov 2024

Melt ponds in the Arctic sea-ice system

Melt ponds form on Arctic sea ice during summertime

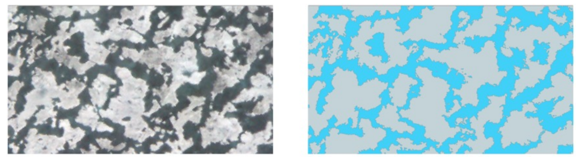


Accumulation of snow and ice surface meltwater

Four stages of evolution

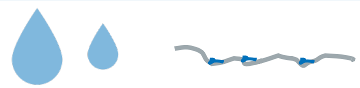
I. Formation (May/Jun)
II. Drainage (Jul)
III. Melt evolution (Jul-Aug)
IV. Freeze up (Aug/Sep)

Eicken et al. 2002



Typically cover 20-40% of the ice surface

Key role in the surface heat budget



Reservoir for freshwater, Impact the ecosystem and momentum transfer

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Why studying ponds?

Ponds lower the ice albedo with a positive feedback

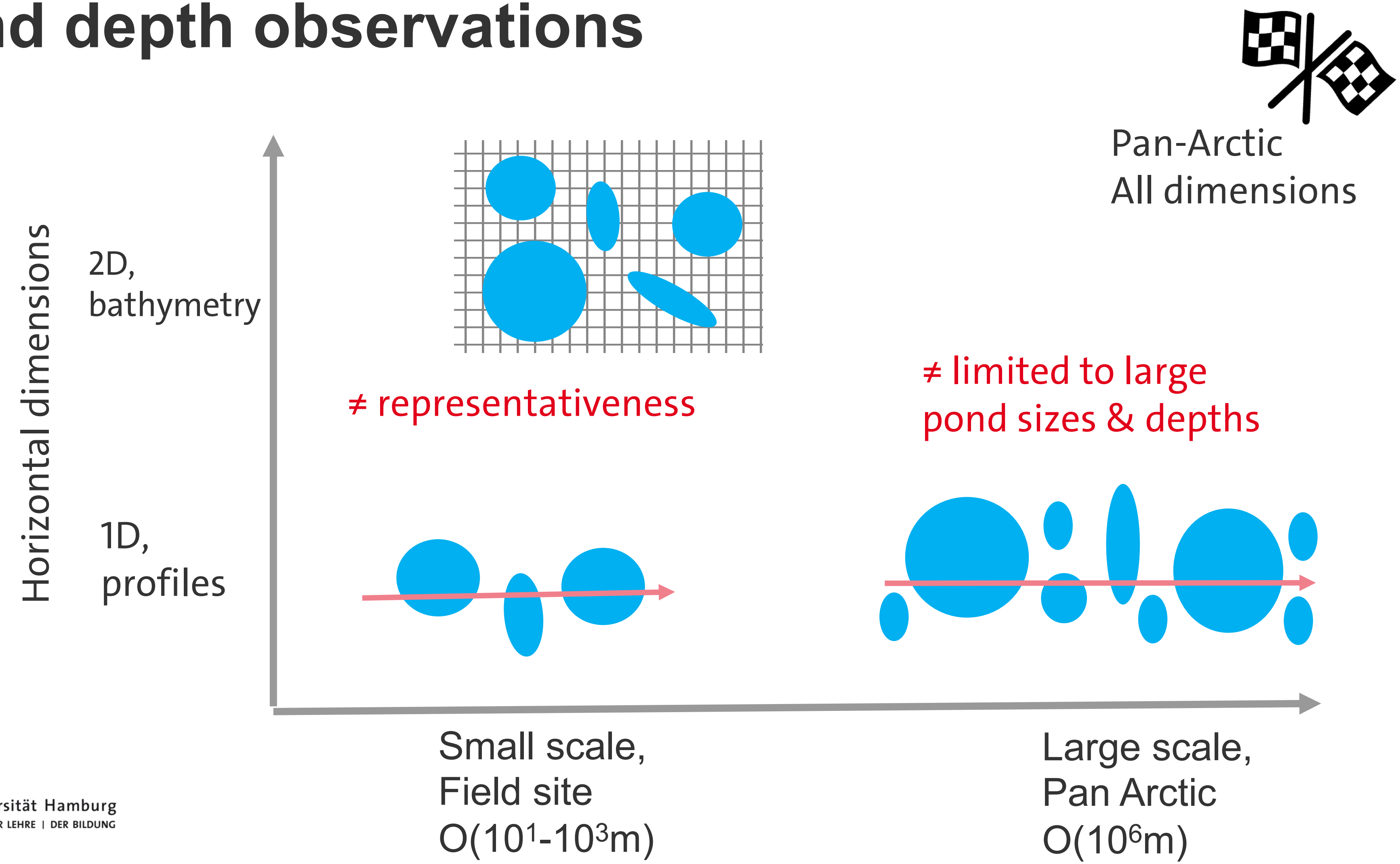
Perovich et al. 2002

Mismatch between Observations and Models

Webster et al. 2022

➜ understanding ponds is essential for the description, understanding, and simulation of the Arctic climate- and ecosystem. Pond depth is an important parameter in models.

