Surface Water & Ocean Topography

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Principle of interferometry

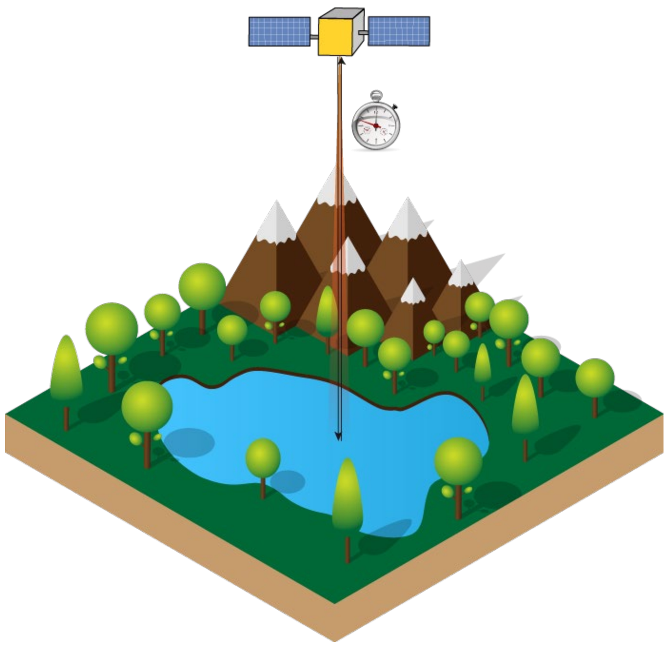
Scientific objectives

First results

Lakes Survey from remote sensing techniques

CEDS 2024

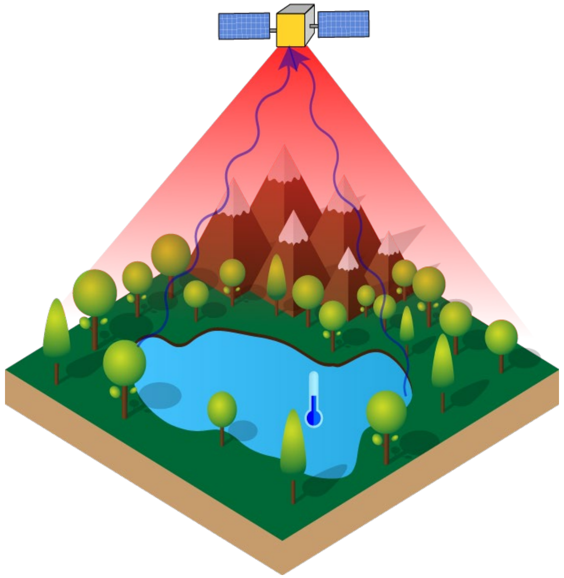
Water Level



Radar altimetry (active sensor)

- Repetitive
- Independent to cloud cover
- Only large lakes
- Mono variable

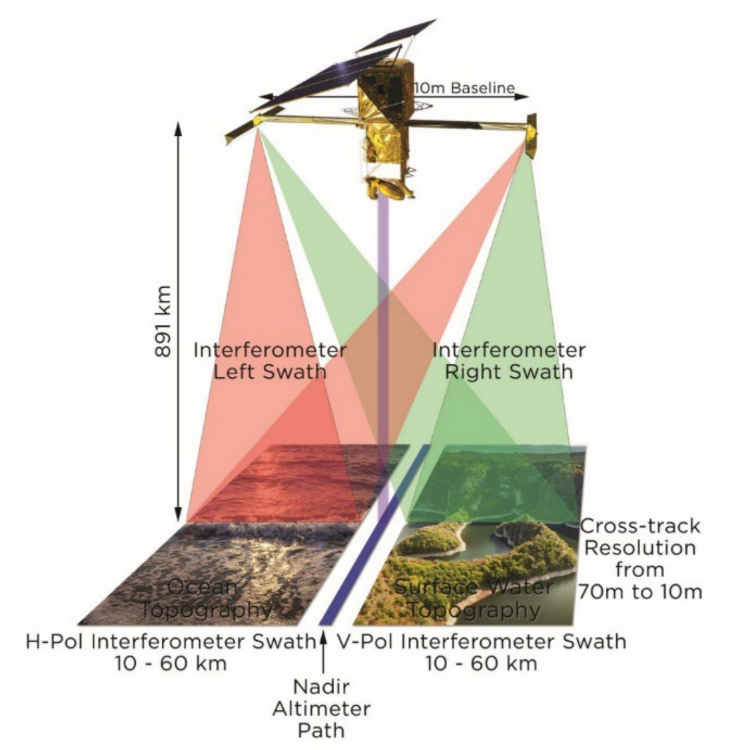
Water extent



Optical imagery (passive sensors)

- Repetitive
- All size lakes
- Cloud dependent
- Mono variable

Water level, extent and volume changes

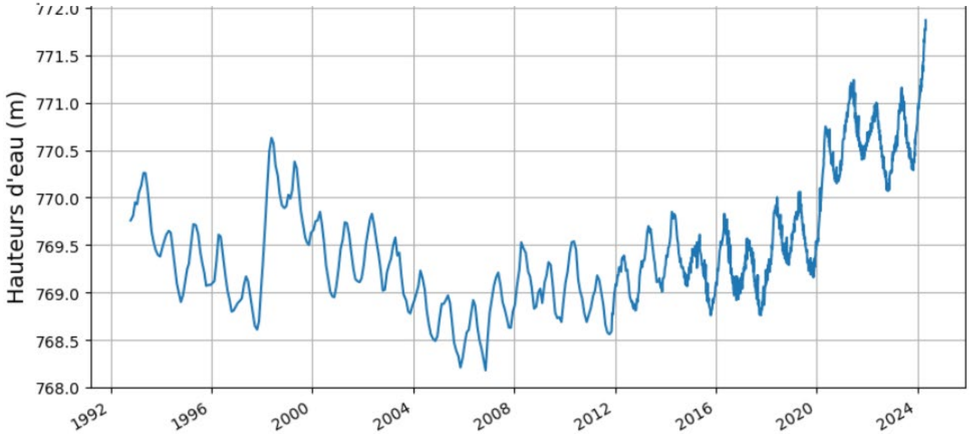


Radar interferometry (active sensors)

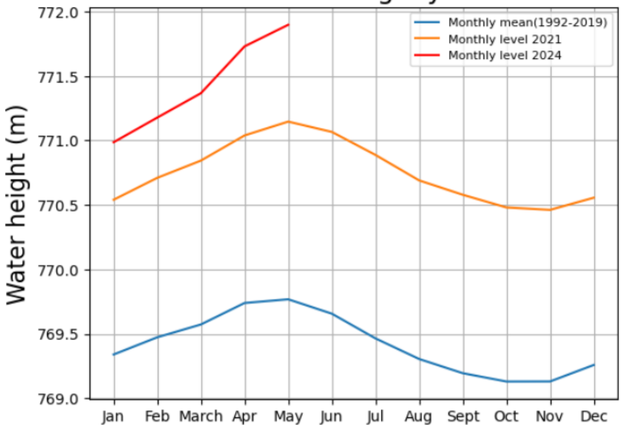
- Repetitive
- All size lakes
- Independent to cloud cover
- Multi-variable variable

Example of application over the Lake Tanganyika

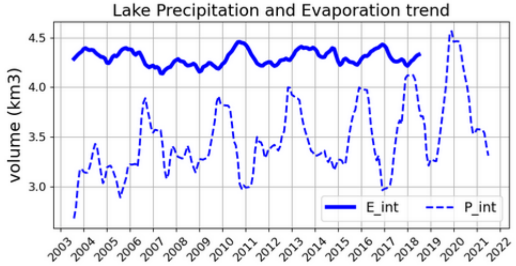
Water level changes of lake Tanganyika (1992-2004 from satellite altimetry)

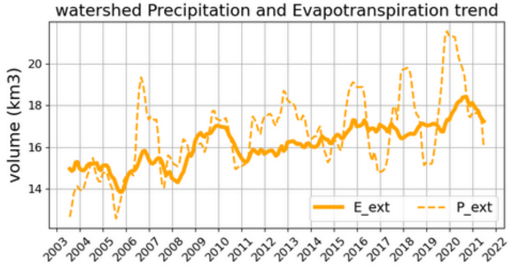


Saisonalité des hauteurs d'eau (m)
du Lac Tanganyika

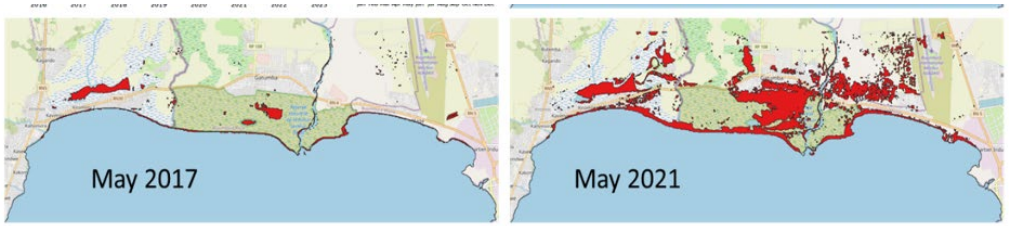


Seasonailty of water height from average year, previous maximum (2021) and 2024



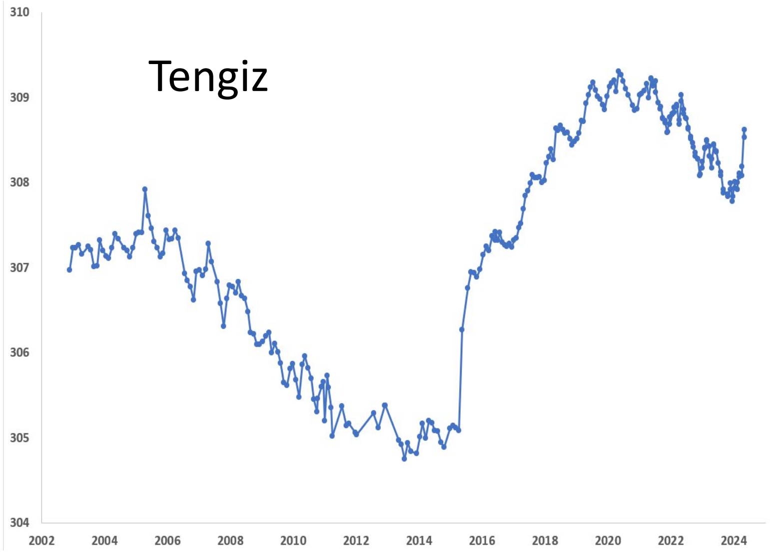


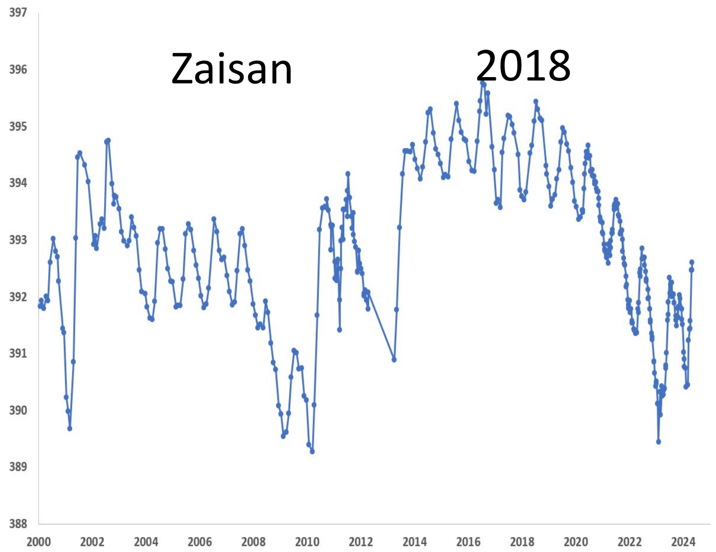
- Extreme inundation are observed in 2021 & 2024 and well identified by satellite altimetry
- Satellite imagery allows to map the flooding areas precisely (With sentinel-2)
- Climate data records and models allows to attribute the LWL variation to increasing precipitation on the lake watershed

