Tracking the volume changes of shallow lakes in West Africa: comparison of existing methods to derive the height-area relationship

F. Girard[1,5], L. Kergoat[1], H. Nikiema[2], M. Wubda[2], J.-M. Dipama[2], A. Touré[3], I. Mainassara[3], R. Yonoba[4], T. Fowé[4], M. de Fleury[1], N. Taburet[5], M. Grippa[1]

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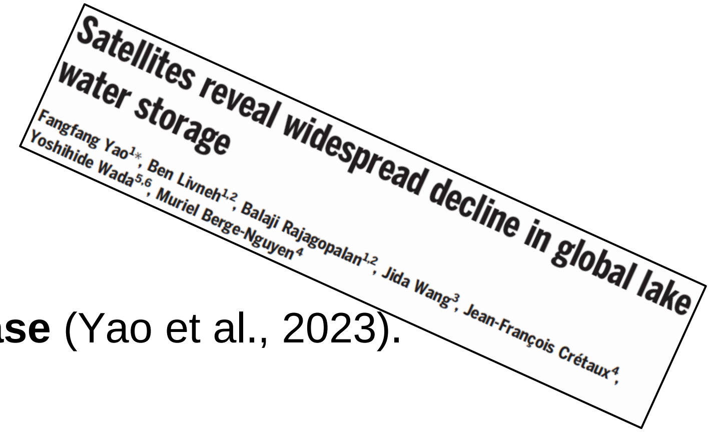
Lake volume change: a key variable

- **3%** of the global land area (Messager et al., 2016)
- **87%** of Earth's liquid surface fresh water (USGS)



Satellites reveal widespread decline in global lake water storage

Fangfang Yao[1*], Ben Livneh[1,2], Balaji Rajagopalan[1,2], Jida Wang[3], Jean-François Crétaux[4], Yoshihide Wada[5,6], Muriel Berge-Nguyen[4]

Over the past 3 decades, **53% of the largest global lakes** have shown a significant **decrease** (Yao et al., 2023).

Lakes ecosystem services: modulated by water storage!

fresh water and food supply

natural habitats

recreational services

cycling of pollutants and nutrients

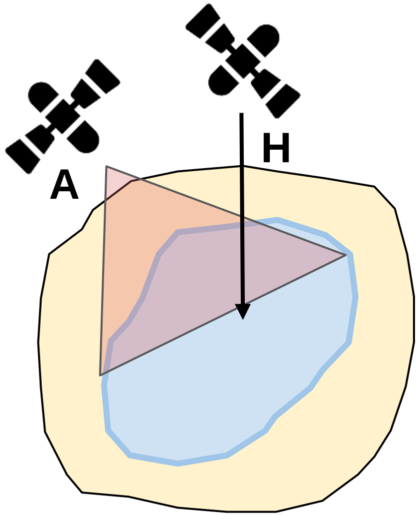
Volume change monitoring applications:

- impact of **climate change** and **human activities** on **water resources**
- **ecosystems sustainability**
- **reservoirs** and **human water** consumption management
- inputs to **hydrological models**

Benefits of remote sensing

In situ measurements: spatially sparse, irregular temporal coverage.
West Africa: few instrumented lakes

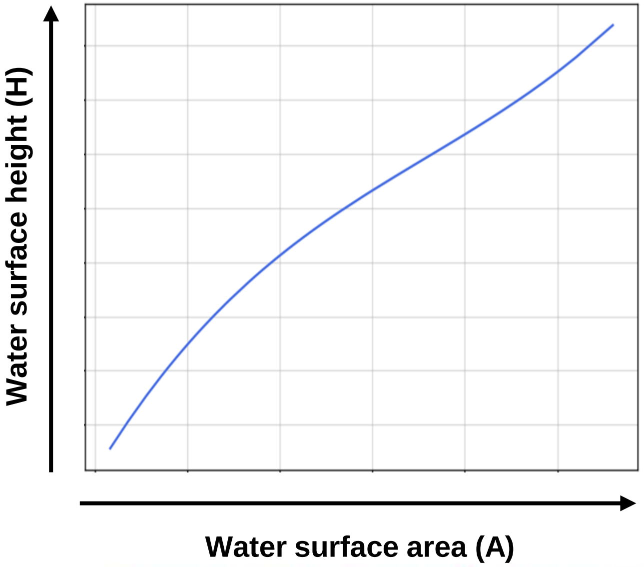
Repeated and **widely spread** observations of **water surface height** (H) and **area** (A).
Sentinel-3&6, CryoSat-2, ICESat-1&2: **resolution < 300m**
Sentinel-1&2, Landsat constellation: **resolution < 30m**
SWOT covers +**90% of inland areas** (Biancamaria et al., 2016)



Combination of H and A allows estimating **volume changes** of more and more **small and medium-sized lakes (< 100km²)**
Volume changes can be measured using the **height-area relationship** with $\Delta V = \int_{H_1}^{H_2} A(H)dH$

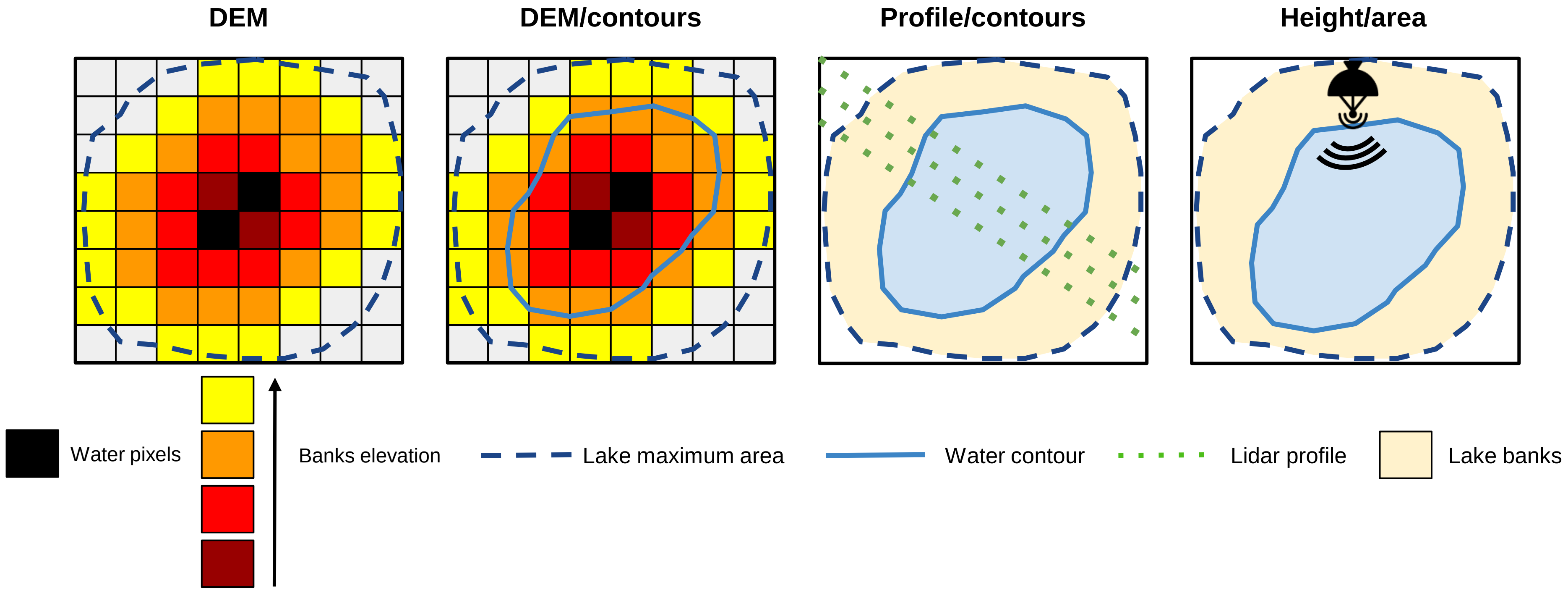
Height-area relationship benefits:

- Getting rid of some lake **morphology assumptions**
- Using **only one variable**, either H or A, to compute volume changes
- **Densifying** H or A time series



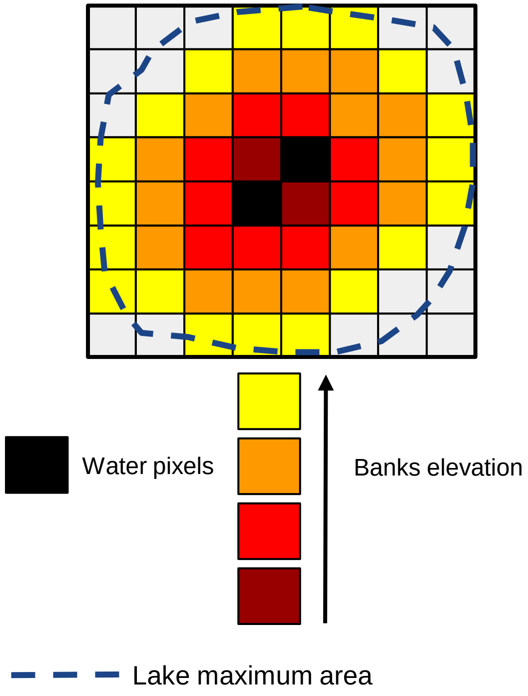
Studied methods

- **Few studies compare the methods** to derive the height-area relationship from **recent remote sensing data.**
- Here we propose a **comparison of four methods**:

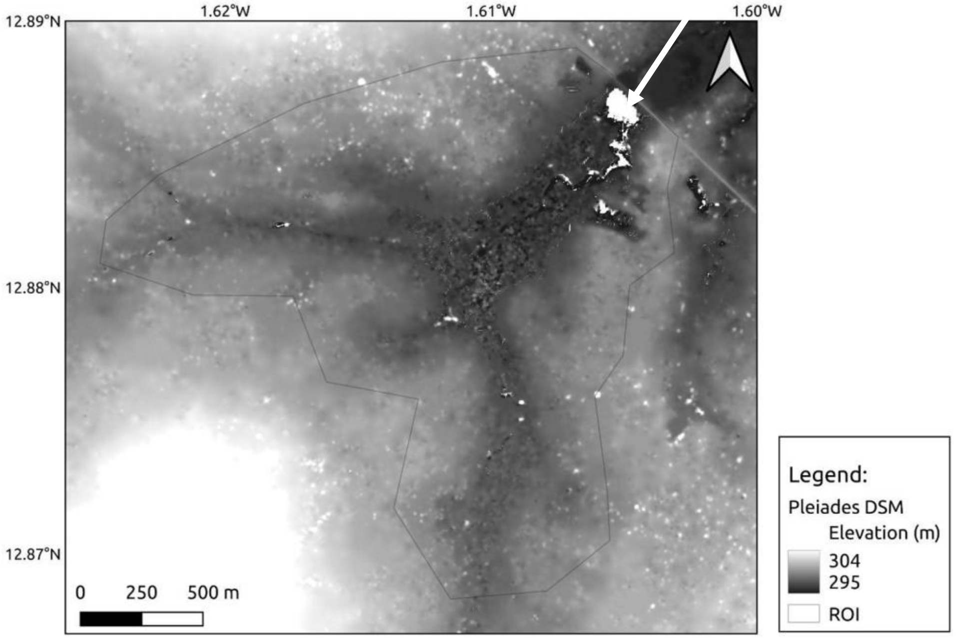


Studied methods: DEM

DEM



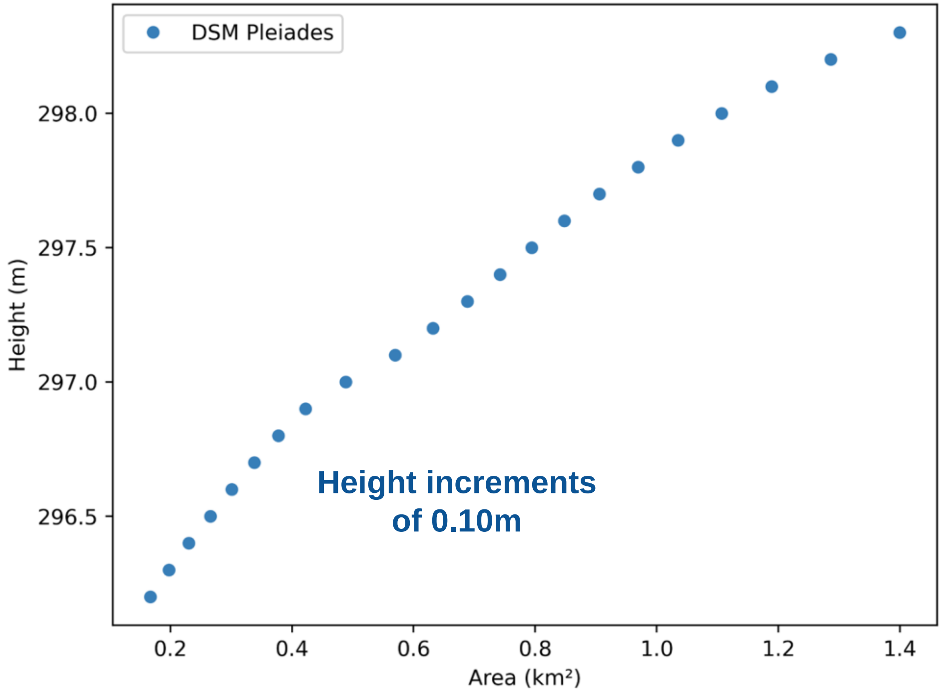
Residual water surface is masked



Pleiades DSM (MicMac software)
Horizontal resolution: 1m x 1m

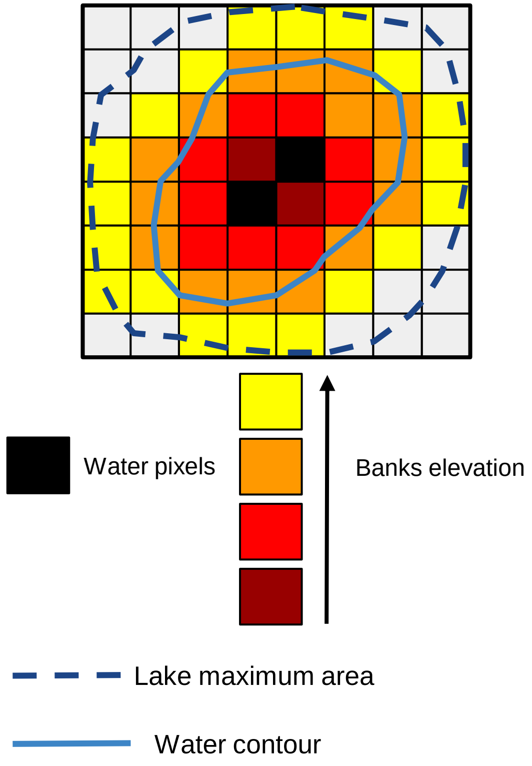
Images ordered when lakes are **as dry as possible**

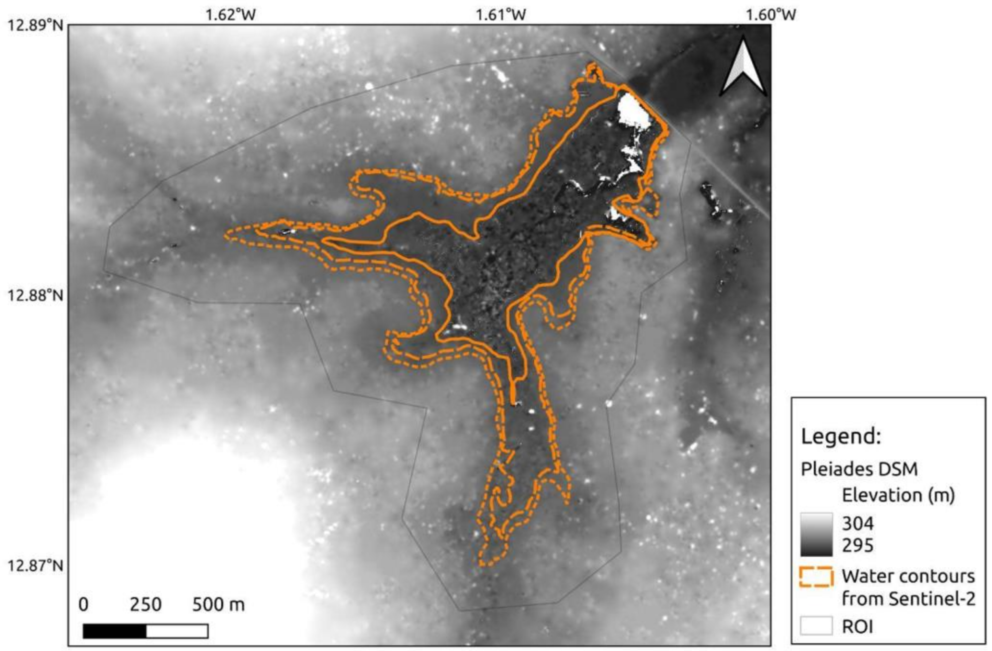
Height-area relationship



Studied methods: DEM/contours

DEM/contours

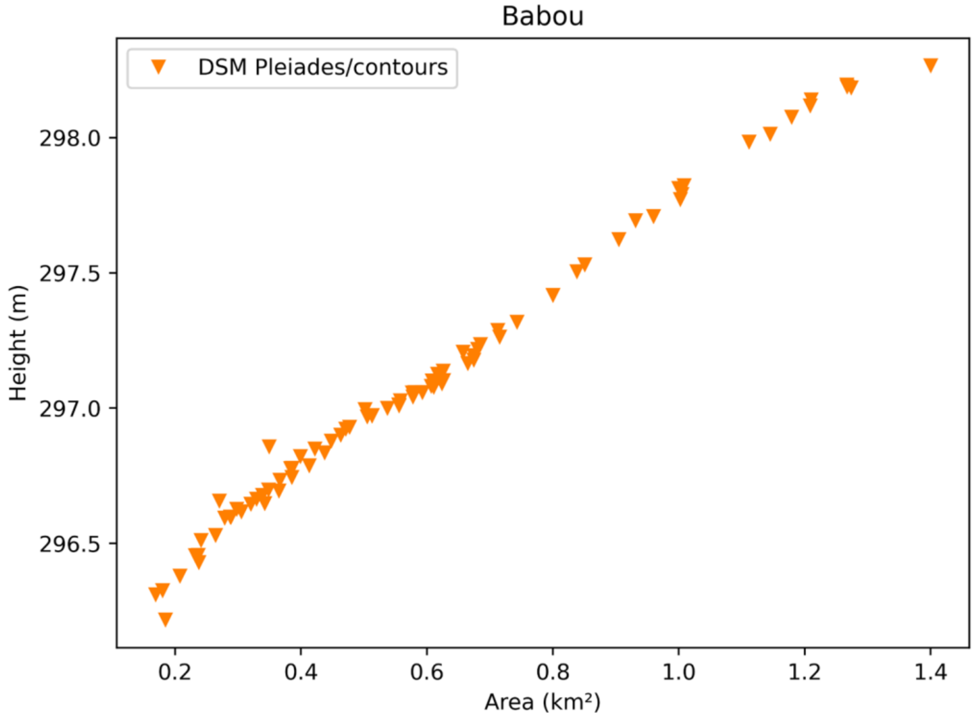




Pleiades DSM (MicMac software)
Horizontal resolution: 1m x 1m

Sentinel-2 images (MNDWI)
Horizontal resolution: 20m x 20m

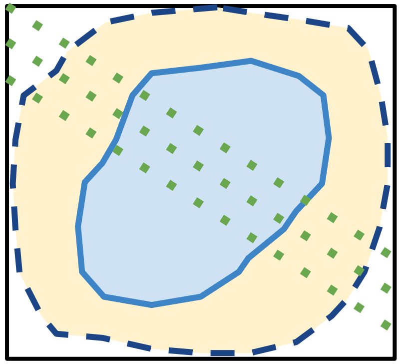
Height-area relationship

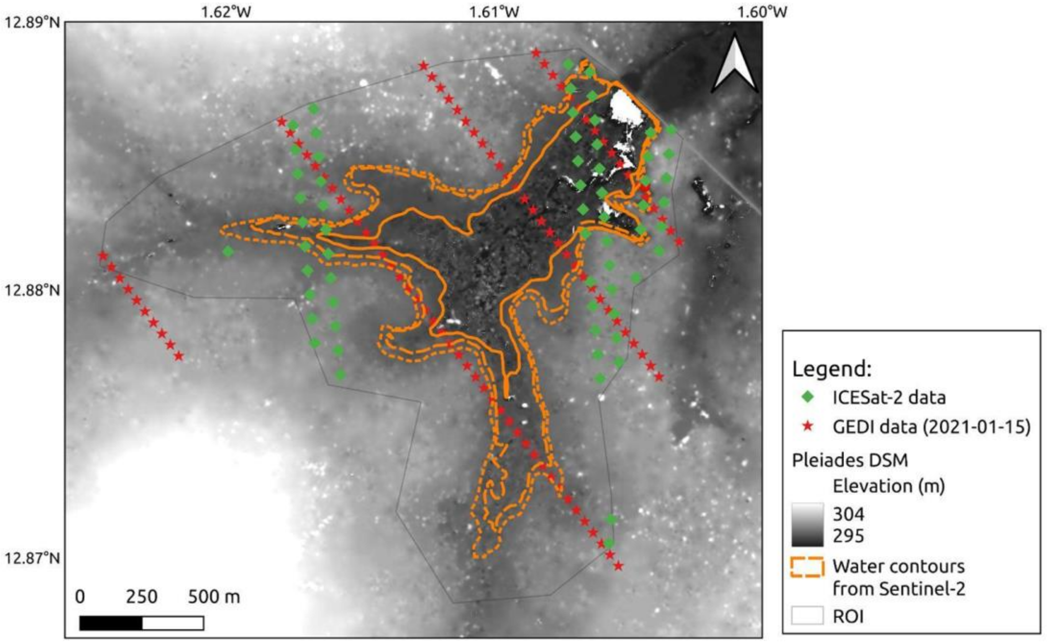


Outliers removal: MAD criterium
(Kannan et al., 2015)