Pond depth observations



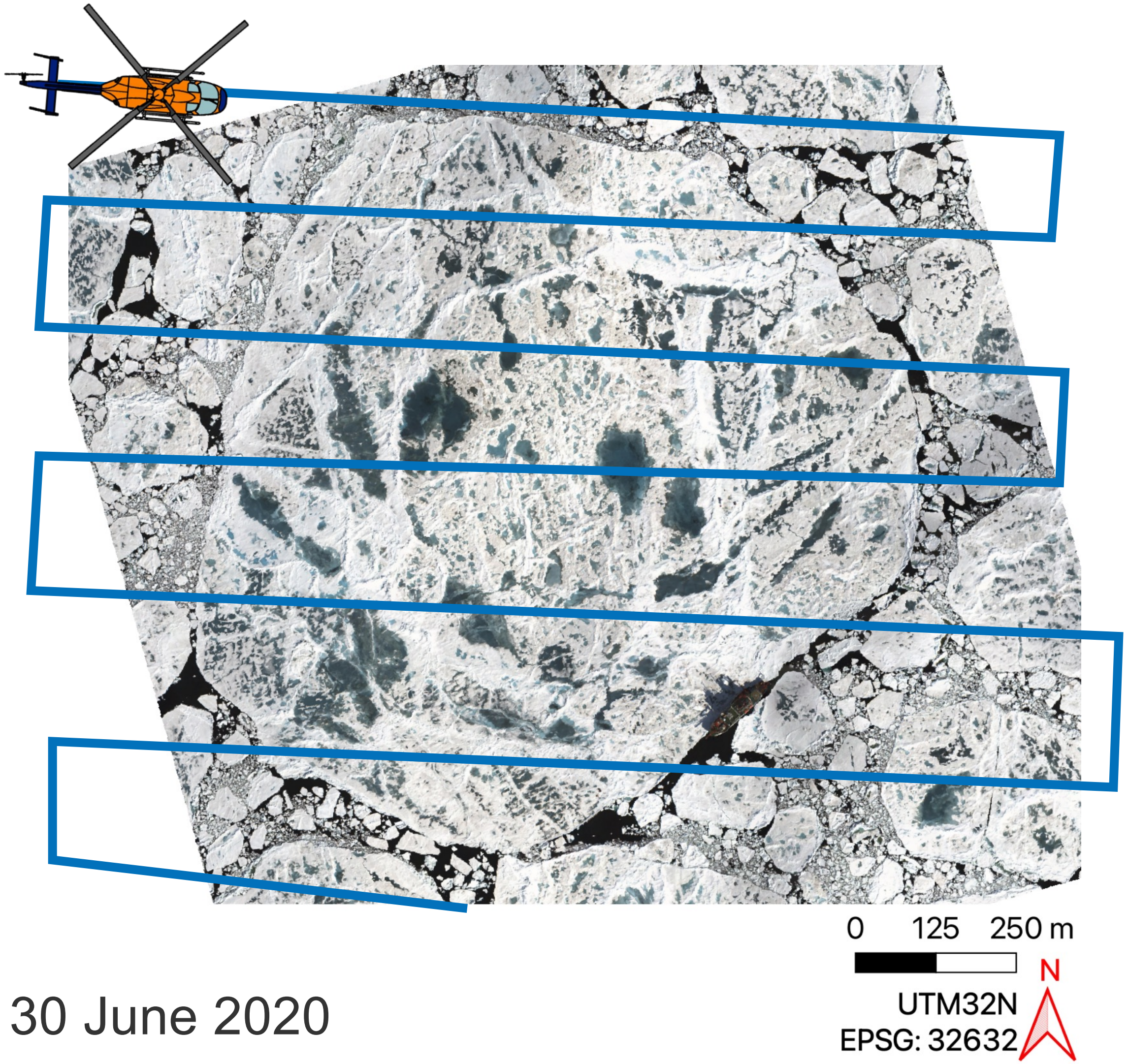
Helicopter-borne aerial imaging of an ice floe

CANON EOS 1D Mark III DSLR, 14mm lens, nadir oriented

Mowing-the-lawn pattern over a drifting ice floe

Stitching of overlapping images to an orthomosaic map

~20cm ground sampling distance (pond sizes typically O(1m-100m))



30 June 2020

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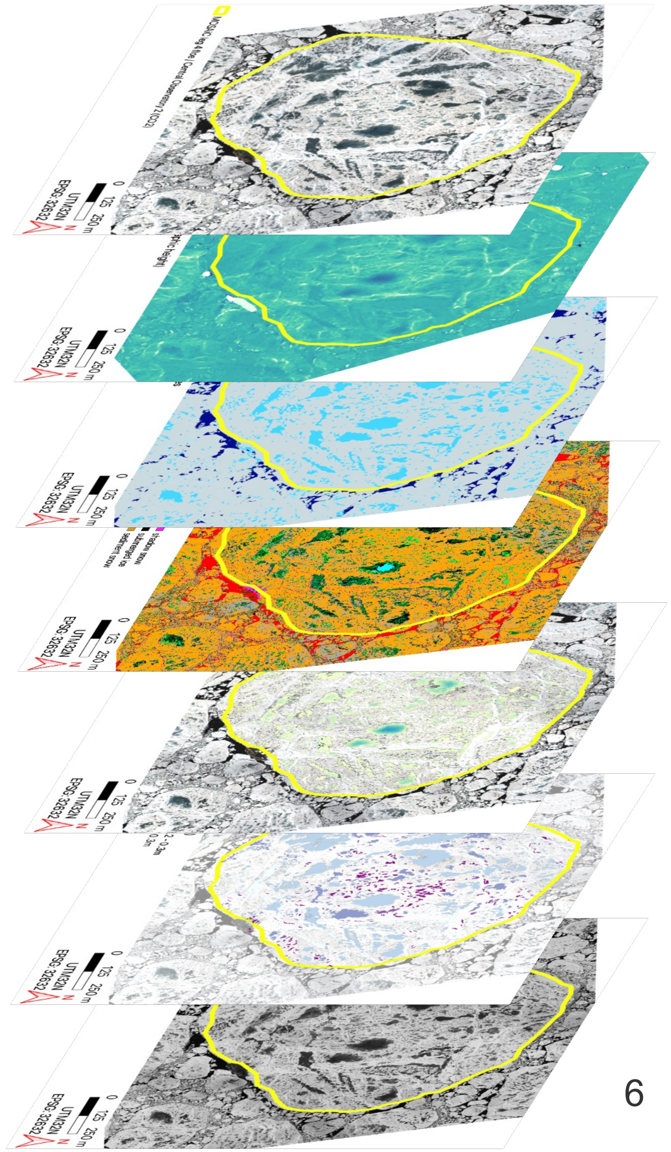
Multidimensional analysis

- High-resolution aerial RGB images, orthomosaics
- Digital elevation model (DEM) from a photogrammetric surface reconstruction
- Different levels of surface type classification (e.g. snow, ice, melt ponds)
- Pond bathymetry and pond level a.s.l
- Albedo estimate

(PhD Thesis Fuchs, 2023)