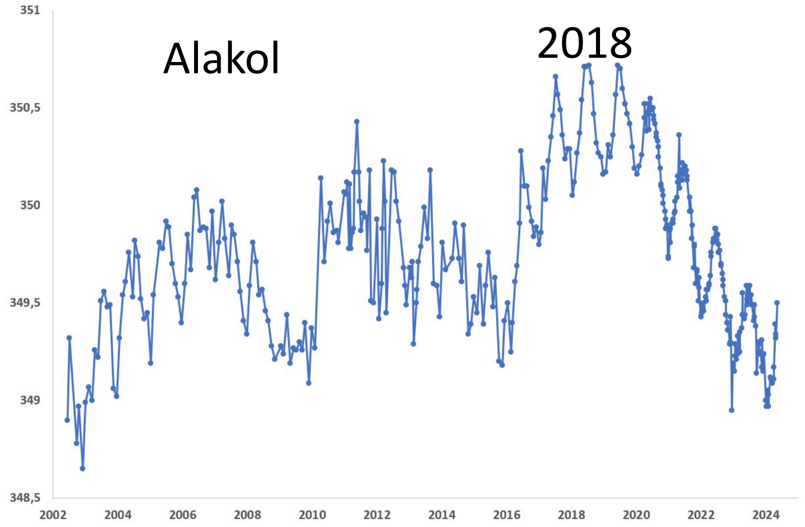


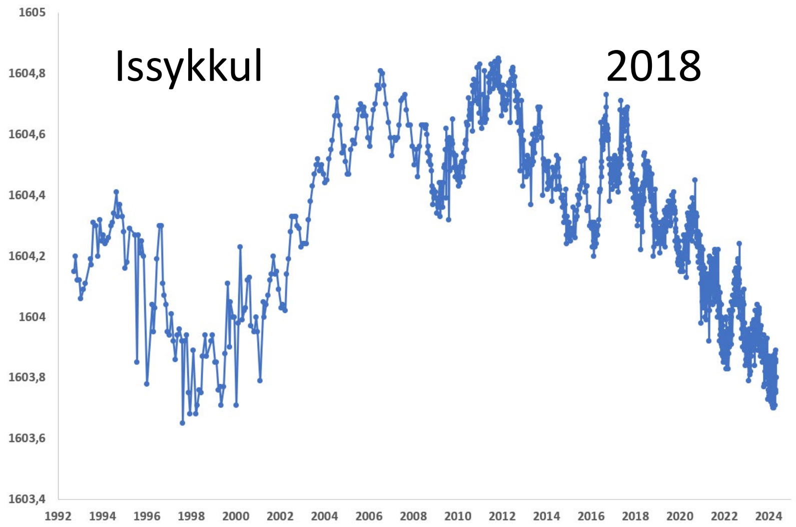
Gbetkom, Cretaux et al., 2024, Remote Sensing Application: society and environment

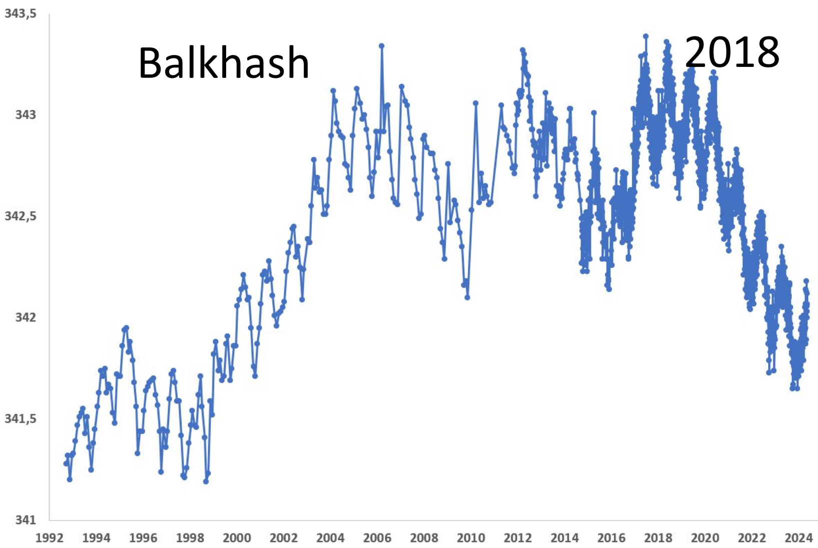
Water level variations over large lakes in Central Asia

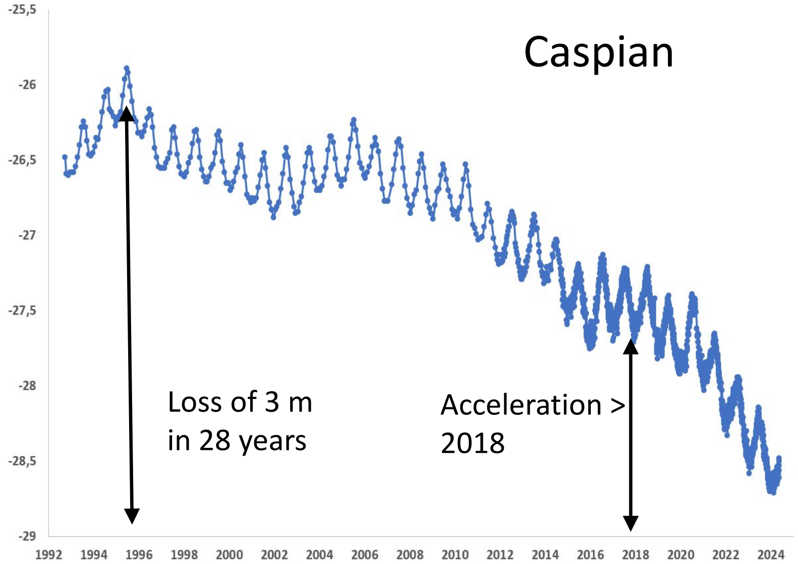










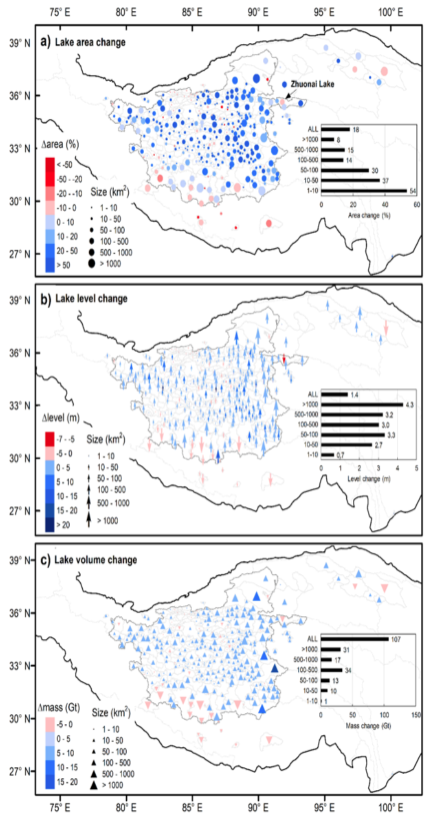


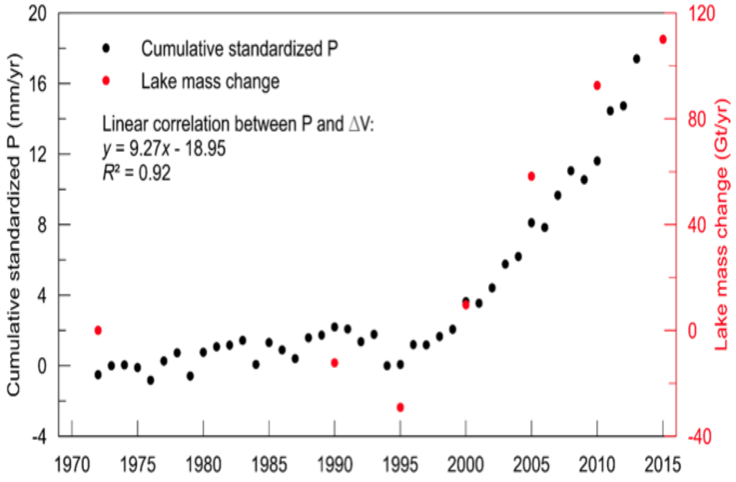
We see that all large lakes (except Tengiz) are shrinking since ~2018
Evolution in time of Issykkul, Alakol & Balkhash very similar => signature of regional climate change

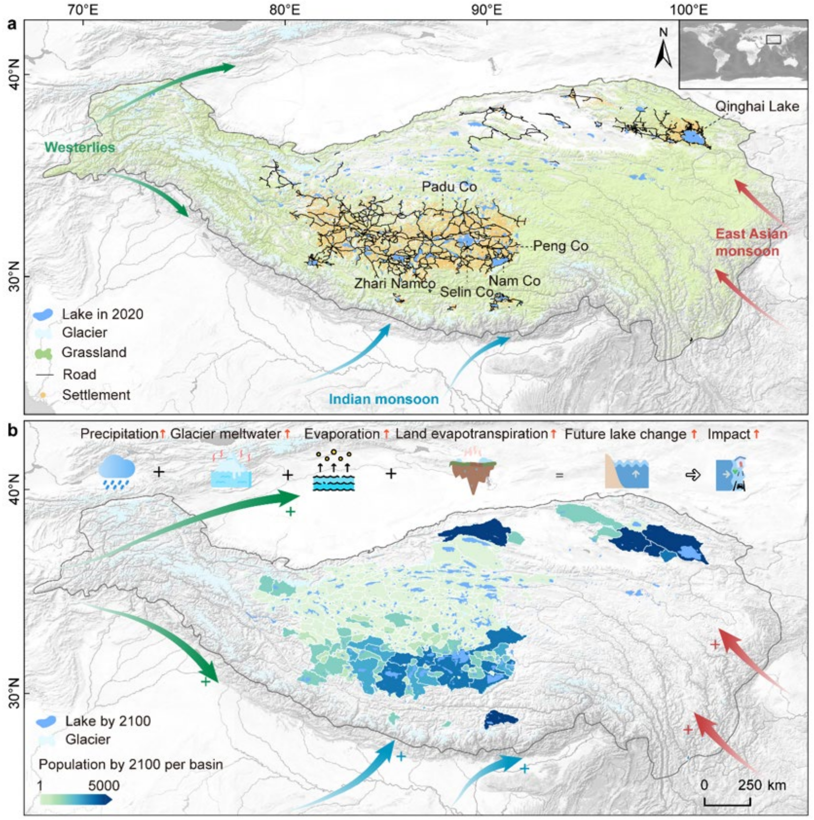
An example where SWOT will teach us a lot on linkage between lakes and climate