Studied methods: Profile/contours

Profile/contours



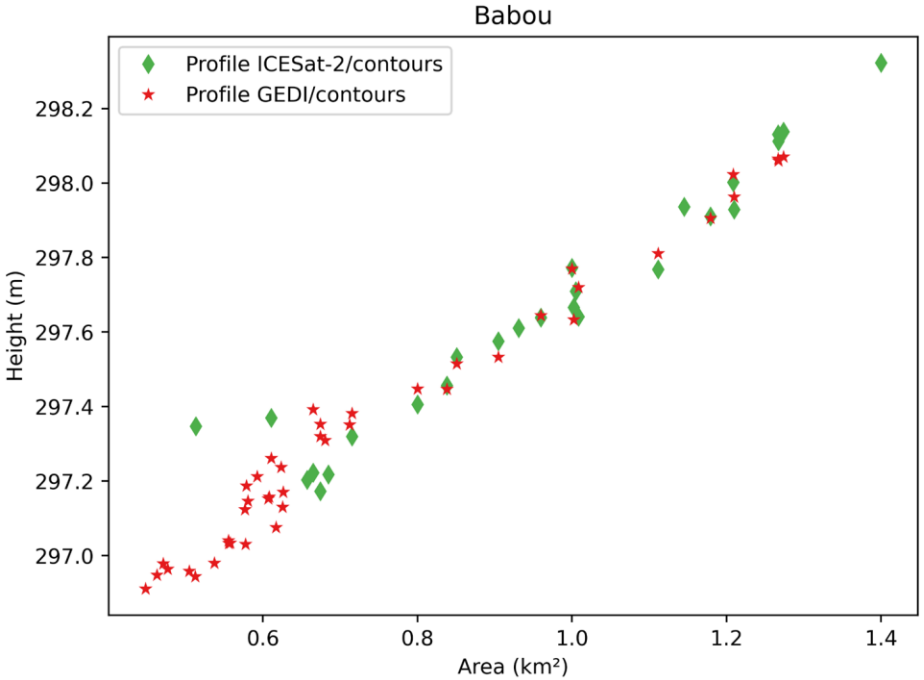


ICESat-2 lidar altimetry (ATL08)
Along-track resolution: 100m, 3x2 beams

GEDI lidar altimetry (L2A)
Along-track resolution: 60m, 8 beams

Sentinel-2 images (MNDWI)
Horizontal resolution: 20m x 20m

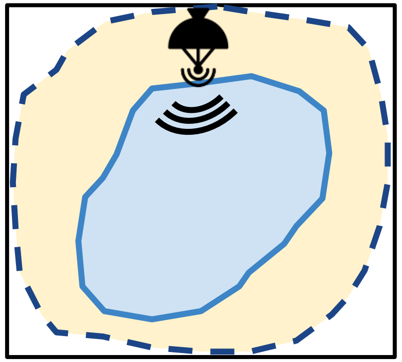
Height-area relationship



2 different height-area relationships

Studied methods: Height/area

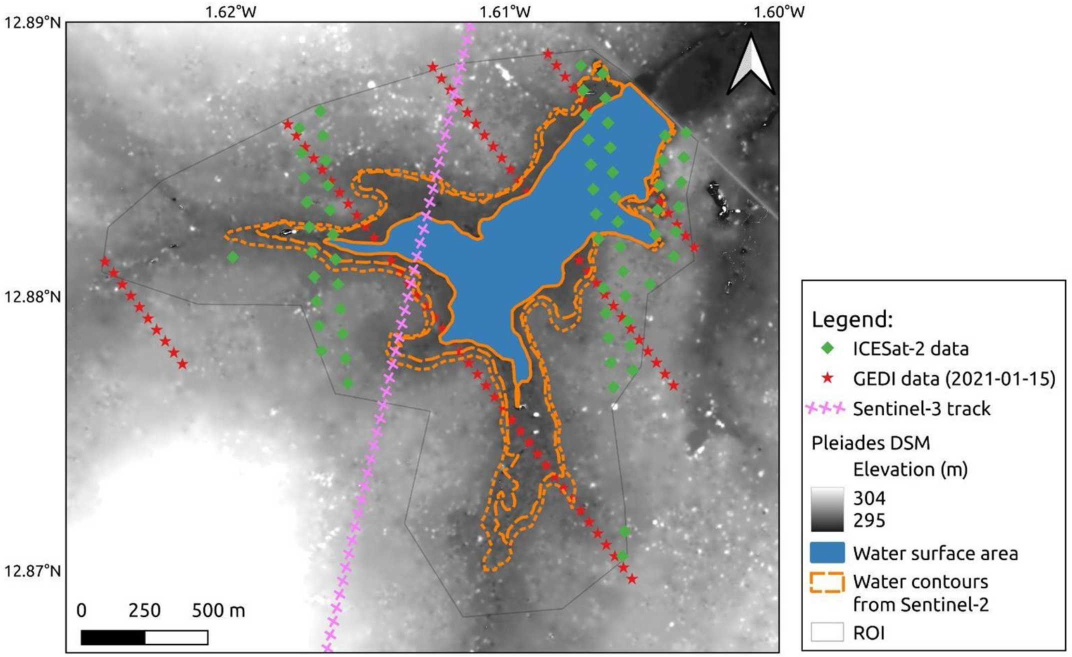
Height/area



Lake banks

Lake maximum area

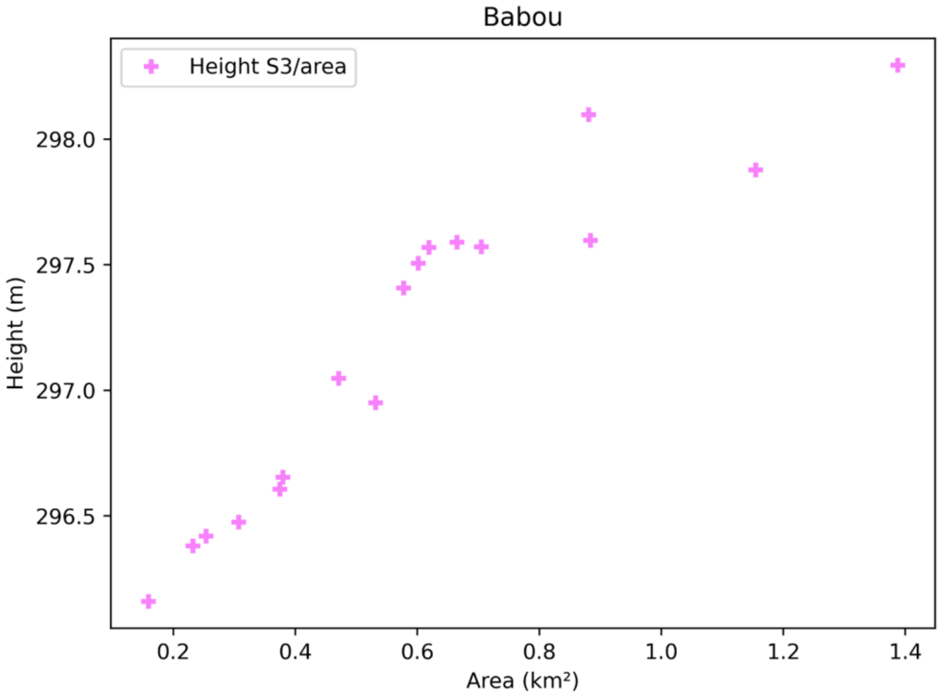
Water contour



Sentinel-3 radar altimetry (OCOG)
Along-track resolution: 300m

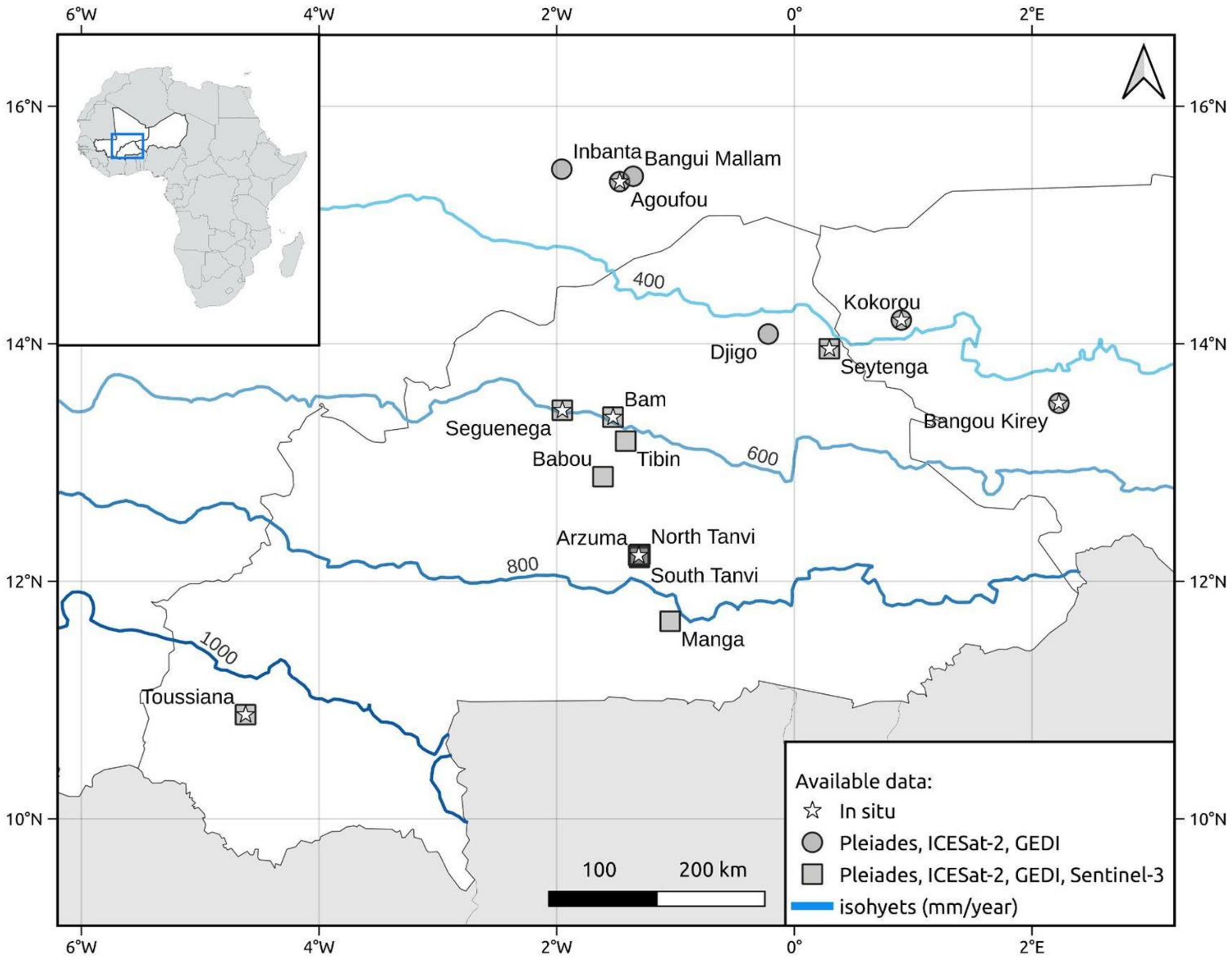
Sentinel-2 images (MNDWI)
Horizontal resolution: 20m x 20m