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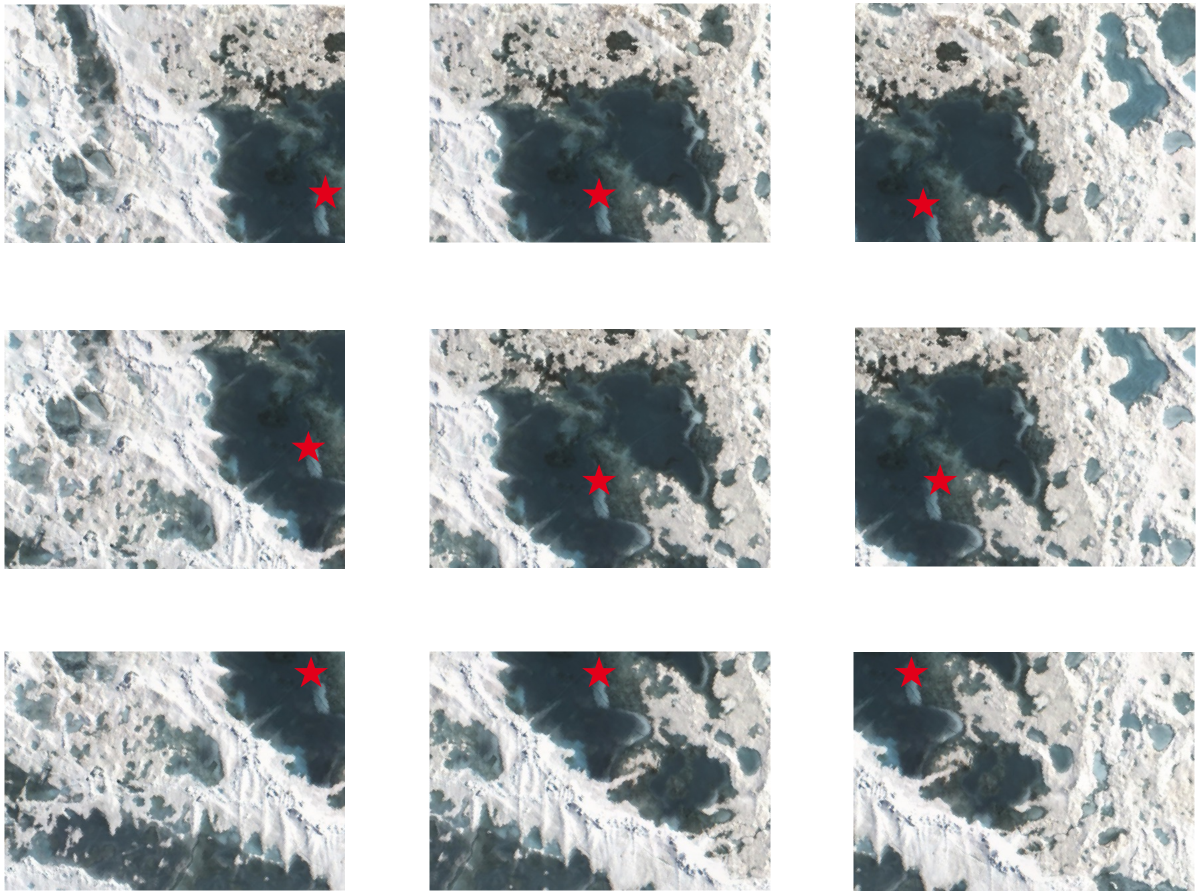
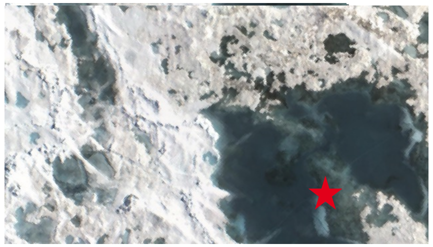
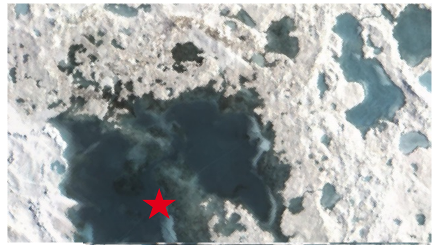
From images to surface topography

Classical aerial photogrammetry using Agisoft



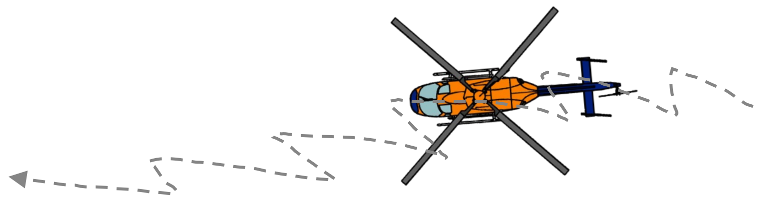
From images to surface topography





Classical aerial photogrammetry using Agisoft

Determination of artificial recording positions in a Lagrangian view to correct for the ice drift (up to 1 m s^{-1})