Satellite altimetry & imagery revealed very strong increased of the lake level, extent (+~11,400 km^2) and volume (+~160 km^3) over the last 20 years on lakes over the whole Tibetan Plateau

Climatic assessment of the causes have proven that for ~80% the increase is due to higher rainfall over the TP



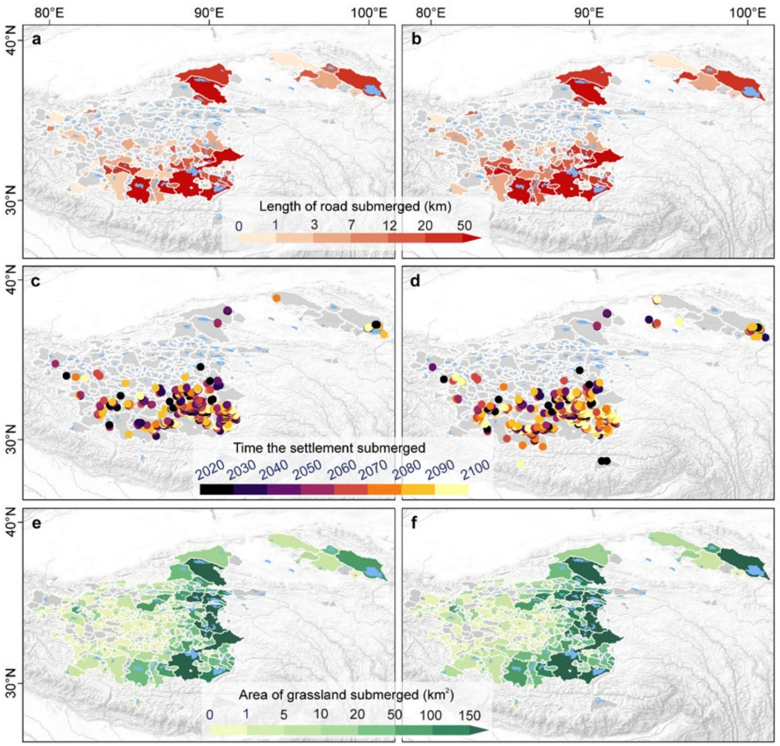




Strong intensification of the East Asian and the Indian monsoon, and the westerlies will provoke drastic land overflow, and extension of lake surface with strong societal consequences

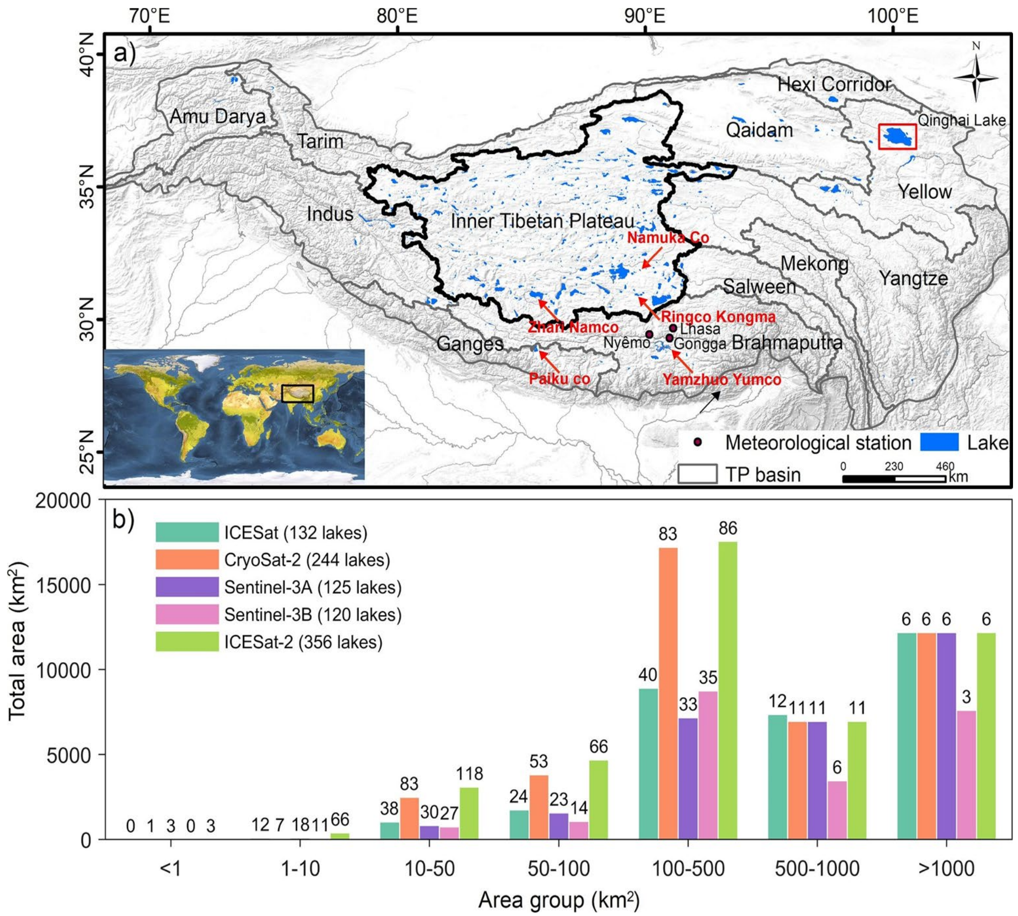
Zhang G., Bolch T., Chen W., and Cretaux J-F., *Sc of the total Environment*, 2021,

Prediction over the Tibetan Plateau for the next decades under CMIP scenarios



By the end of this century, under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 Respectively it is projected that:

- Lake extent will increase by ~67% and volume by 650 to 900 gt
- 1023±281, 959±274 and 1481±421 km of roads will be inundated
- 5.66, 7.40 and 5.78 million people are projected to be populated across the TP
- a total inundation area of 8533, 9132, and 11576 km^2 of grasslands, wetlands, croplands, forests, and sparse vegetation



Only 30 % of lakes are covered from classical satellite altimetry

F Xu., G. Zhang., R.I.Woolway., K. Yang., Y. Wada., J. Wang., and J-F Cretaux, *Nature Geosciences*, 2024

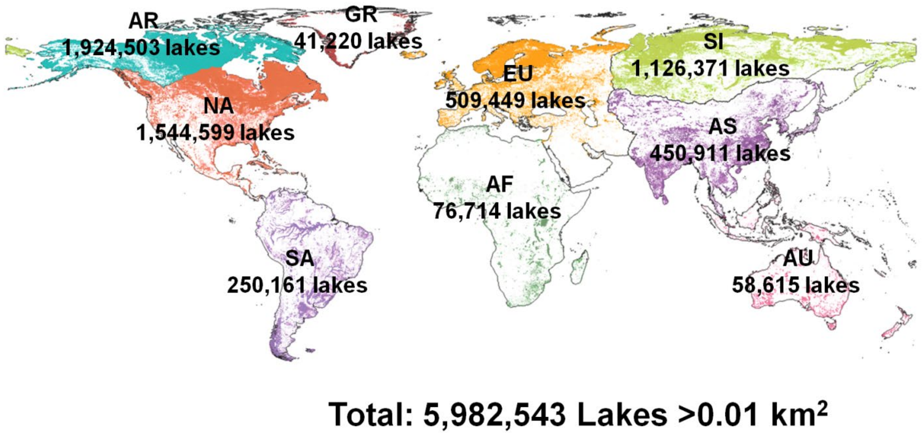
Global lakes & rivers survey from SWOT

SWOT measurements and products

Lakes

Height, extent & volume changes on lakes larger than 250 m x 250 m (~1.8 M such lakes worldwide, most of these are small lakes not observed on the ground or from satellites)

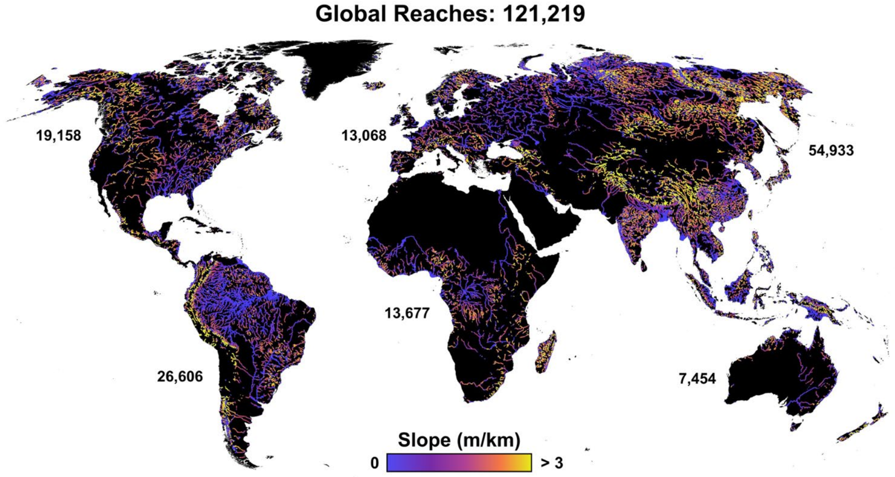
⇒This will allow calculating water storage changes
⇒This will allow understanding the role of lake in water cycle



Rivers

Height, slope and width of rivers larger than 100 m

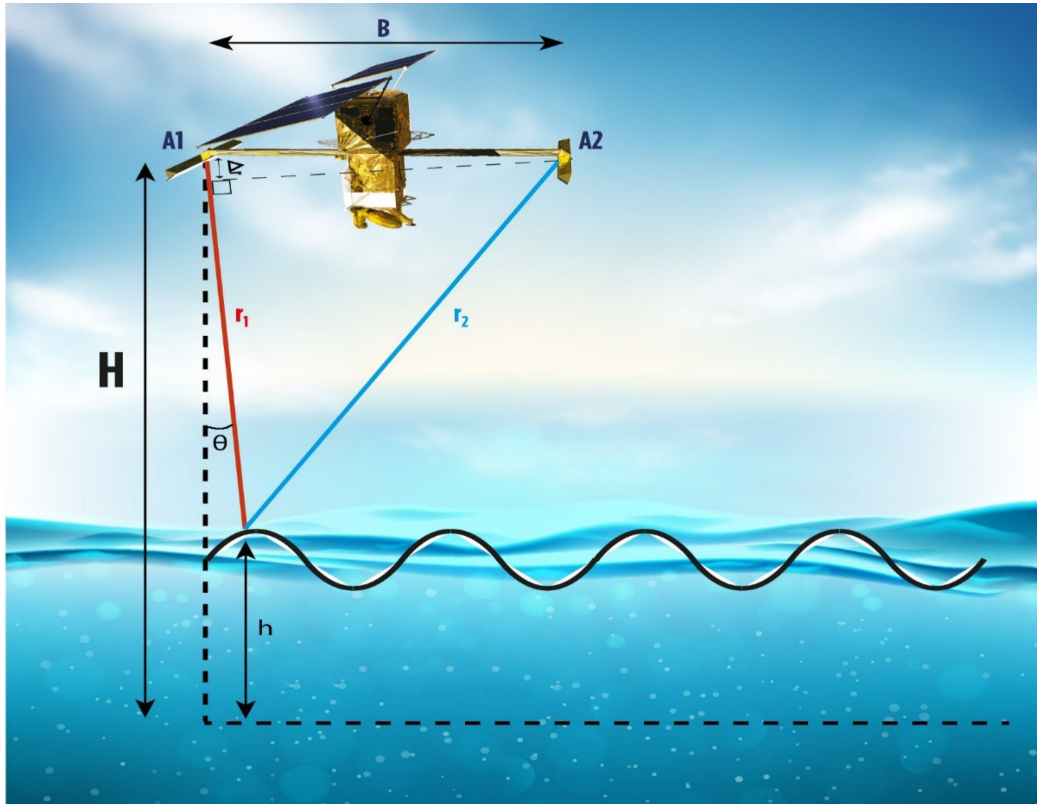
⇒This will allow calculating discharges along pre-defined reaches of 10 km
⇒This will allow understanding the role of rivers in water cycle and on sea level changes
⇒This will allow understanding the interaction with floodplain and groundwater dynamics at basin scale



Measurements will be released every 21 days and every passes on shape of vector files, pixel cloud and rasters

SWOT measurements, how does it works?