Height-area relationship



- Thresholds on **sigma0** and **waveform peakiness**
- **Matching** within **+/- 3 days** (de Fleury et al., 2022)

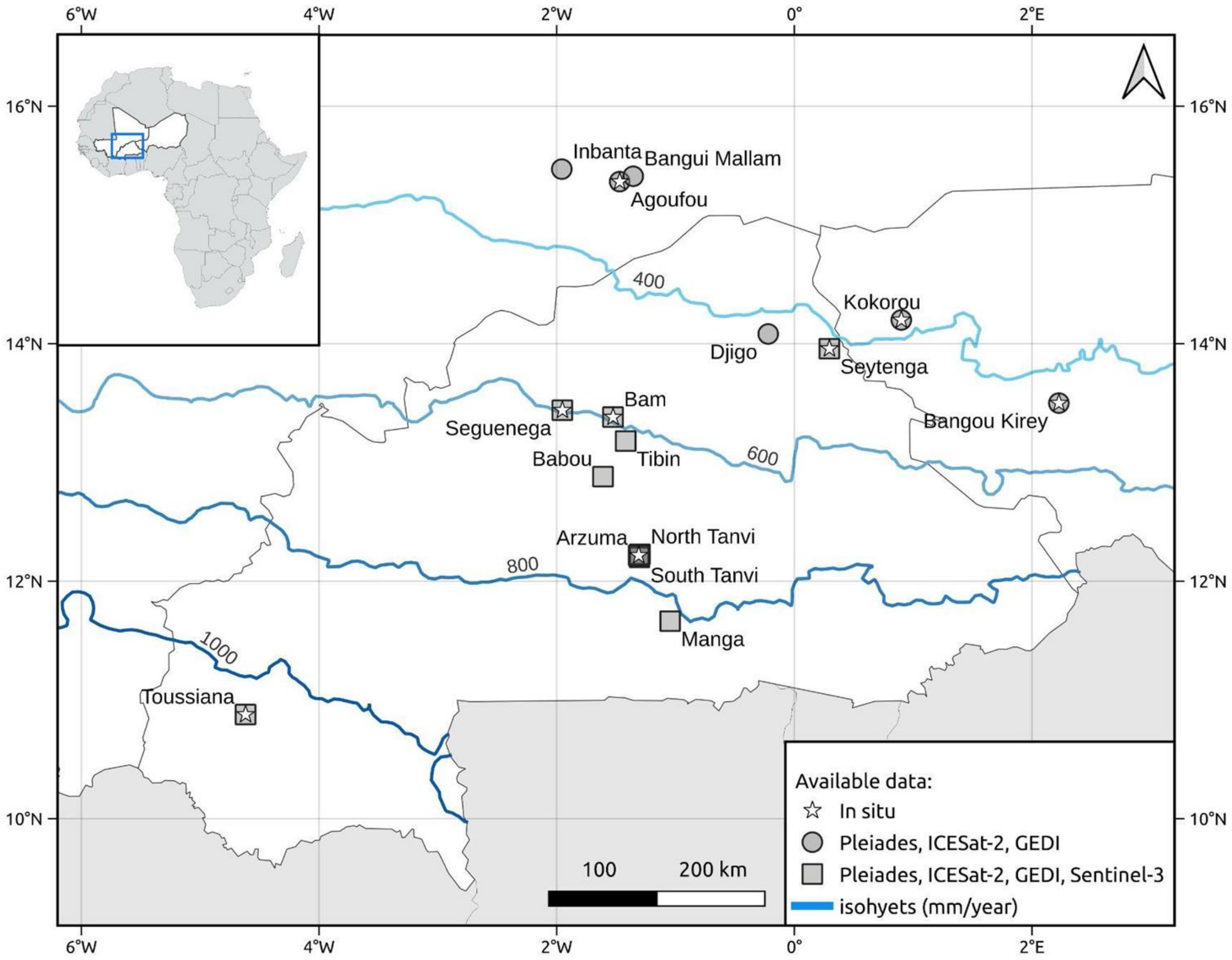
Study area



Study area:

- **Location:** Central Sahel (Mali, Niger, Burkina Faso), 10.8°N - 15.5°N
- **Rainfall:** 200mm/y (North) to 1000mm/y (South)
- **Wet season:** Jun-Oct (tropical monsoon)
- **Dry season:** Oct-May (very low cloudiness).

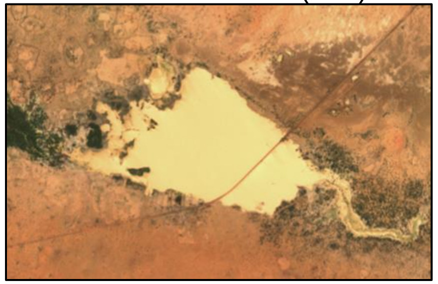
Study area



Studied lakes:

- **16 studied lakes** (10 reservoirs, 6 natural lakes)
- **Varied areas:** 0.22km² - 21km². **Depth:** mostly < 5m deep
- **Varied optical water types:** open water, moderate to high turbidity, temporary or permanent aquatic vegetation

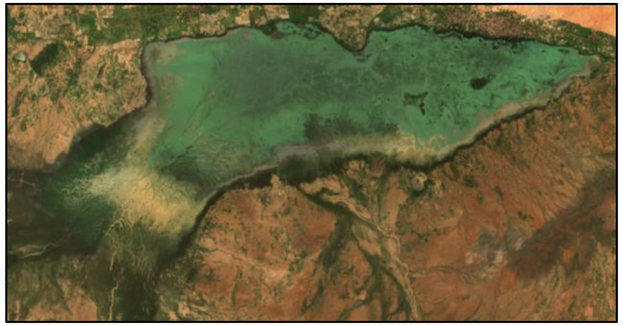
Agoufou,
mean area 2.0 km² (Mali)



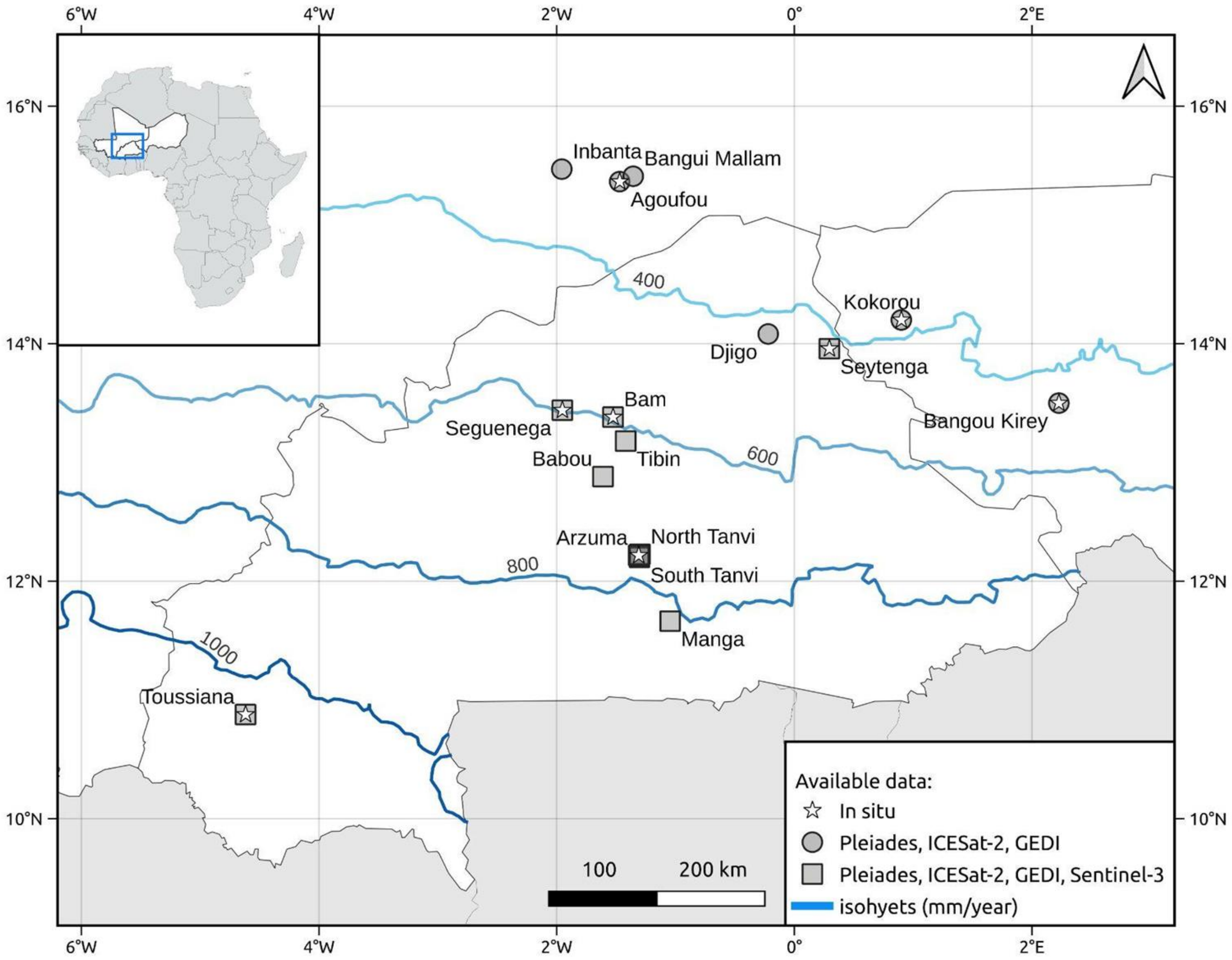
Seguenega, mean area 1.4 km² (BF)

Tanvi Sud,
mean area 0.2 km² (BF)

Kokorou, mean area 21 km² (Niger)