Without Ground Control Points, but scaling reference

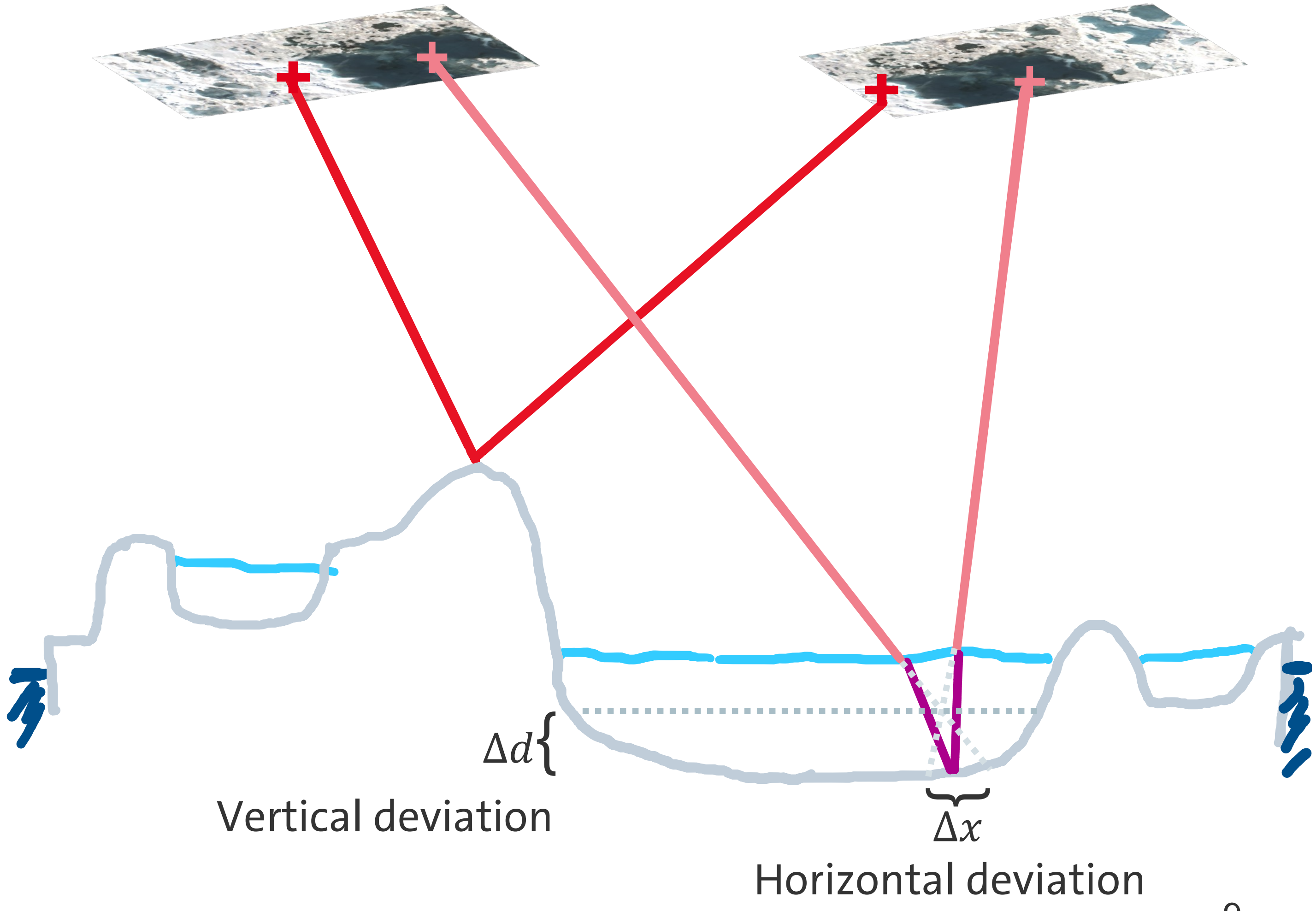
From images to surface topography

Triangulation

Shallow ponds (cm to m), translucent

Retain co-linearity despite refraction at the air—pond interface

Integrated workflow into highly efficient photogrammetry tools



-> Two-media photogrammetry (Mandlburger, 2022)

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Impact and correction of refraction

Horizontal deviation

$$\Delta x = f(h_{flight}, d_{ponds}, \kappa(\alpha_i))$$

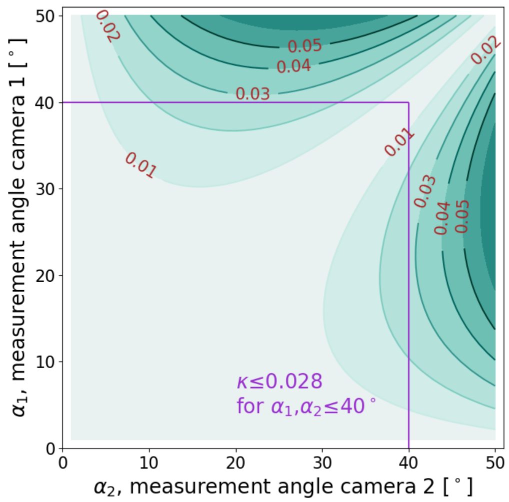
α: measurement angle

! Causes mismatches in the alignment !

Should be avoided with:

$\Delta x <$ GSD

Requirement: $\kappa \leq 0.028$

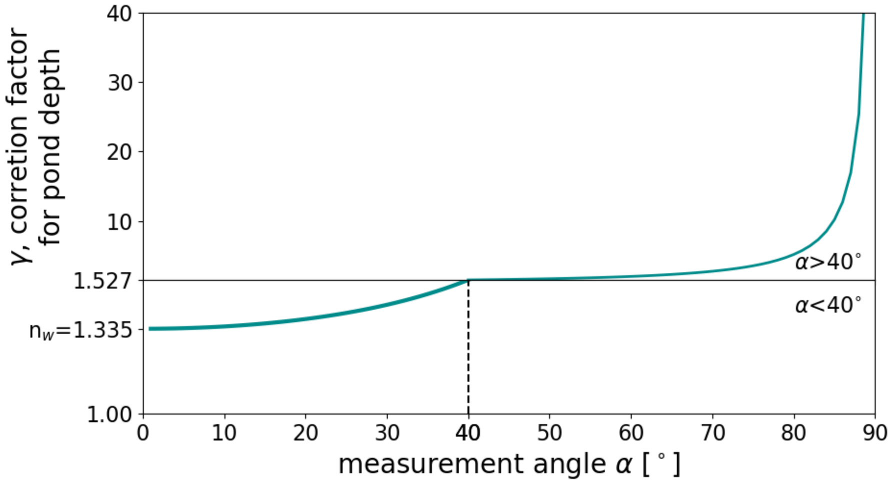


Fuchs et al. 2024

Fulfilled with $\alpha < 40°$

Vertical deviation

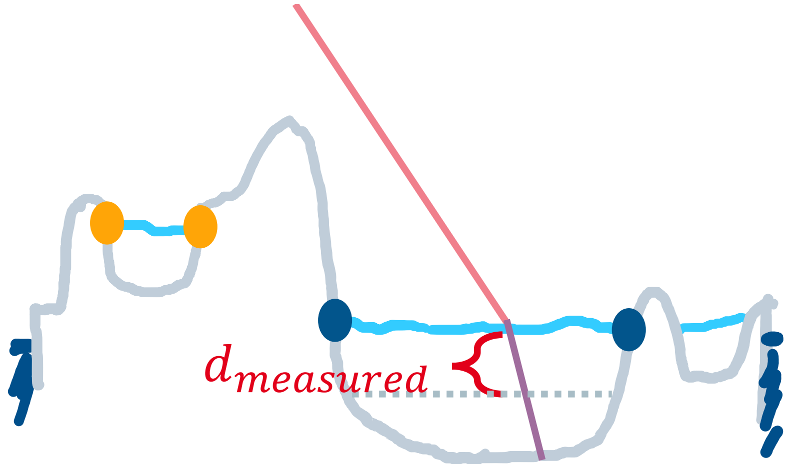
$$d_{pond} = \gamma \cdot d_{measured}$$



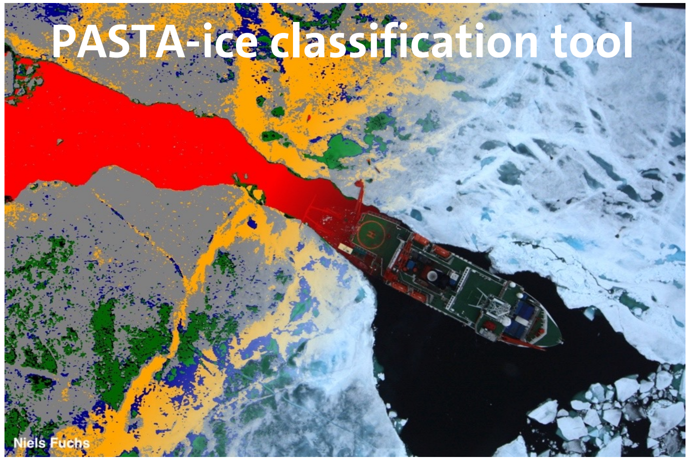
Fuchs et al. 2024

Correction factor: $\gamma = n = 1.335$

Automatic pond surface detection

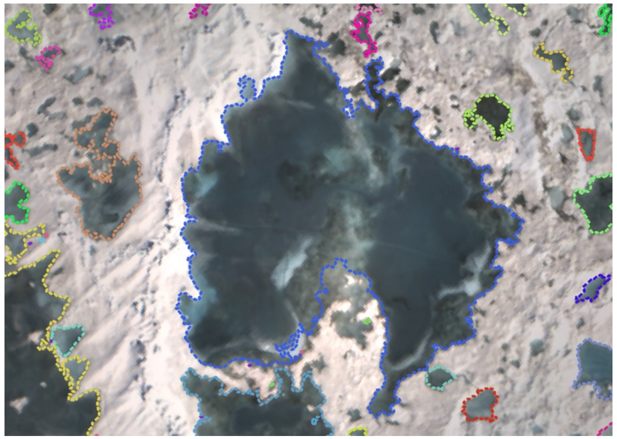


Automatic surface-type classification tool to derive pond margins



Fuchs, 2023

Extract pond margins from DEM



For each pond:

- Apparent depth $d_{measured}$ to converted it to actual depth d_{pond}
- Pond level a.s.l.