CEDS 2024



Water surface is detected through the radiometry

Both antenna will receive the same signal reflected on the surface, but it won't have travelled the same distance. This enable to compute the surface height.

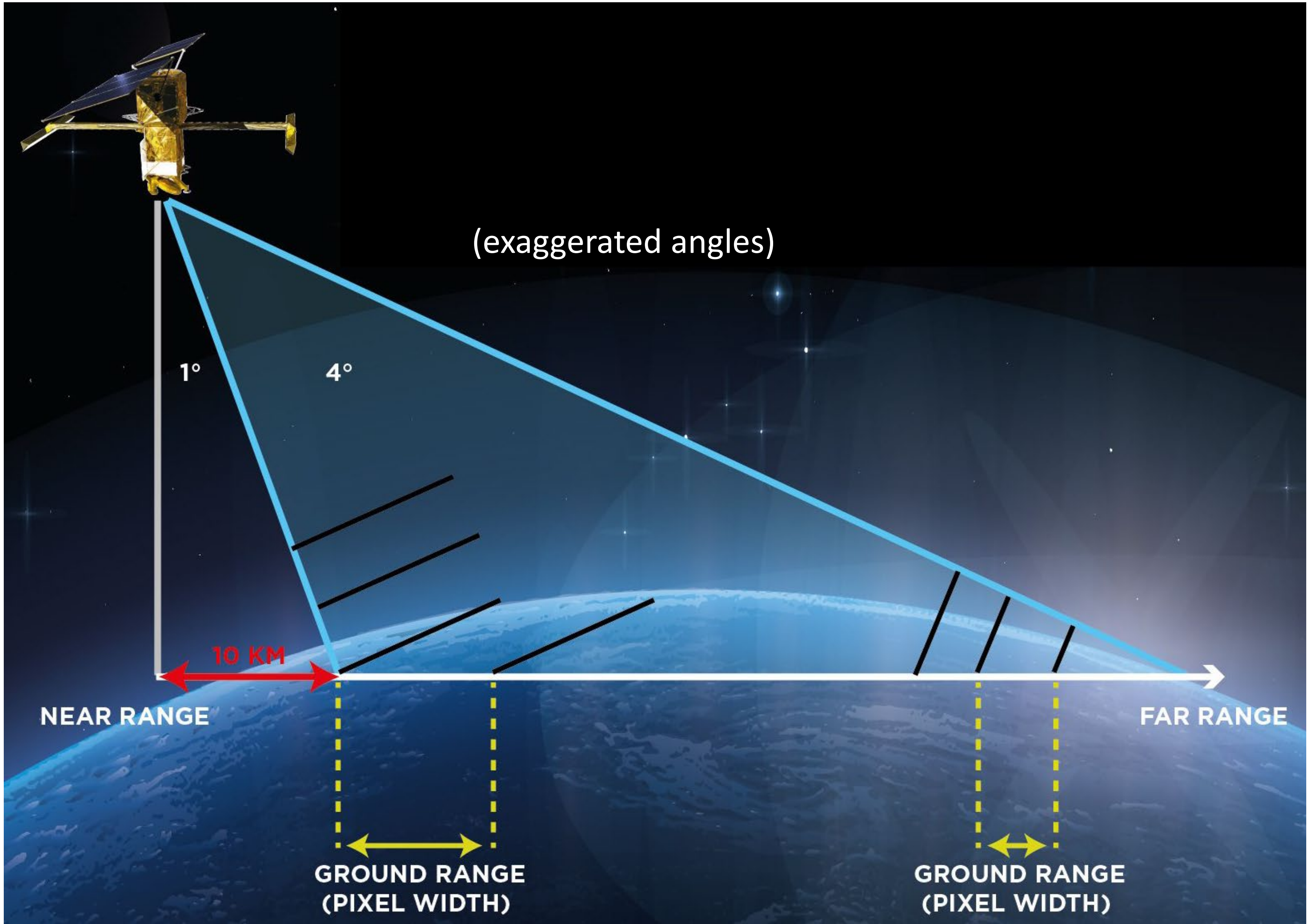
r1 is measured using the round-trip time between the satellite and the surface
(**r1** - **r2**) is also estimated

θ is deduced from r1-r2 and B (distance between the two antennas).

H (satellite altitude) is measured by precise location system onboard (Doris, GPS/GNSS)

The water height is **h = H – r1 cos (θ)**

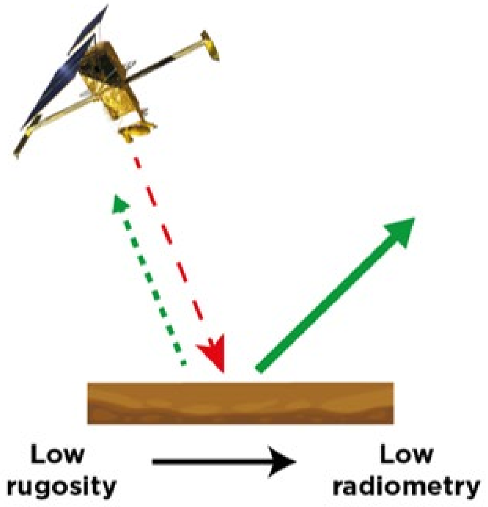
Swot swath and pixel geometry (side view)



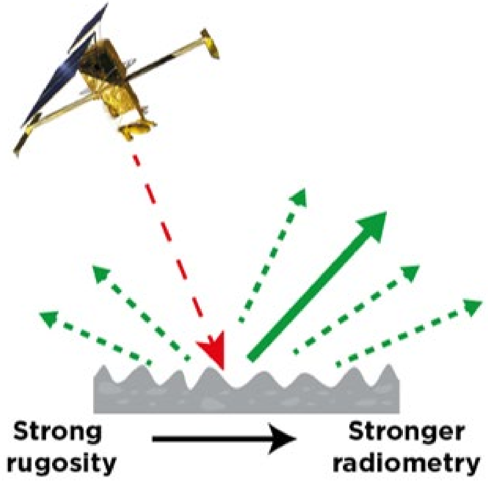
- Resolution loss at near range
- +/- 10 km blind zone around nadir
- Land / water contrast reduced at far range since water is reflecting more at small incidence, while land is reflecting about the same way at all incidence (land is rougher than water)

Advantages / drawbacks

- **Among the advantages:**
  - Resolution
  - swath, i.e., the ability of retrieving 2D data in a single satellite passage which is not currently possible with altimetry (either classical or « SAR » altimetry)
  - Very innovative concept, technically challenging

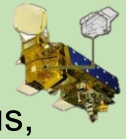


- **The possible drawbacks**
  - The use of the Ka-band, while enabling higher resolution (smaller footprint), should provide with less data when it's raining.
  - Very innovative concept, technically challenging
  - When rugosity of water surface is small => **dark water**



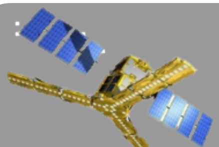
Global Water Cycle on the Earth

CEDS 2024



S2/S3
LANDSAT, Venµs,
ECOSTRESS
TRISHNA
SBG, LSTM

Jason, S3
Saral Altika
SWOT



SMOS, SMAP,
AMSR-E, SSMI

Ground water

Precipitation — Run-off

$$P - E - Q = \Delta SW + \Delta SM + \Delta GW$$

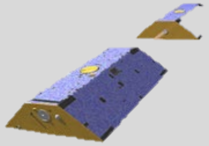
Evapotranspiration

Surface Water — Soil Moisture — Ground Water

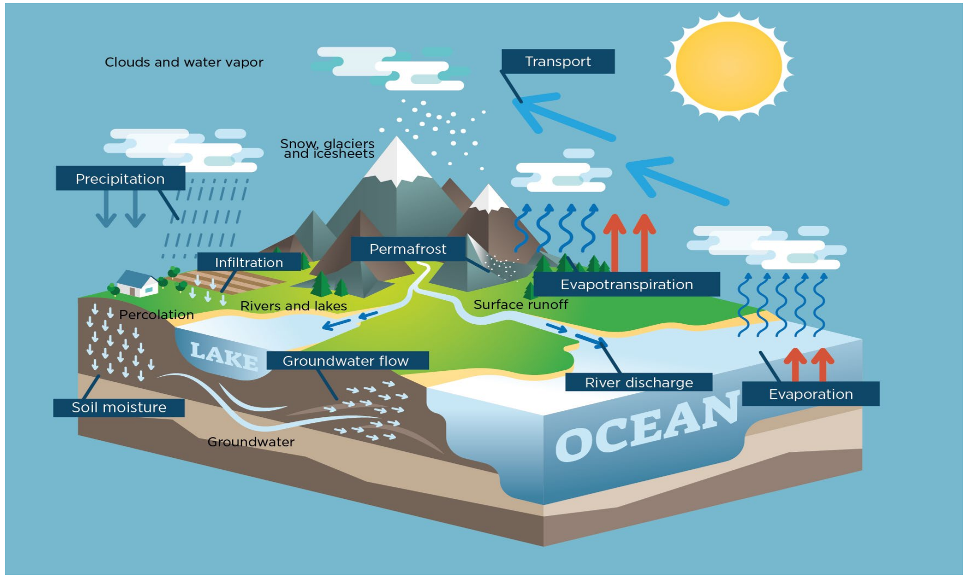
Δ Water Storage

GPM,
Megha-Tropiques
C2OMODO

SWOT



GRACE,
GRACE-FO
Marvel



Nadir altimetry, satellite imagery and assimilation into models already allows quantification of Q & DS, but on on a limited number of lakes & rivers

Lakes volume changes from SWOT

Volume changes will be derived from the measurements of heights and extent

Objectives: Investigating errors expected from the SWOT products (the volume changes) & applications on several cases studies (Sahelian pounds, Brazilian reservoirs, Canadian & French lakes) have been done using simulations.