Study area



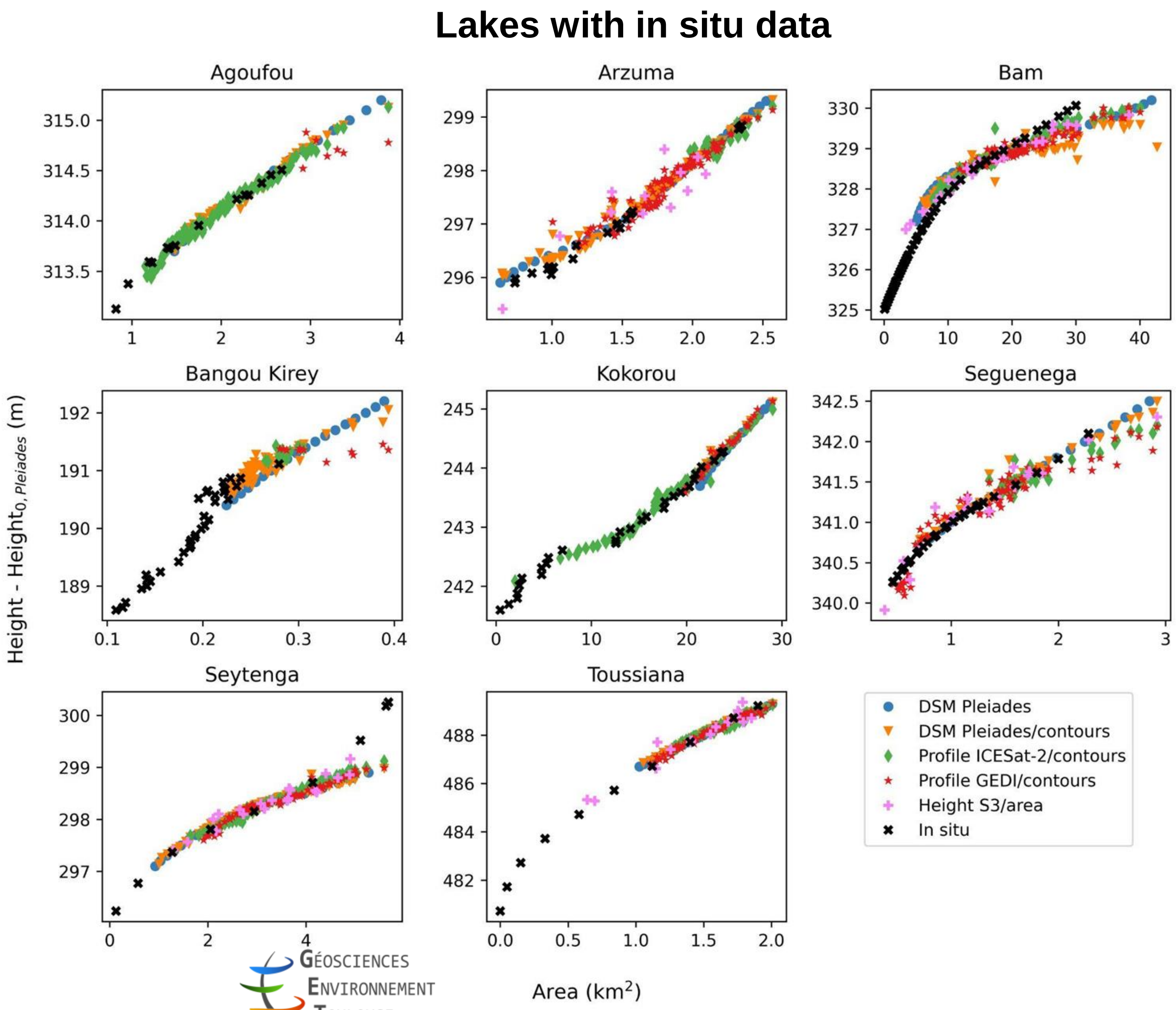
Remote sensing data:

- Pleiades DSMs, ICESat-2 and GEDI data **over the 16 lakes**
- Sentinel-3 radar data **over 10 lakes**

In situ data:

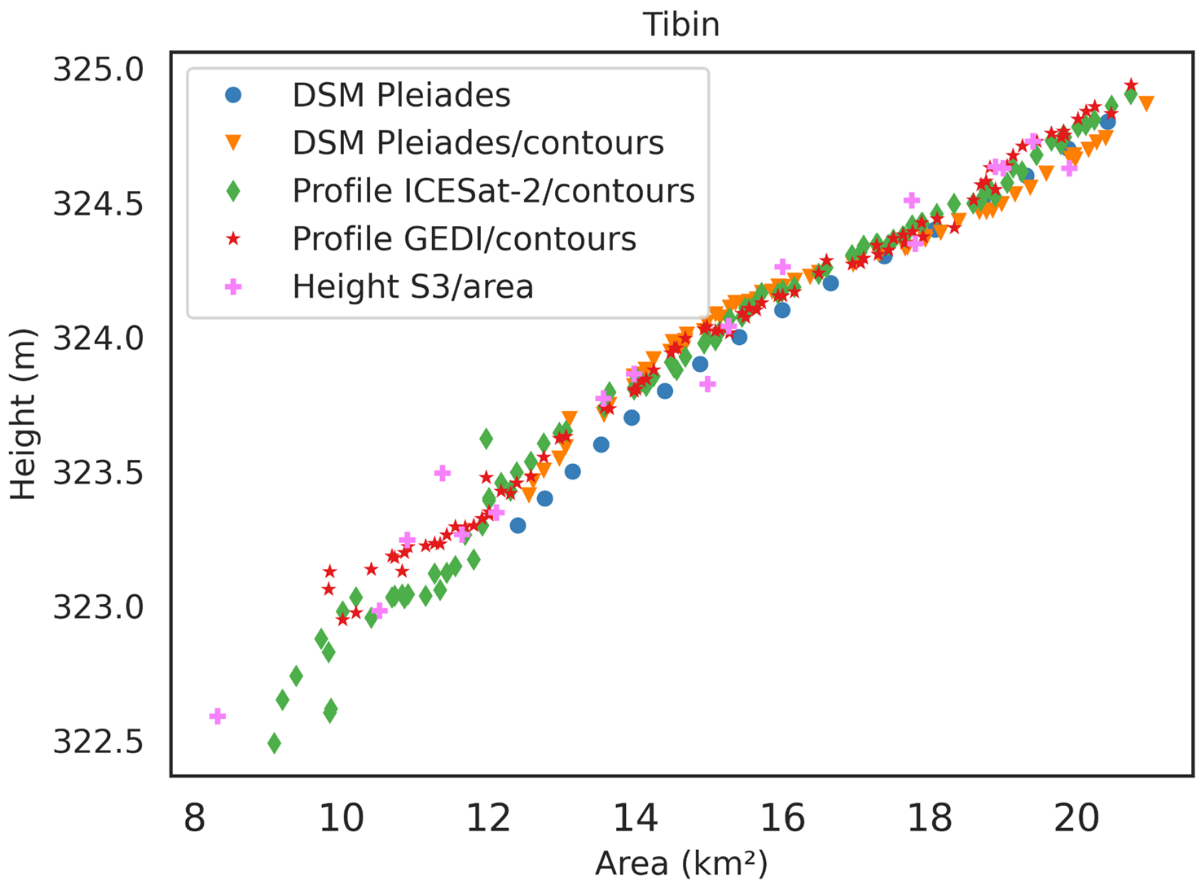
- In situ data over **8 lakes**
- Different types and from **different sources**
- **Real-time** WSH time series from **pressure transducers** data (2 lakes)
- **Historical** WSH time series from **gauge measurements** (1 lake)
- **Hypsometric curves** from water management agency or existing studies (5 lakes)

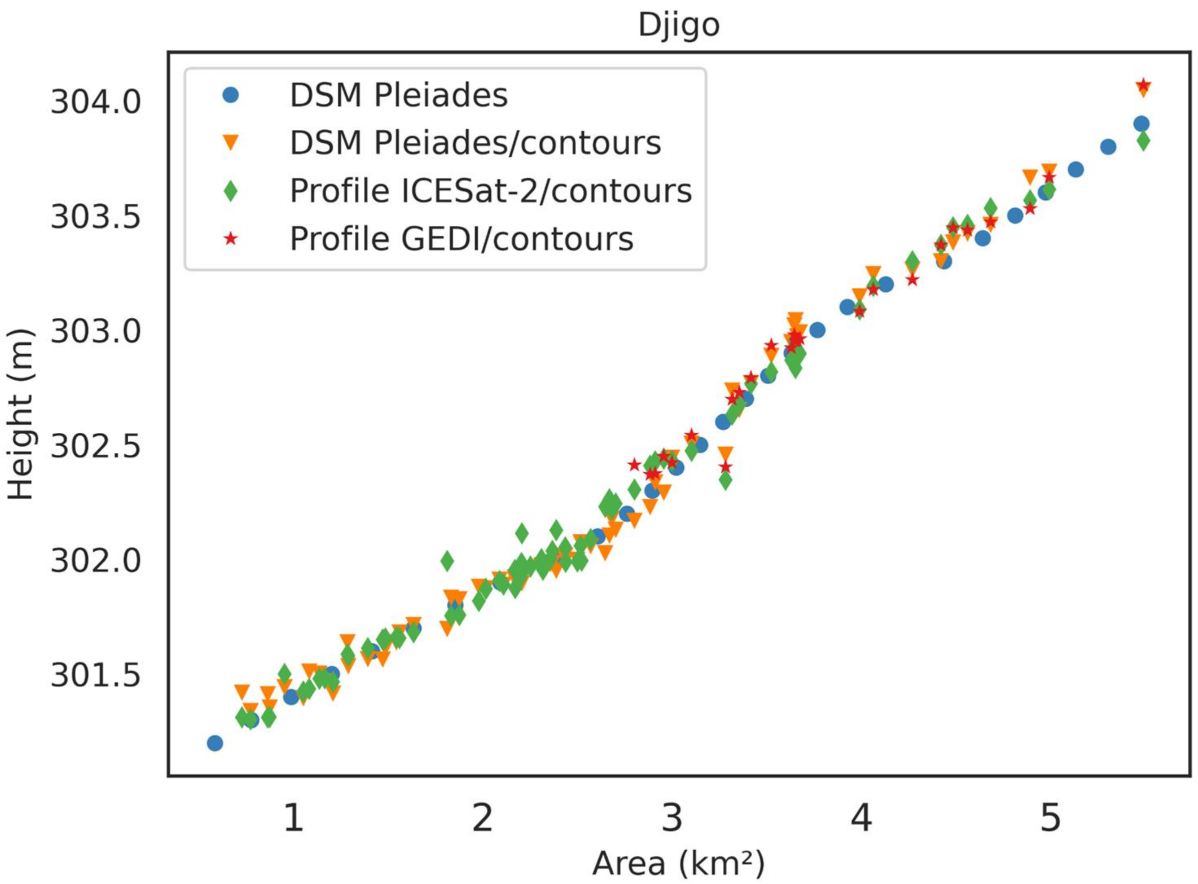
Results: H-A relationships



- Generally **good agreement between each method**
- Small height amplitudes ranging from 1.5m to 5m, with **most amplitudes below 3m**
- Generally **good agreement** of all methods **with in situ data**, except for two reservoirs where all EO methods still remain consistent.
- Most **RMSE values < 0.30m**