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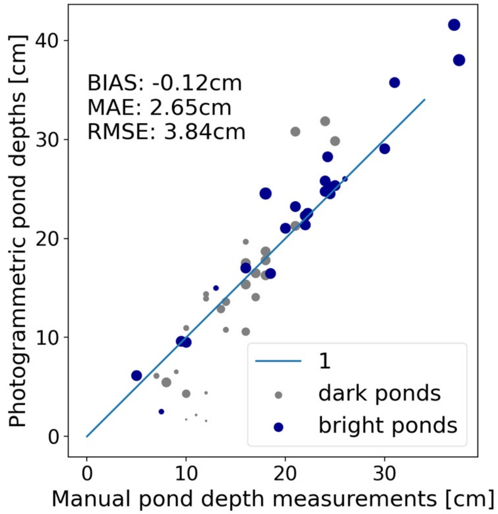
Ponds are confined objects without slopes or waves

Evaluation against:

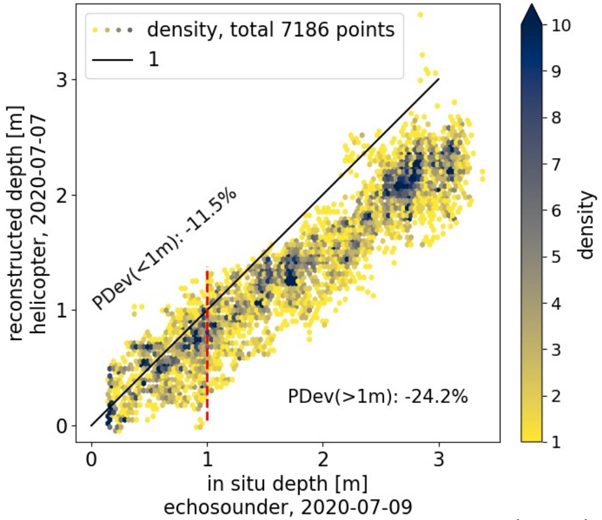
Manual depth measurements

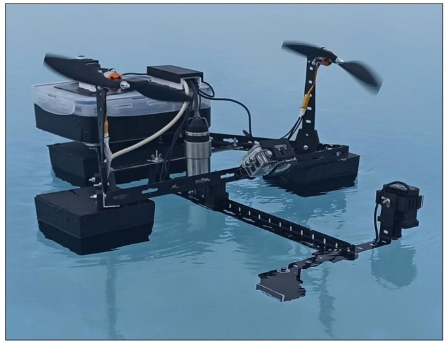


Fuchs et al. 2024

! cavities at the pond bottom

Echosounder depth measurements





Böötle, CAU Kiel

Fuchs et al. 2024

! time lag of 2days during intense melting

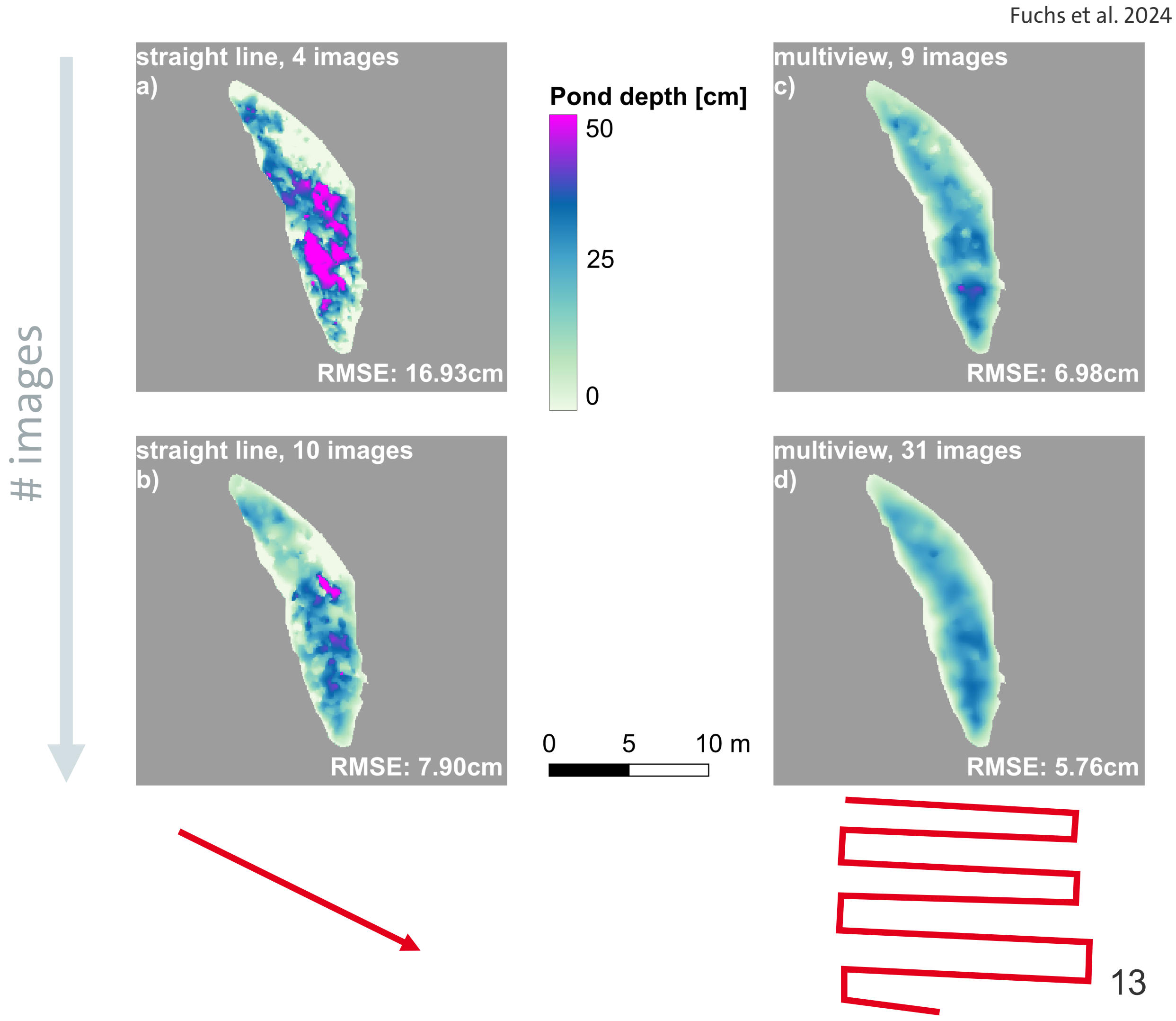
Flight pattern

Improved reconstruction through:

+ More overlap

++ Lateral overlap

between single images



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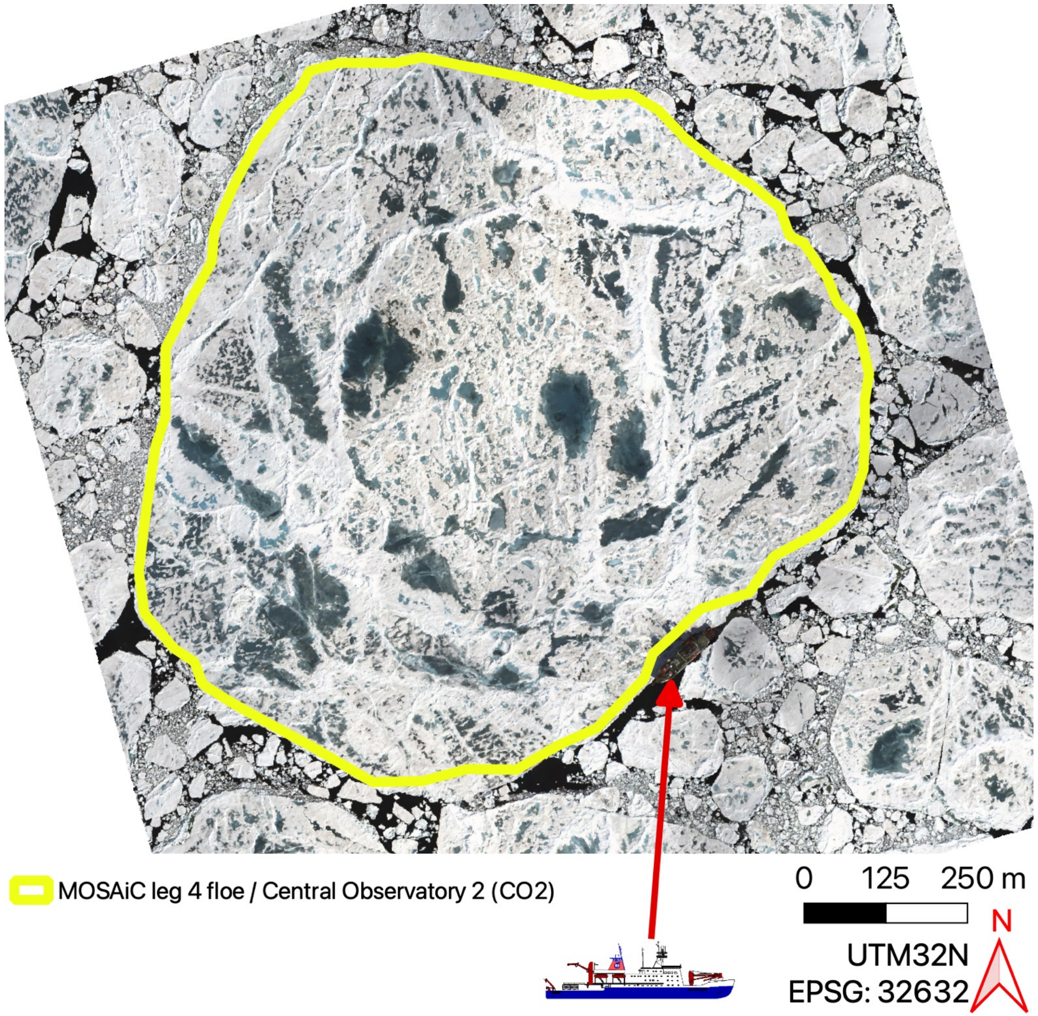
MOSAiC campaign

One-year drift campaign of RV Polarstern through the central Arctic 2019-2020

Interdisciplinary study of the full seasonal cycle



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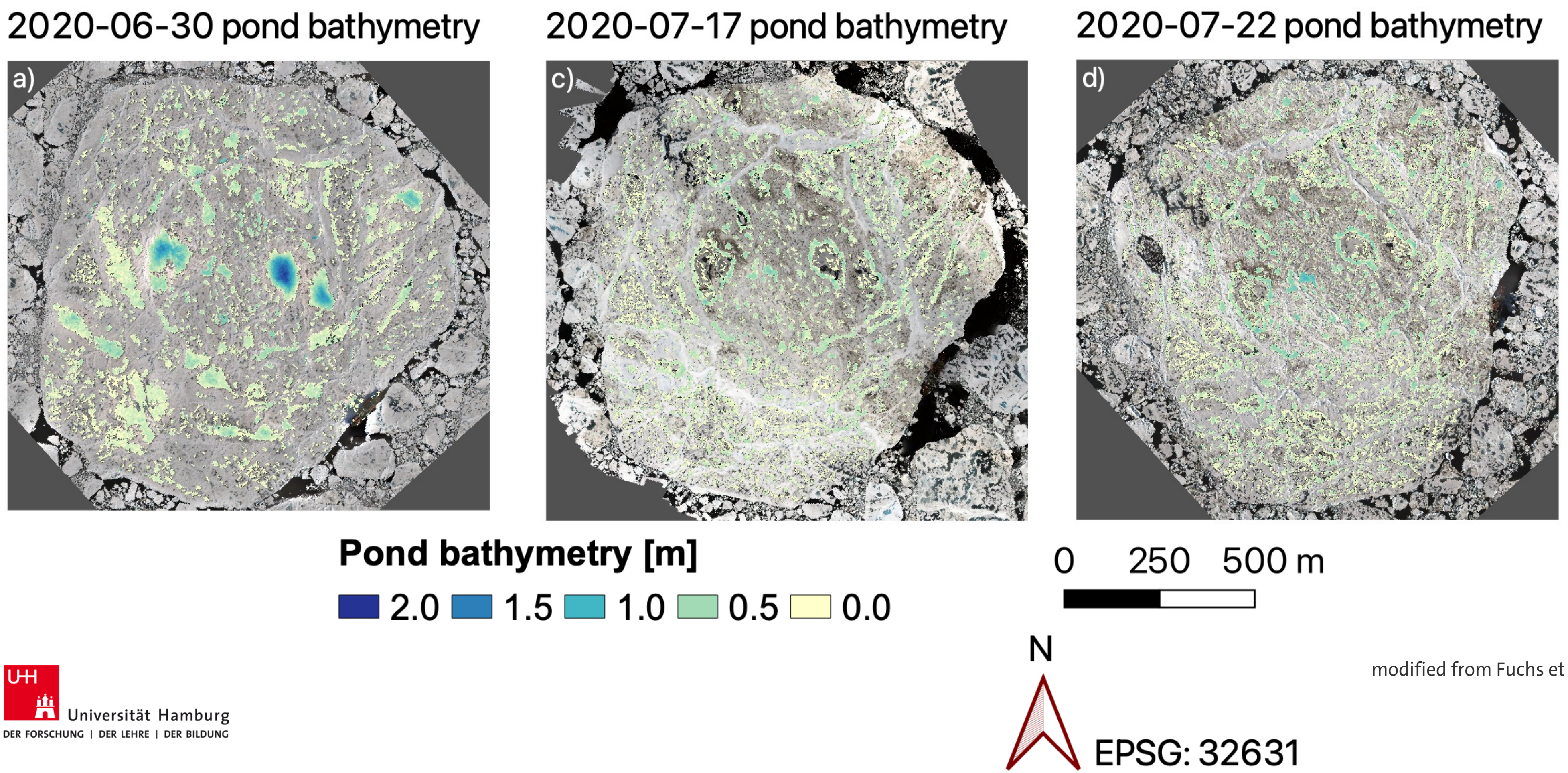
Focus of summer study period was an ice floe of ~1 km^2 NW of Svalbard