Algorithm proposed has been implemented on the LOCNES processing chain for operational production

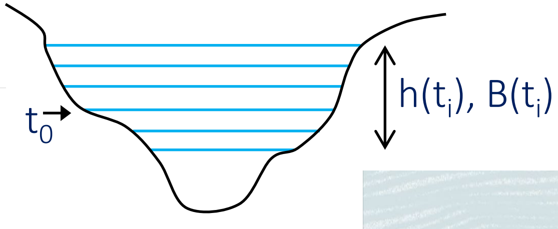
$$\Delta V\left(\frac{t_i}{t_0}\right) = \Delta V\left(\frac{t_{i-1}}{t_0}\right) + \frac{[B(t_i)+B(t_{i-1})+\sqrt{B(t_i)*B(t_{i-1})}]}{3} . [h(t_i) - h(t_{i-1})]$$

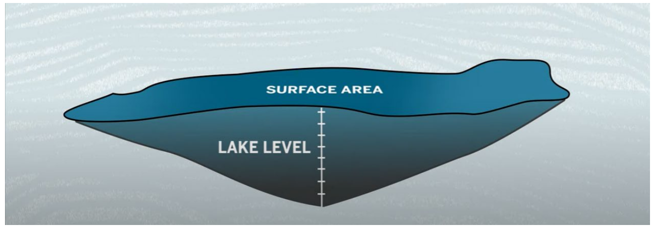
(quadratic case)

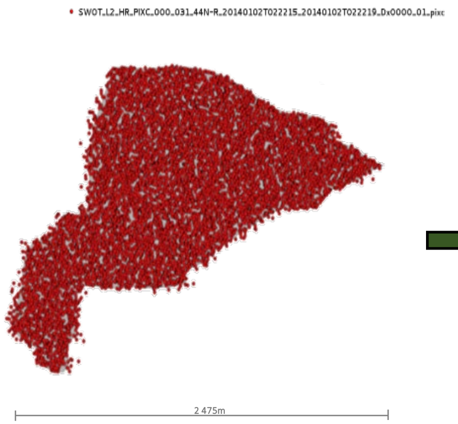
$$\Delta V\left(\frac{t_i}{t_0}\right) = \Delta V\left(\frac{t_{i-1}}{t_0}\right) + \frac{[B(t_i) + B(t_{i-1})]}{2} . [h(t_i) - h(t_{i-1})]$$

(Linear case)

$$\sigma(Me) = \sqrt{\sigma(H1)^2\left(\frac{\partial \Delta V}{\partial H1}\right)^2 + \sigma(H2)^2\left(\frac{\partial \Delta V}{\partial H2}\right)^2 + \sigma(A1)^2\left(\frac{\partial \Delta V}{\partial A1}\right)^2 + \sigma(A2)^2\left(\frac{\partial \Delta V}{\partial A2}\right)^2}$$

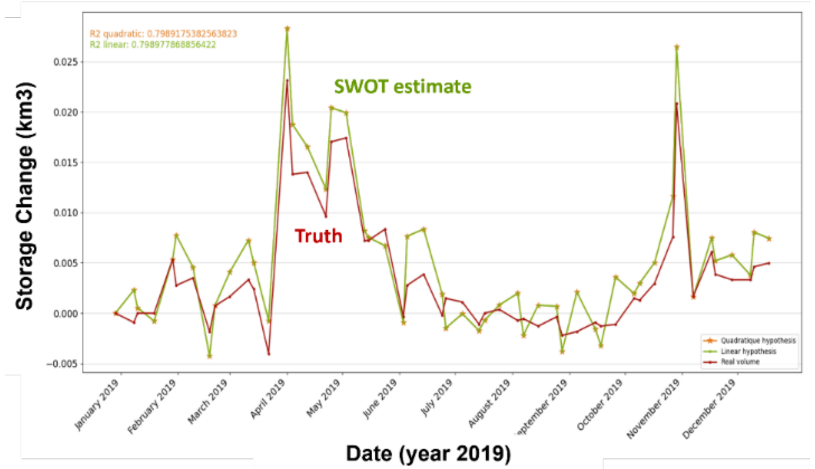






PixC product

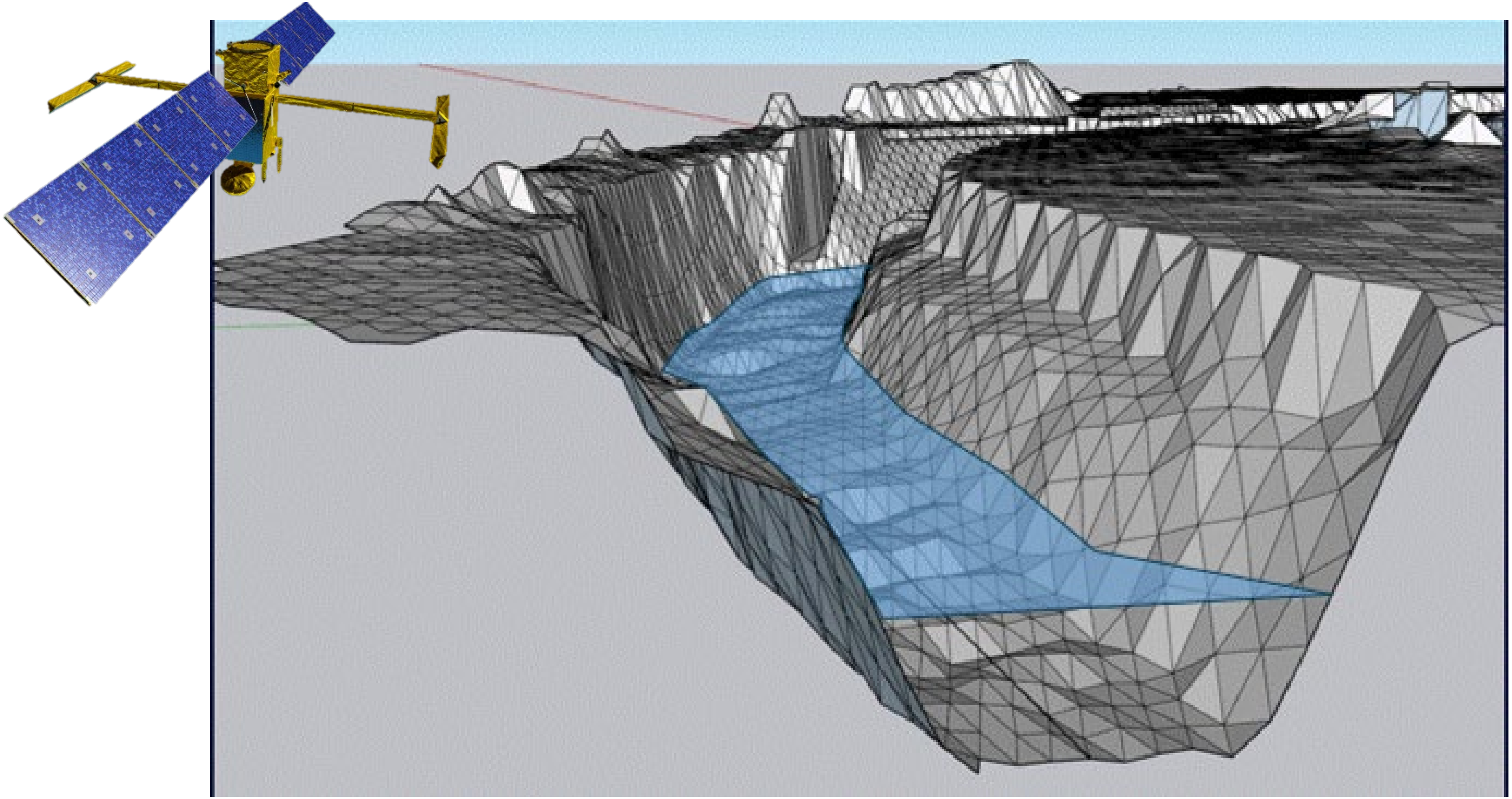
Massawippi lake (area ~1800 ha)



Vector product:
H,E,dV/dt

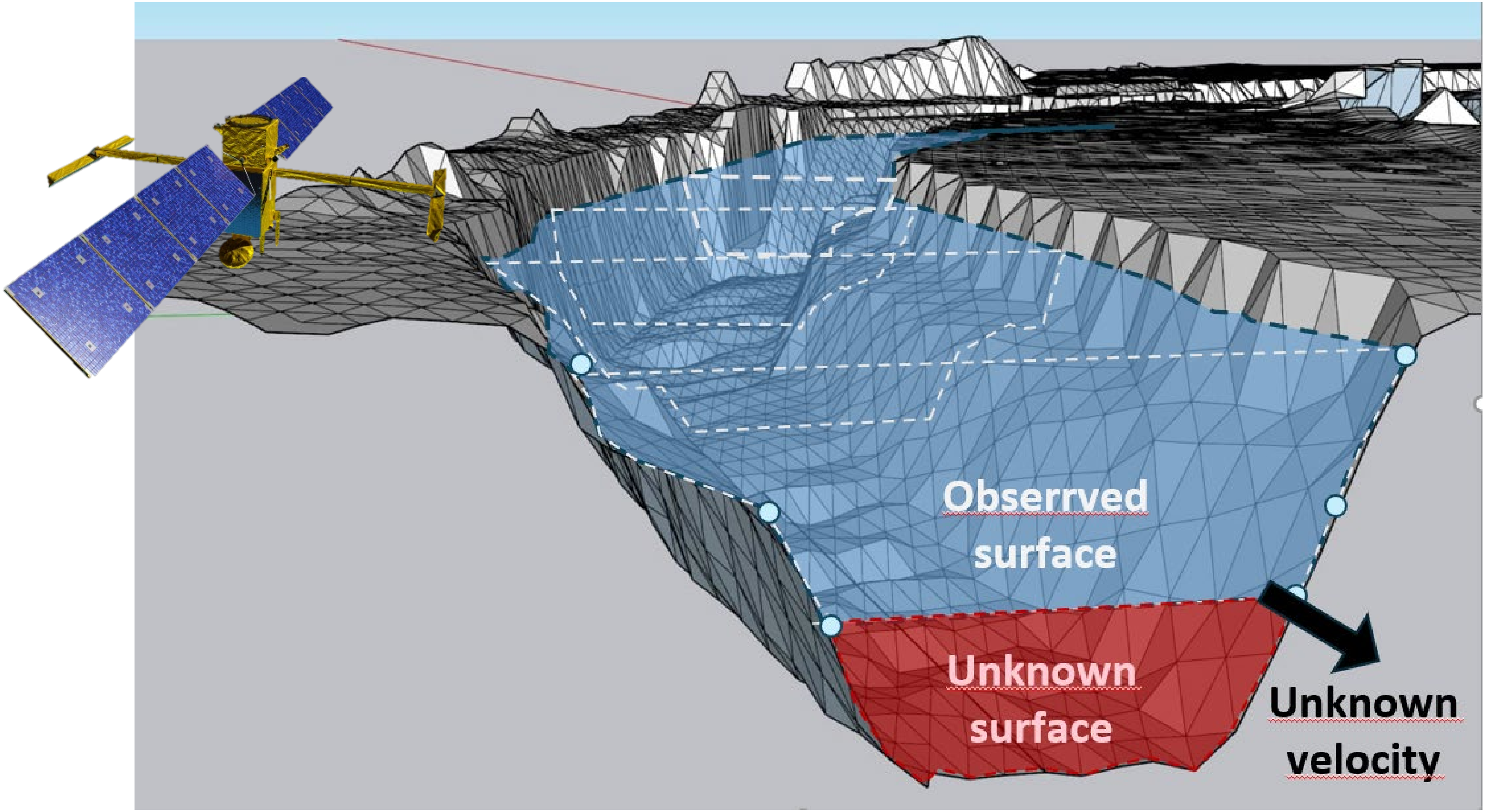
Simulations were done on dozen of lakes of different size and shape
Errors never exceeded 10% (in rare cases) of the real volume changes