Consistent shape patterns

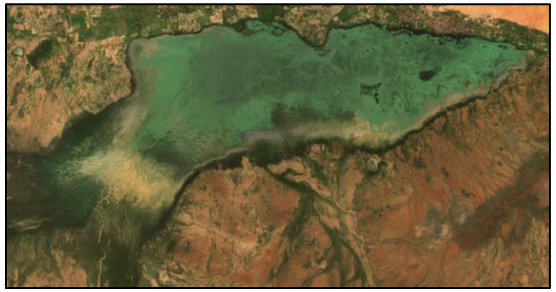


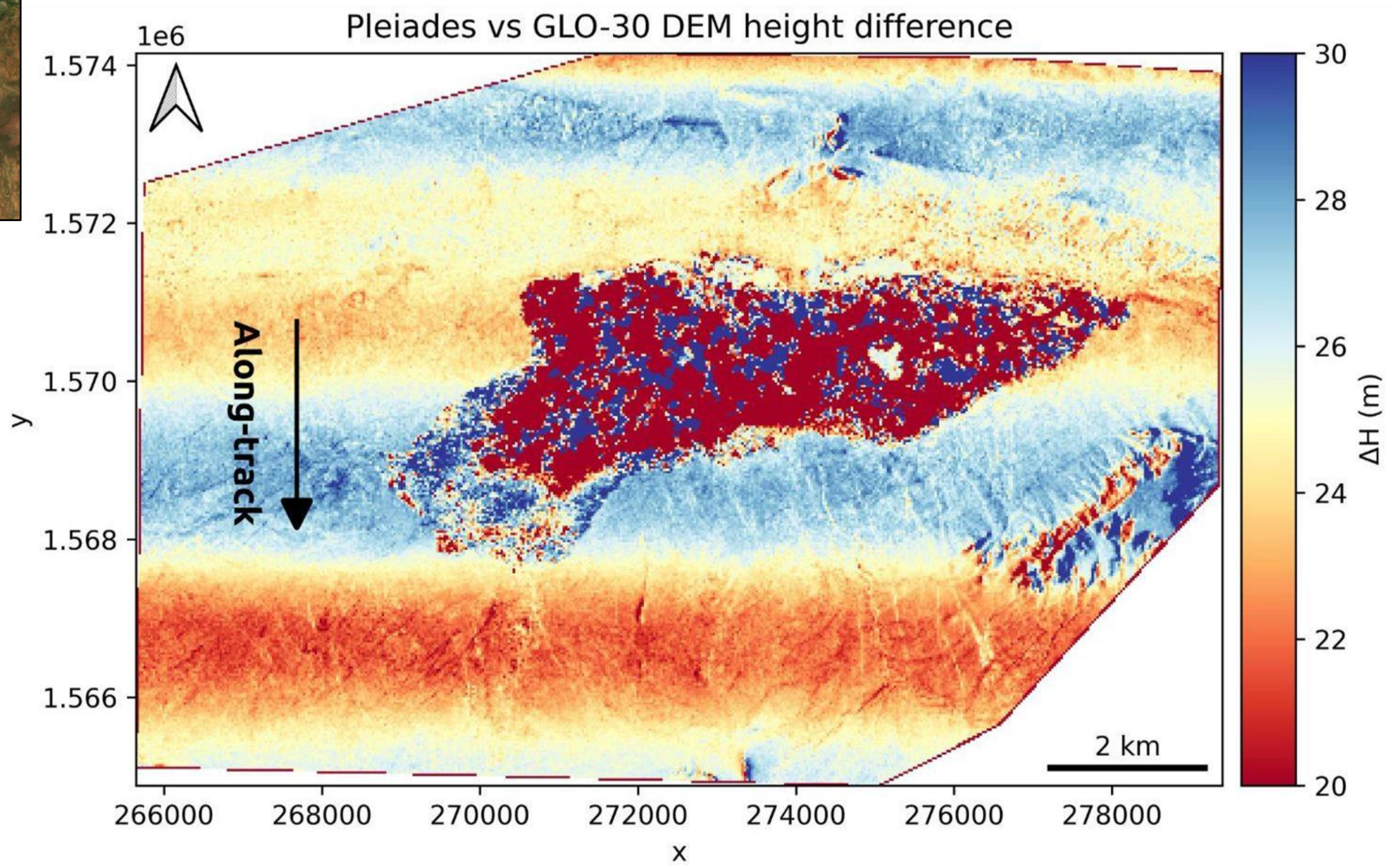


The different methods consistently observe **fine shape patterns** such as **slope breaks**

The curves look more like **degree-3 polynomials** than degree-1 or -2

Pleiades jitter





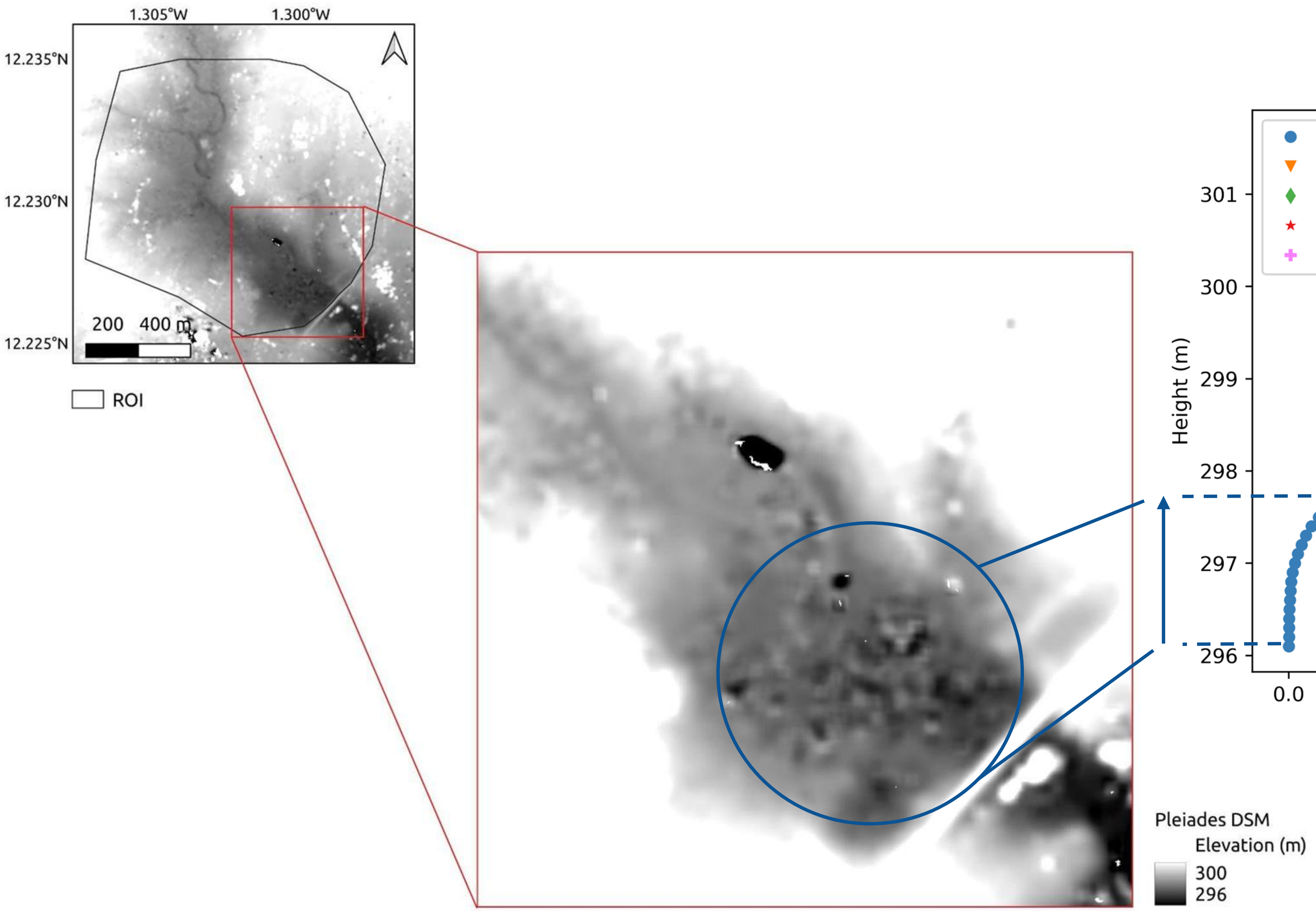
Along-track undulations of several meters over Pleiades DSM due to Pleiades-1B jitter between the two image shots

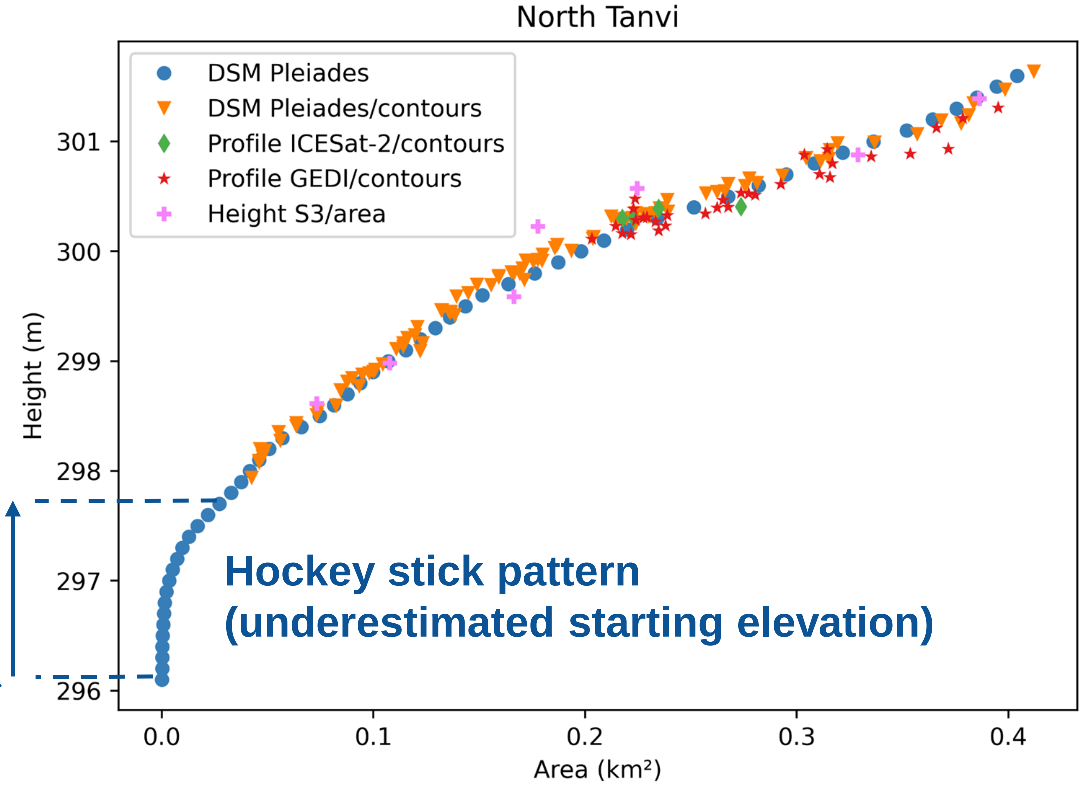
↓

Preliminary checks should be done

Corrected by subtracting the **averaged per line difference** with **Copernicus DEM** (GLO-30)