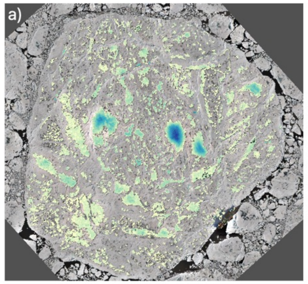
The pond coverage on MOSAiC



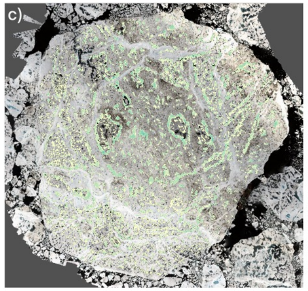
modified from Fuchs et al. 2024

The pond coverage on MOSAiC

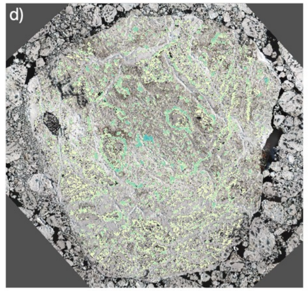
2020-06-30 pond bathymetry



2020-07-17 pond bathymetry



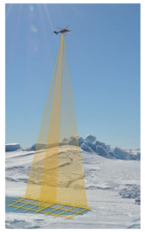
2020-07-22 pond bathymetry



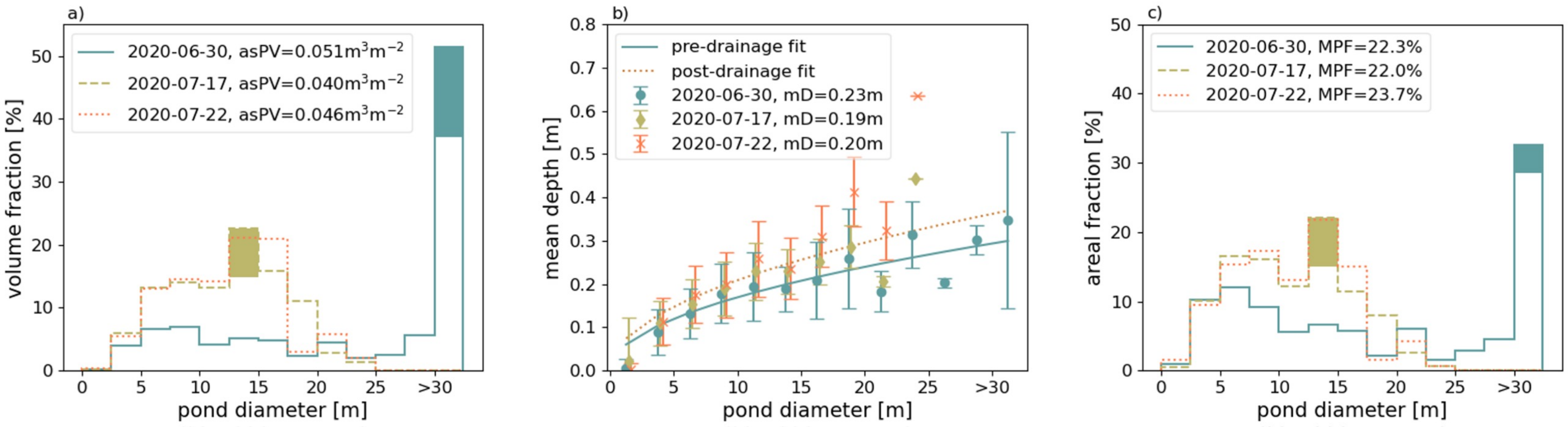
Evolution stage:	End of stage I (pre-drainage)	Start of stage III (post-drainage)	Stage III
Pond depth:	extraordinarily deep ponds (>2m)	very deep ponds disappear, ring-like structure, otherwise constant	further deepening through melting

.....but there is more:

I: Statistics



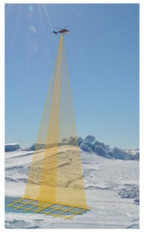
→ Satellites



modified from Fuchs et al. 2024

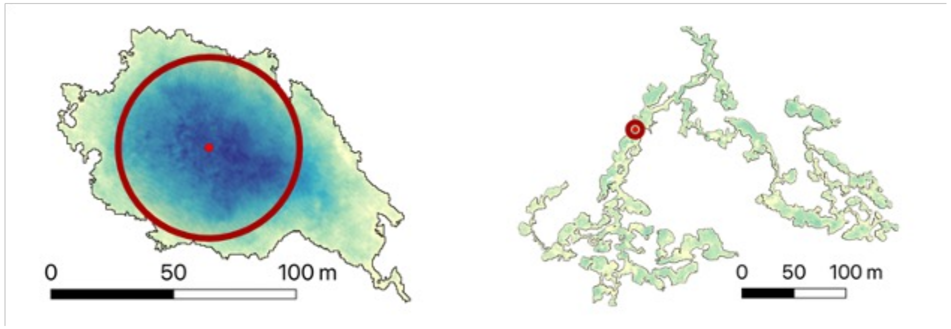
- More than 1600 ponds sampled
- Before drainage: most pond volume in few single large and deep ponds
- After drainage: median of pond volume and areal fraction at approx. 12.5m diameter
- Smaller ponds generally deepen over time