What SWOT measures is changing with the discharge changes
SWOT sees height, width and slope of the river



Source : SWOT science team meeting, Chapel Hill, juin 2024,
Hind Oubanas

Mathematical problem is underconstrain => we do not solve all with SWOT but under some assumptions on friction and bathymetry we may determine approximated discharge

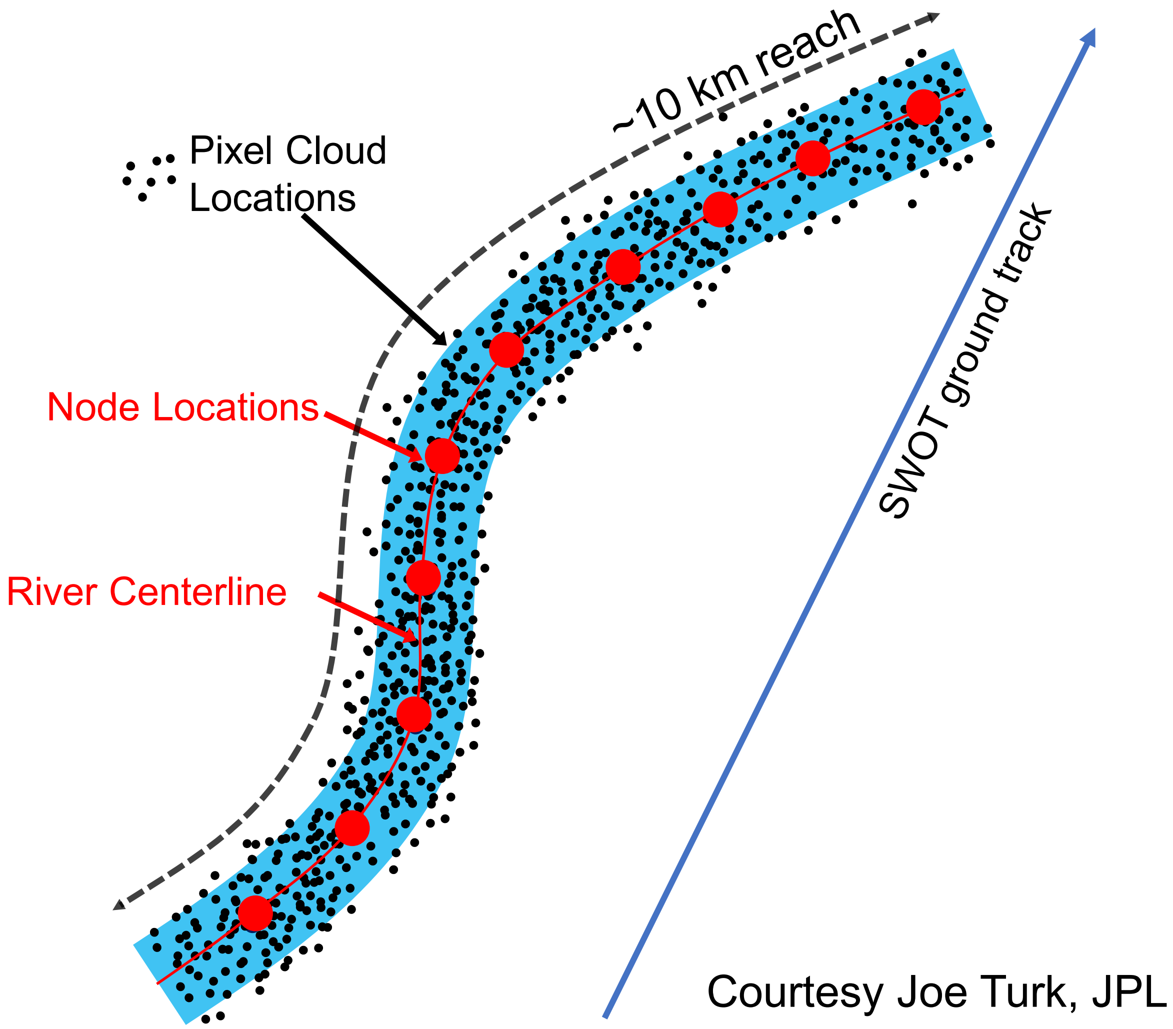


Source : SWOT science team meeting, Chapel Hill, juin 2024, Hind Oubanas

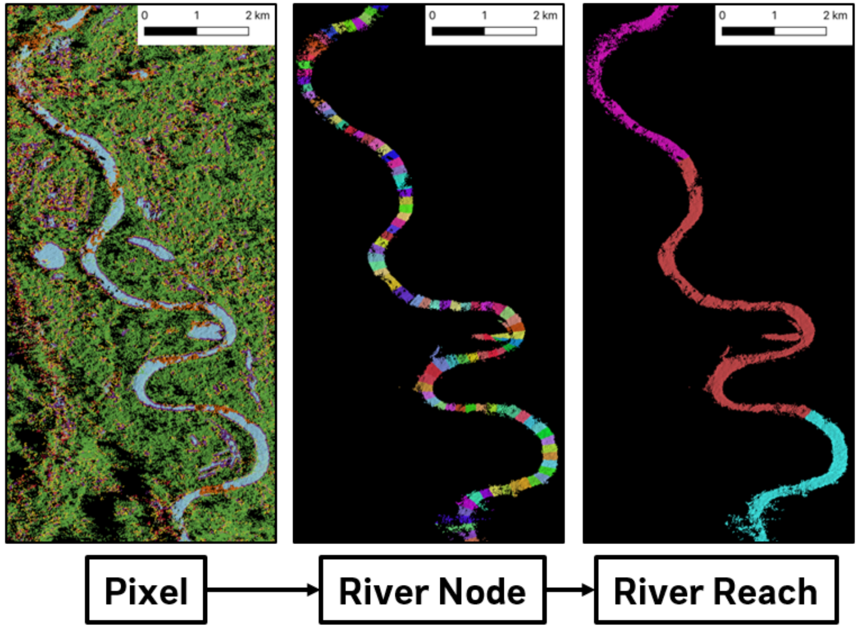
SWOT River SP Data Products (L2_HR_RiverSP)

- Provides vector representation of rivers
- In Shapefile format
- Options:
  - Reaches (~10 km), polylines
  - Nodes (~200 m), points

- Includes elevation, inundation extent, slope (for reaches only), quality flags, corrections
- A granule represents a pass over one continent
- Version C Currently Available



Schematic of SWOT River Data Products



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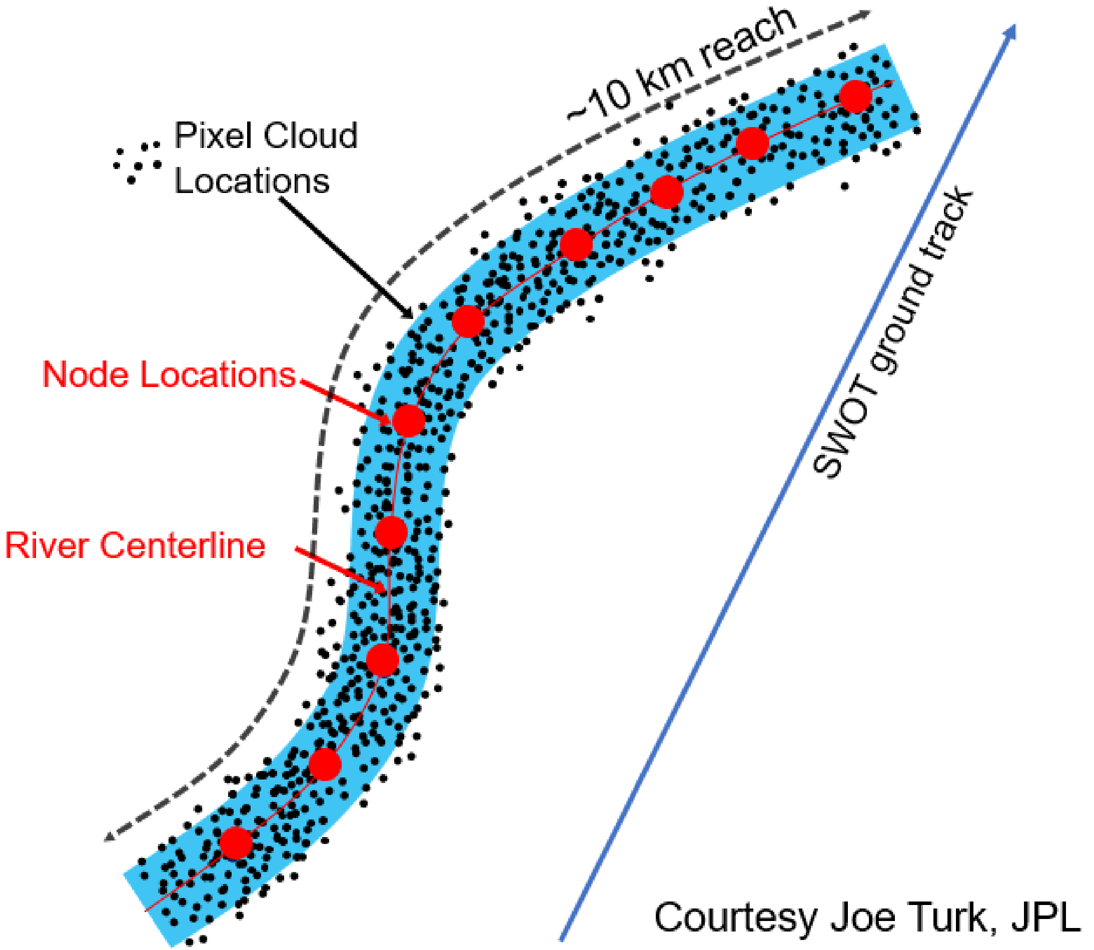