DSM noise impact

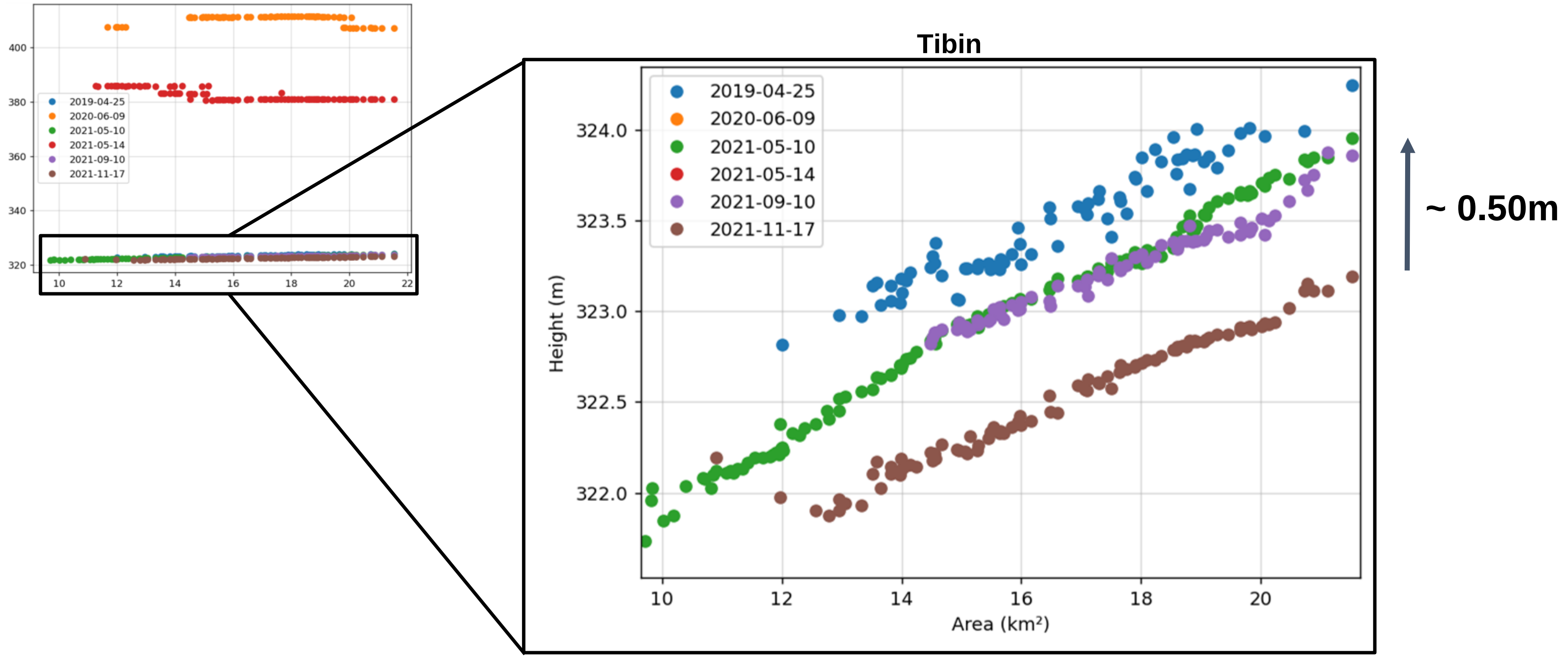




No issue if there is water at Pleiades acquisition time

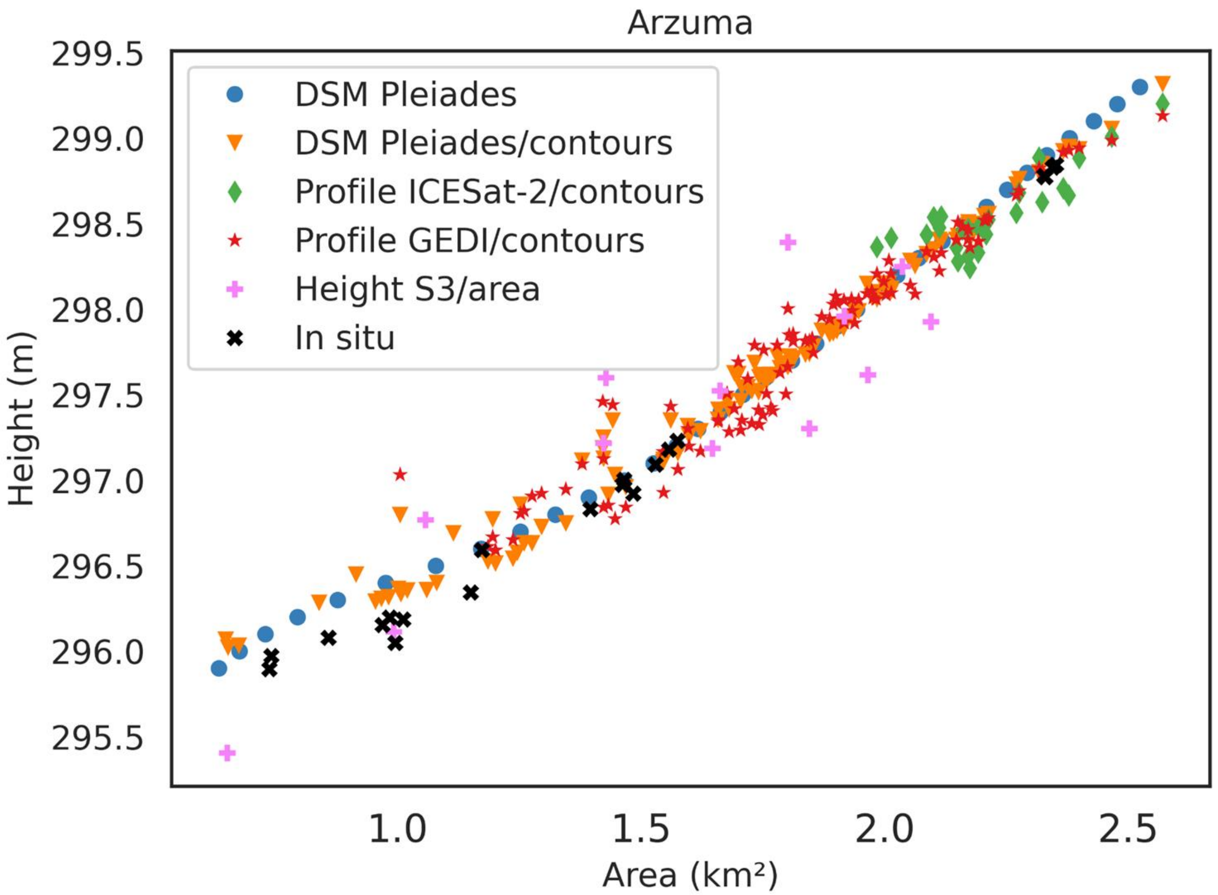
Very smooth area: low pixels correlations

Bias on GEDI data



Elevation biases have been observed among **GEDI data from different acquisition dates**.
We selected the most complete and least noisy date

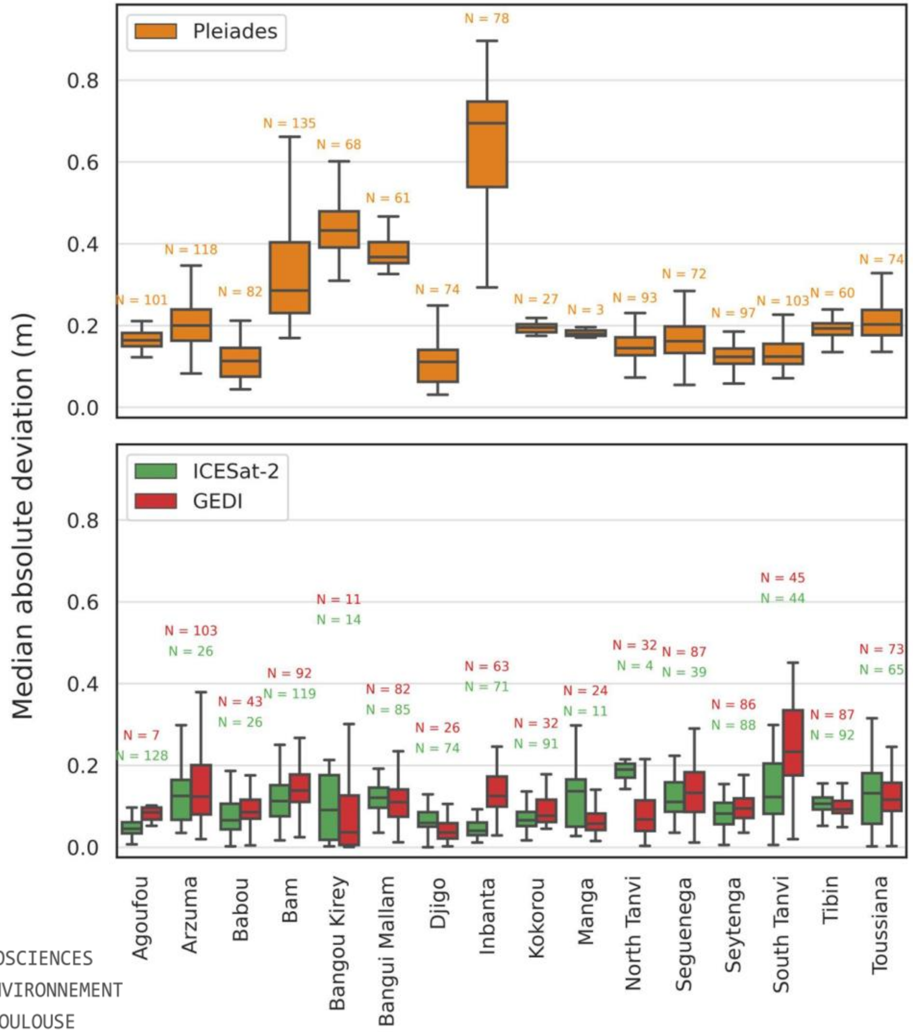
Pieces of caution



- The **dependency of curves extent to acquisition dates** is clearly visible for **lidar-** and **DSM**-derived methods
- **Higher noise** observed on certain **Sentinel-3**-derived curves is attributed to **waveform contamination** or **lake size**

Water elevation precision

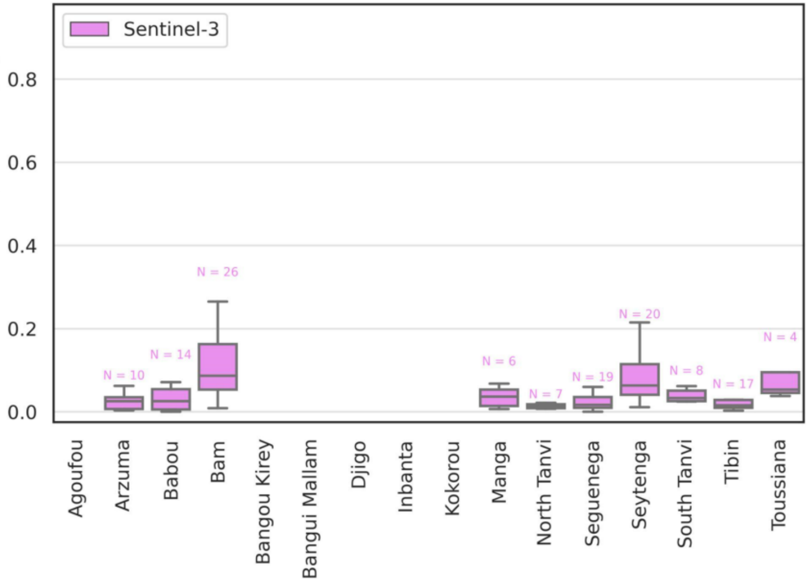
Median Absolute Deviation (MAD) over the contours/transects is used to assess the **water elevation precision** of each method (also includes contour detection precision)