II Upscaling in situ measurements



In situ transects

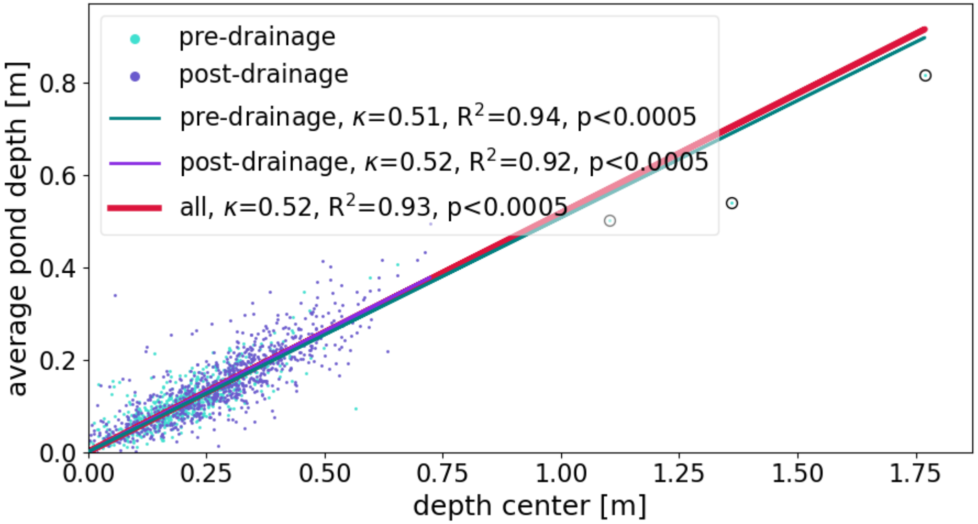
- What can we learn from our >1600 ponds for the design of future in situ measurements of pond depth?



PIA: Pole of Inaccessibility

$$\overline{d_{pond}} = \kappa \cdot d_{PIA}$$

$$\kappa = 0.52, sample > 64\ ponds$$



Fuchs et al. 2024

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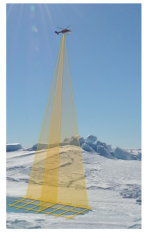
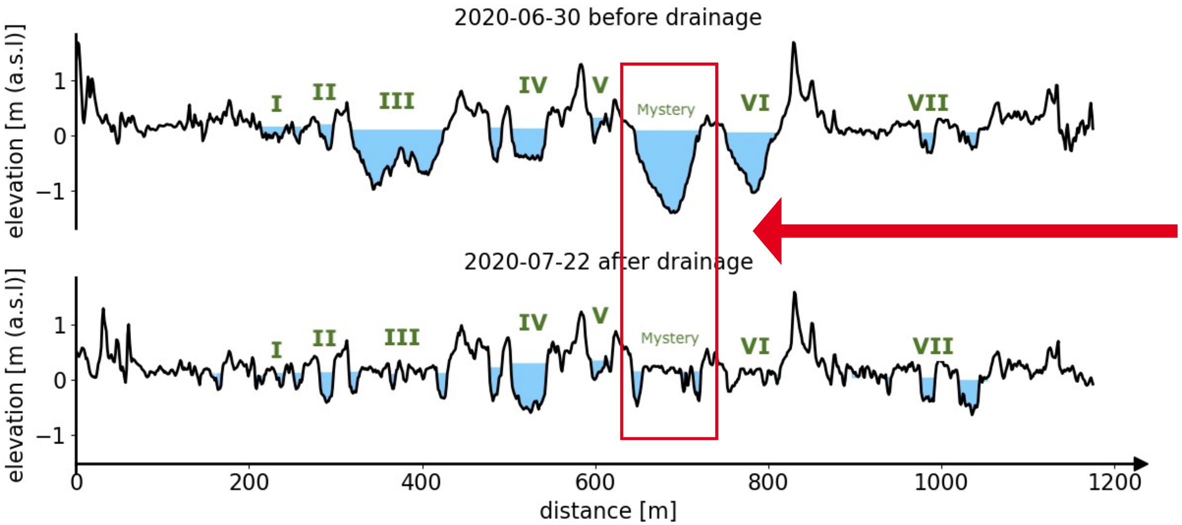
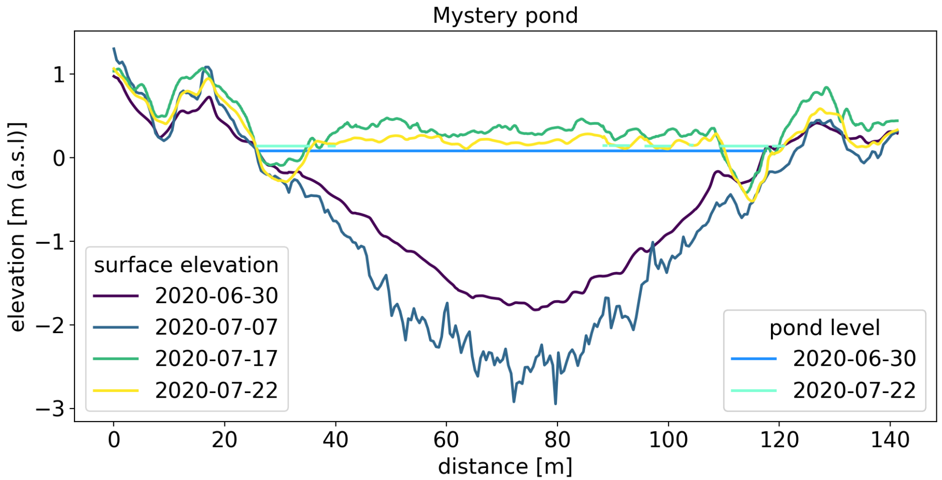
III Pond bottom tracking



Model development





Ductile deformation of the pond bottom
≠ rigid ice cover

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Summary

- Multimedia photogrammetry is a strong tool for melt pond observations
- Workflow is fully integrable into photogrammetry applications
- Automatic detection of pond level facilitates the algorithm
- Depth determination error <4cm or ~12%

Based on:

Fuchs et al., "Sea ice melt pond bathymetry reconstructed from aerial photographs using photogrammetry: a new method applied to MOSAiC data"
–*The Cryosphere* 2024

Fuchs, "A multidimensional analysis of sea ice melt pond properties from aerial images"
– *PhD Thesis Uni Bremen* 2023