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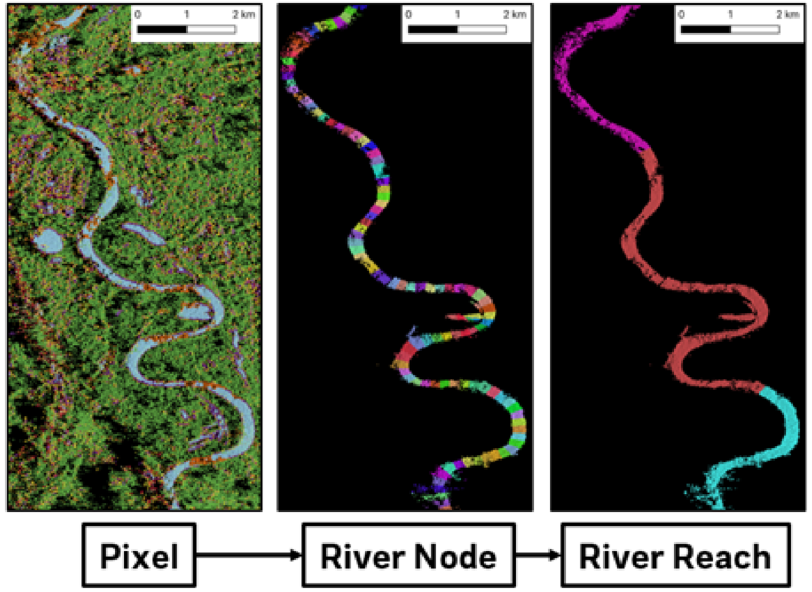
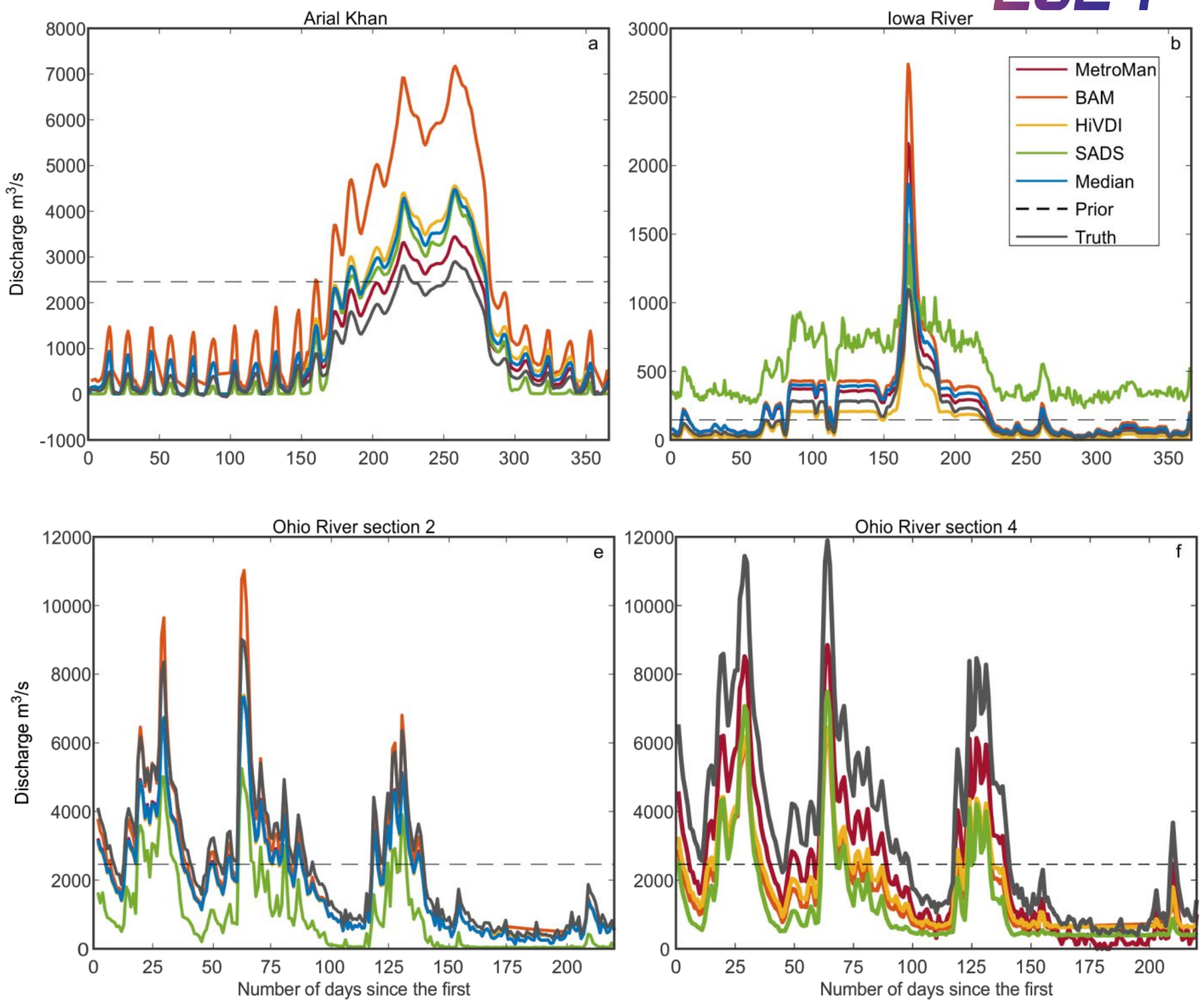


SWOT Discharge algorithm

Because SWOT can measure river width, slope, and water surface elevation, it can be used to estimate discharge using a simple flow equation like Manning's Equation:

$$Q = \frac{1}{n}(\bar{A} + A')^{5/3} W^{-2/3} S^{-1/2}$$

Simulation results suggest that we can expect discharge errors of about 50%, but errors for variations in discharge of about 10-15%.



Implication: we will be able to measure the dynamics of discharge very accurately with SWOT

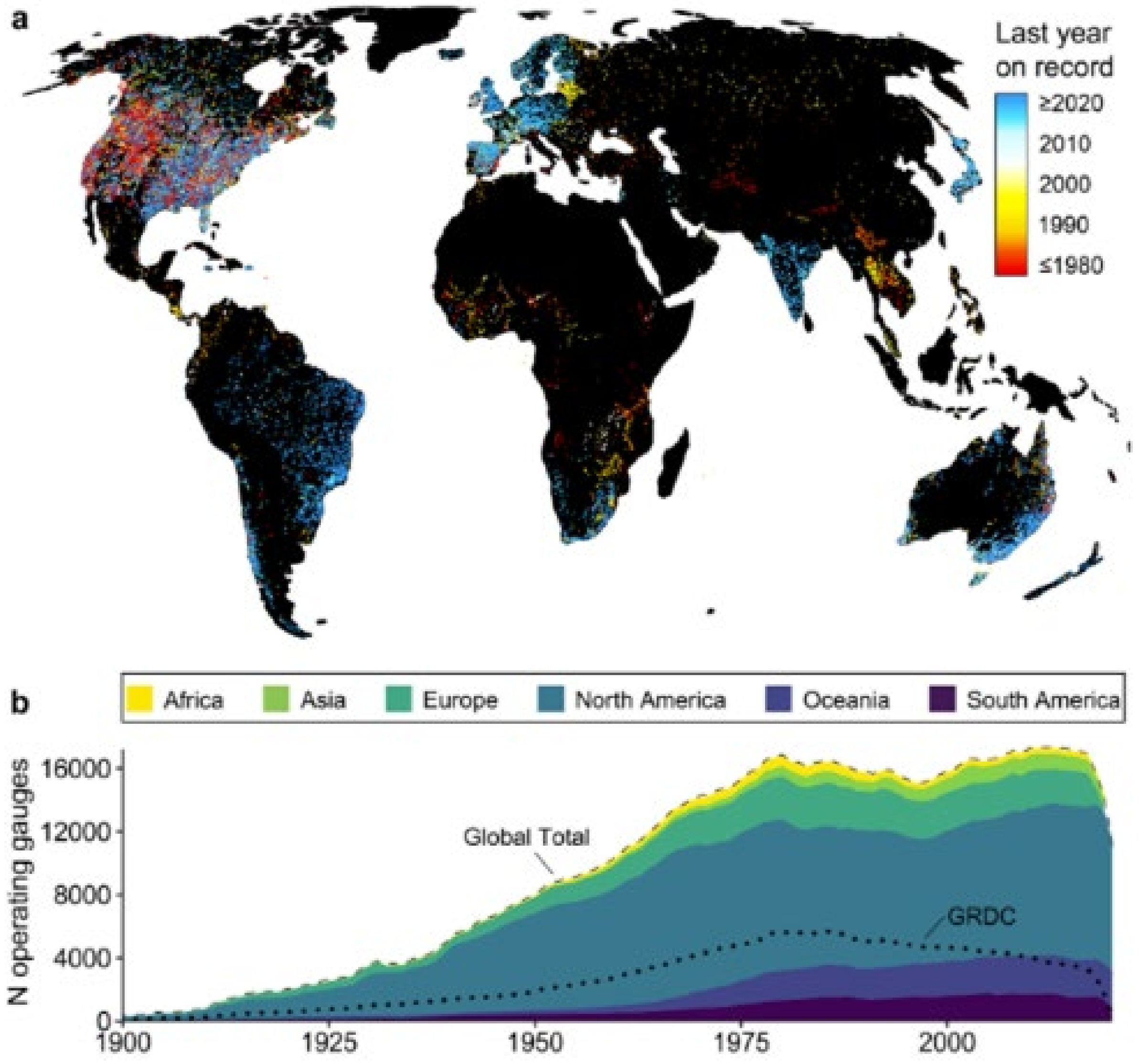
PEPSI 2 Intercomparison challenge *(Frasson et al., 2023)*

How can SWOT Discharge Help Us?

Our current on-the-ground network is good in some places, but not everywhere.

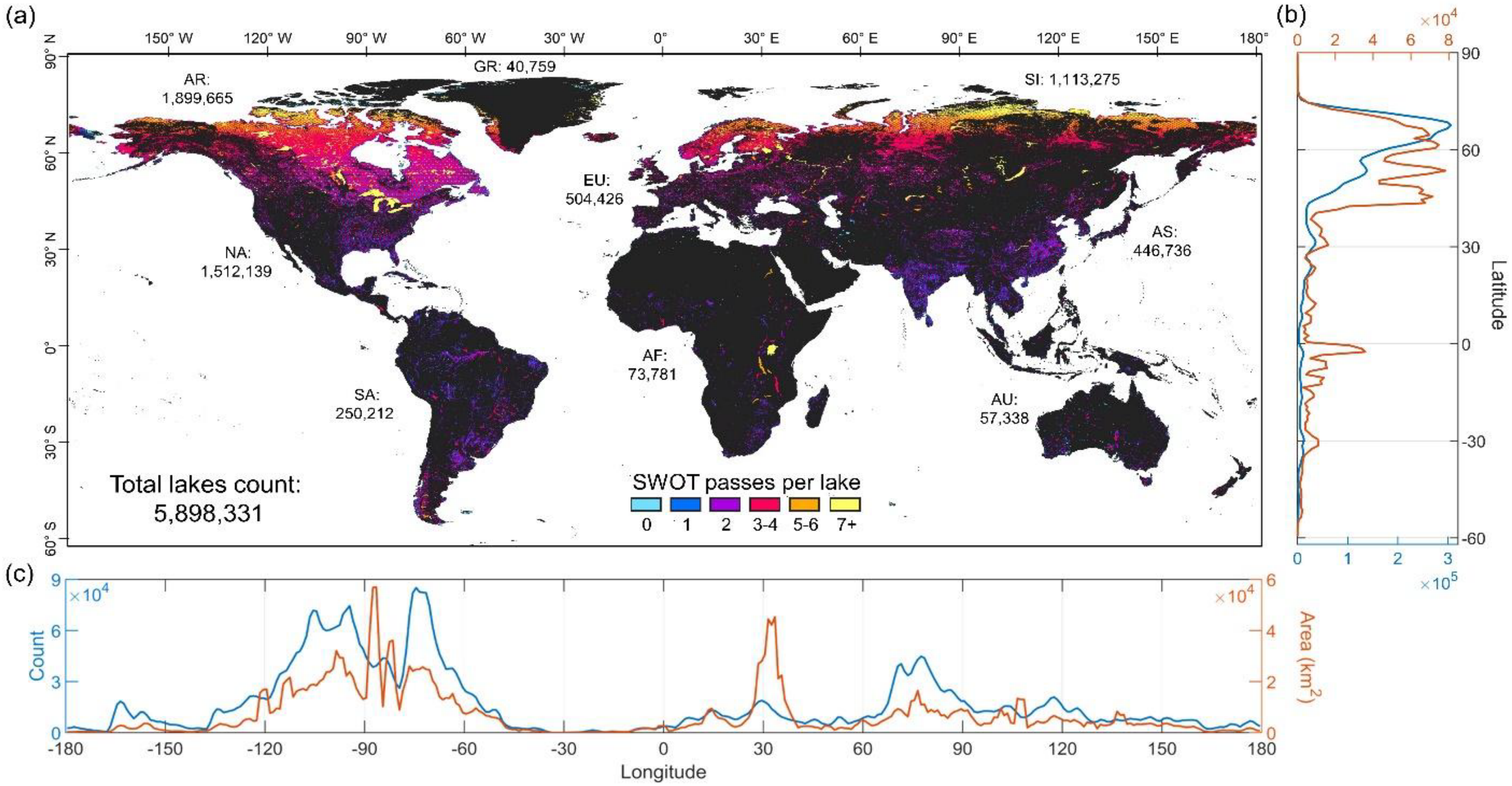
SWOT will not replace these gauges (which measure every 15 minutes!). . .