Median MAD:

- **Pleiades:** most values < 0.20m
- **ICESat-2:** most values < 0.13m
- **GEDI:** most values < 0.13m
- **Sentinel-3:** most values < 0.06m

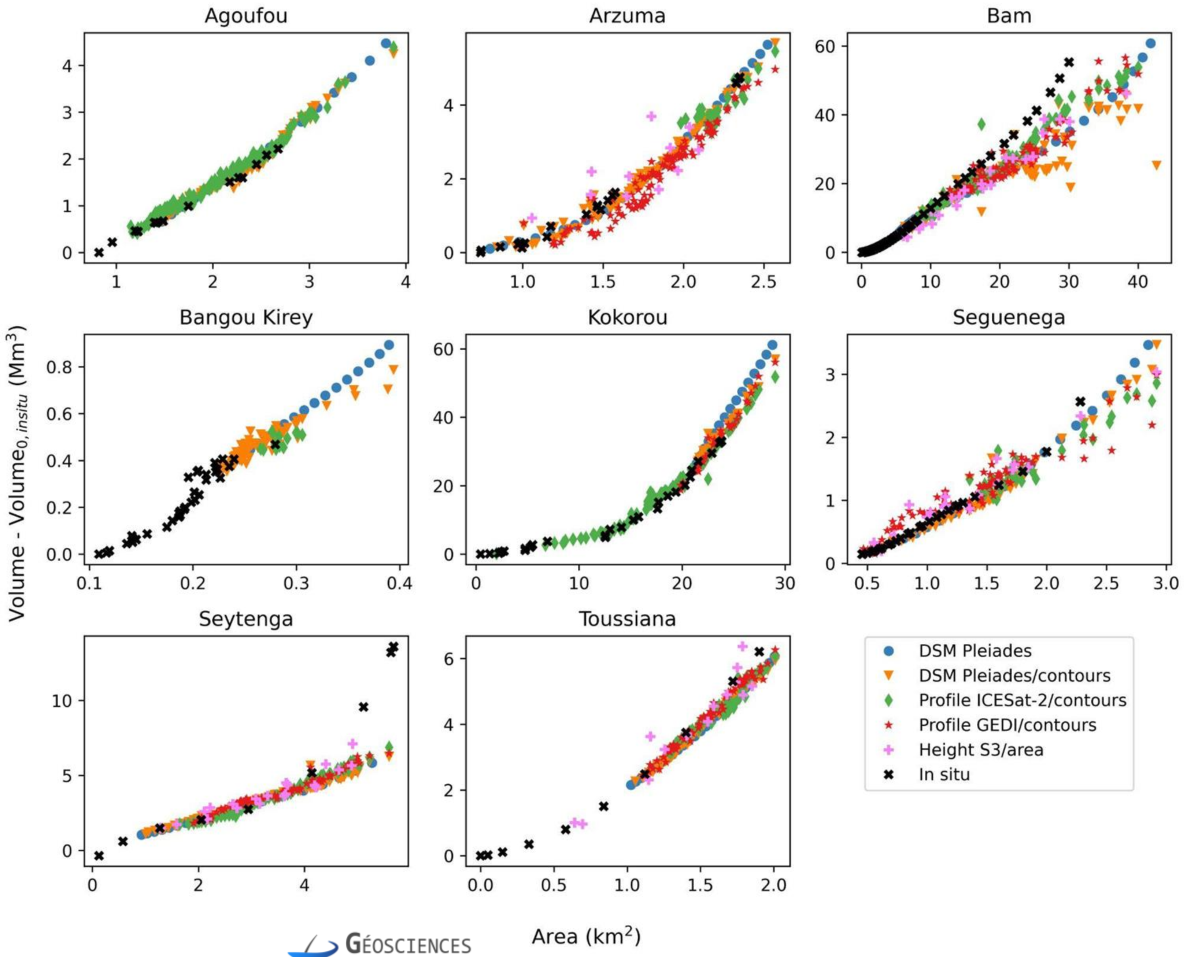
Good precision stability: IQR < 0.20m



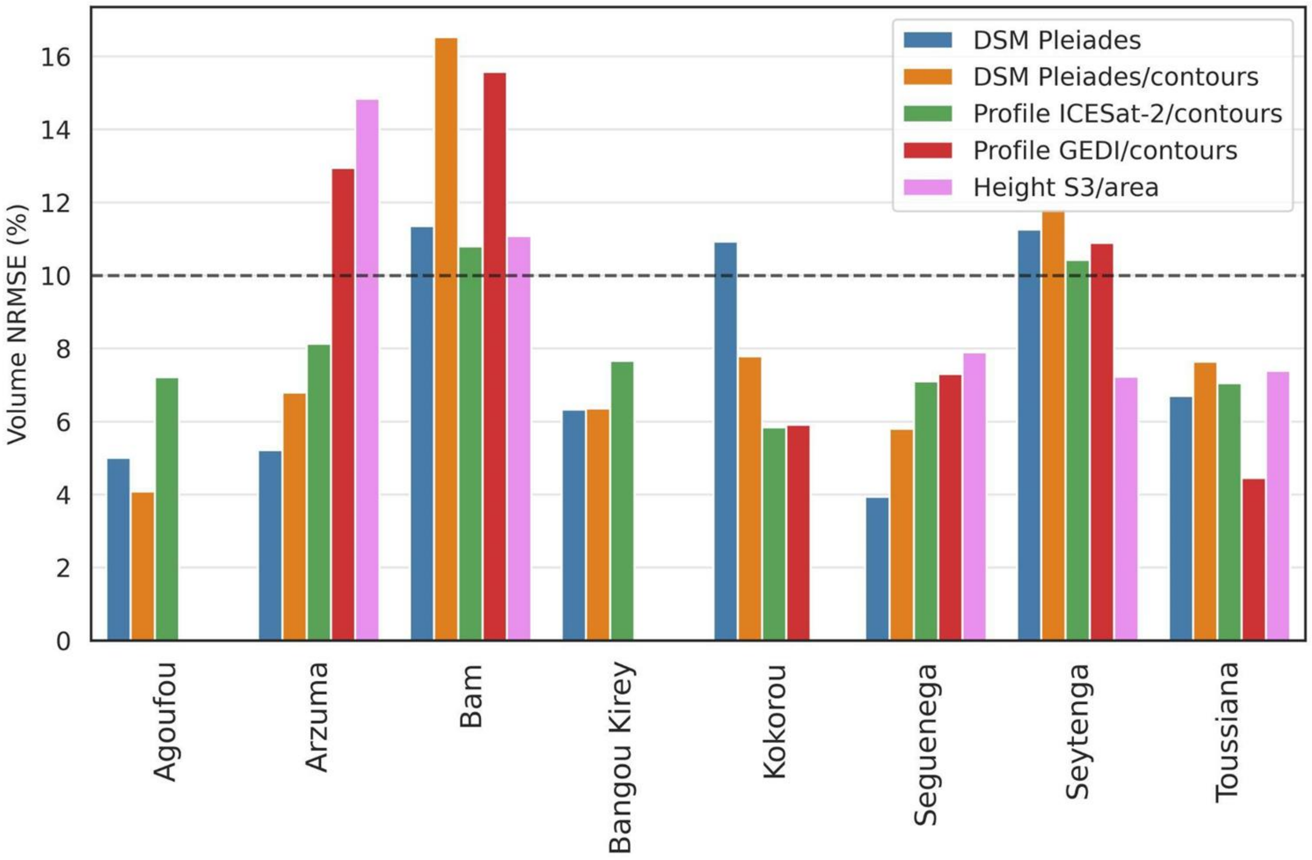
Volume-area curves accuracy

No systematic differences between methods

$$NRMSE = \frac{RMSE}{Obs_{max} - Obs_{min}}$$ (Busker et al., 2019)

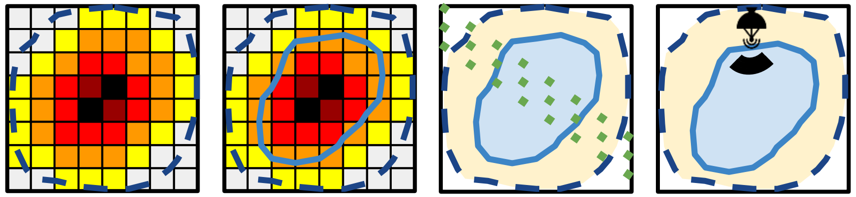


All NRMSE values below 20%, **most below 10%**



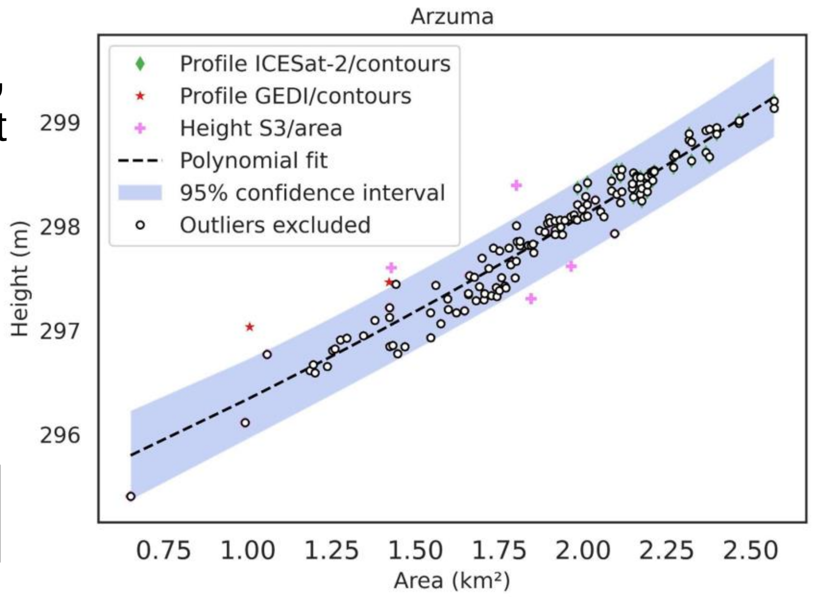
Conclusion and outlook

- Height-area relationships from **4 different methods**
- Comparison over **16 lakes in West Africa.**
- **Different sources of data:** DSMs, optical imagery, lidar, radar altimetry



- **Generally good agreement** between methods and w.r.t. in situ data
- **Consistent** observation of **fine shape patterns** over **small height amplitudes**
- Water elevation retrieved with **generally good precision**

- Some **inherent limitations** of each method have been identified (e.g. **data quality, surface features, temporal coverage**). Spatial coverage or data accessibility must also be discussed.



Outlook:

- Combining data provides **more robust** H-A relationships and **improves extent**
- Particularly interesting for **ungauged lakes** or lakes with **outdated in situ data**

These results will be **published in a paper** currently in preparation (**Girard et al.**)

THANK YOU FOR YOUR ATTENTION!

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