. . . But having discharge every 1-2 weeks all over the globe would be revolutionary!



Riggs et al., 2023

How can SWOT storage change on lakes Help Us?



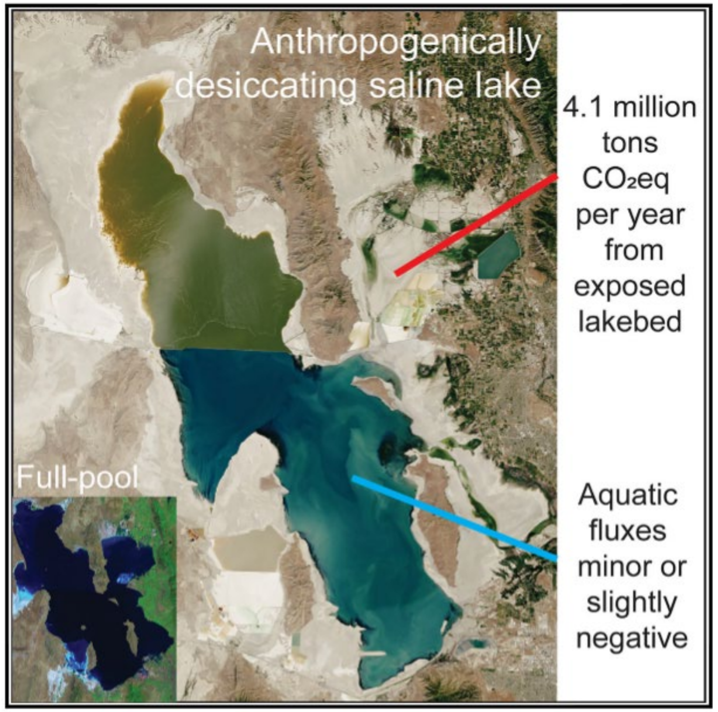
Our current on-the-ground network is good in some places, but not everywhere (same as rivers).

Current remote sensing allows to tracks volume changes of lakes on only few hundreds of large lakes

Millions of small lakes contributes to GhG emission in a way which we cannot yet quantify

Lakes contribute to global water cycle in way which also needs to be quantified precisely

Role of small lakes and saline lakes in GhG emission



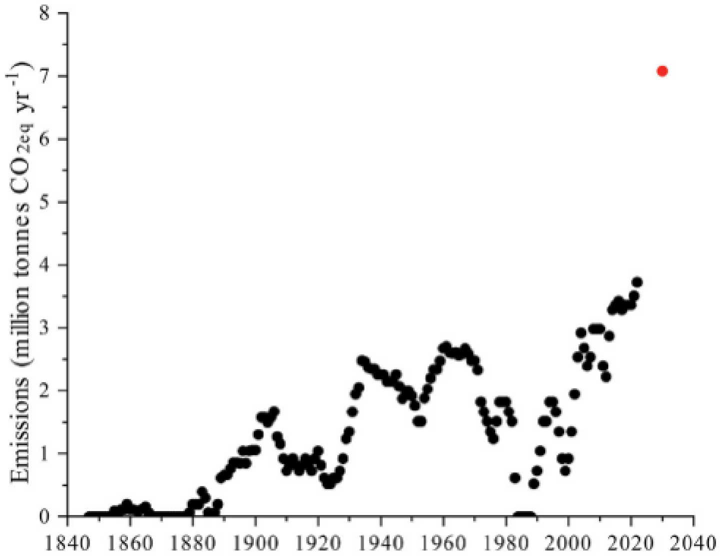
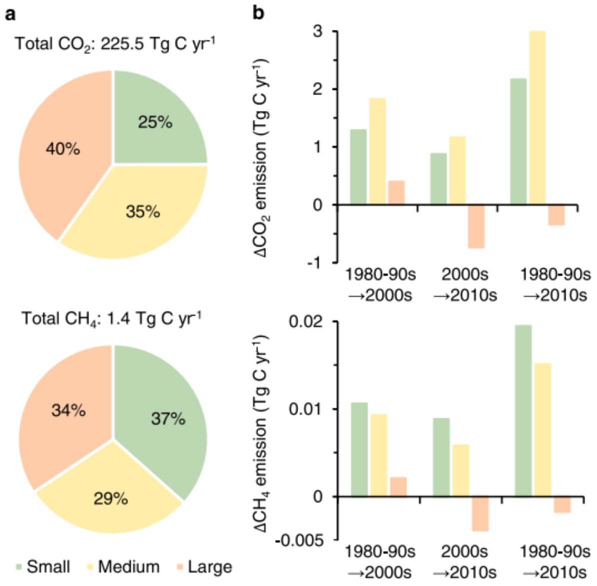


Figure 4. Temporal trend in GSL fluxes

Estimated annual anthropogenic CO_{2eq} release from GSL's dry bed over time (black circles). The red circle represents hypothetical maximum dry-flux rate assuming 100% lake desiccation by 2030.



When lakes dry up, their exposed lake beds become sources of GhG

The degree to which desiccation generates new GhG emissions to the atmosphere has not been fully explored

desiccation of freshwater systems including ponds, potentially due to or exacerbated by anthropogenic climate change, may be increasingly important sources of GHGs to the atmosphere

Mapping of lakes > 0.03 km2 (3.4 Millions) from sat imagery in 3 periods (1980-1999; 2000-2009 and 2010-2019) => allows to examine change in CO2 and CH4 throughout the study period

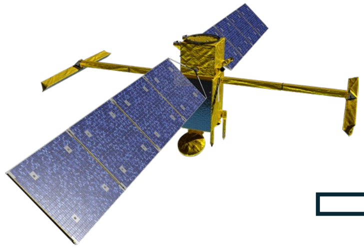
Small lakes (< 1km2) account for 15% of global lake area but showed higher long-term temporal variability than large and medium-sized lakes.

Small lakes is the first contributors of CH4 emissions

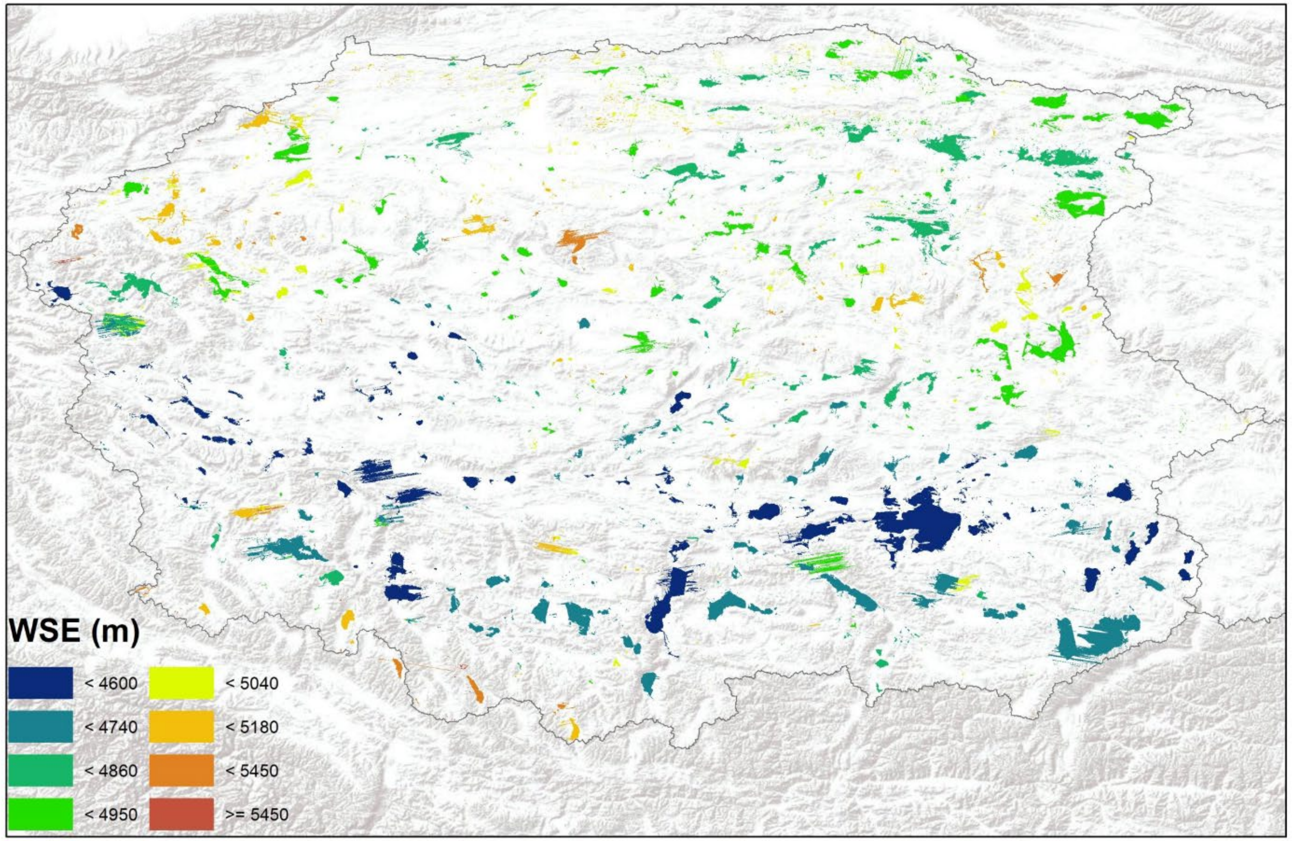
A desiccating saline lake bed is a significant source of anthropogenic greenhouse gas emissions Cobo et al., 2024, One Earth

Mapping global lake dynamics reveals the emerging roles of small lakes Pi et al., 2022, Nature com

SWOT over the Tibetan Plateau’s lakes



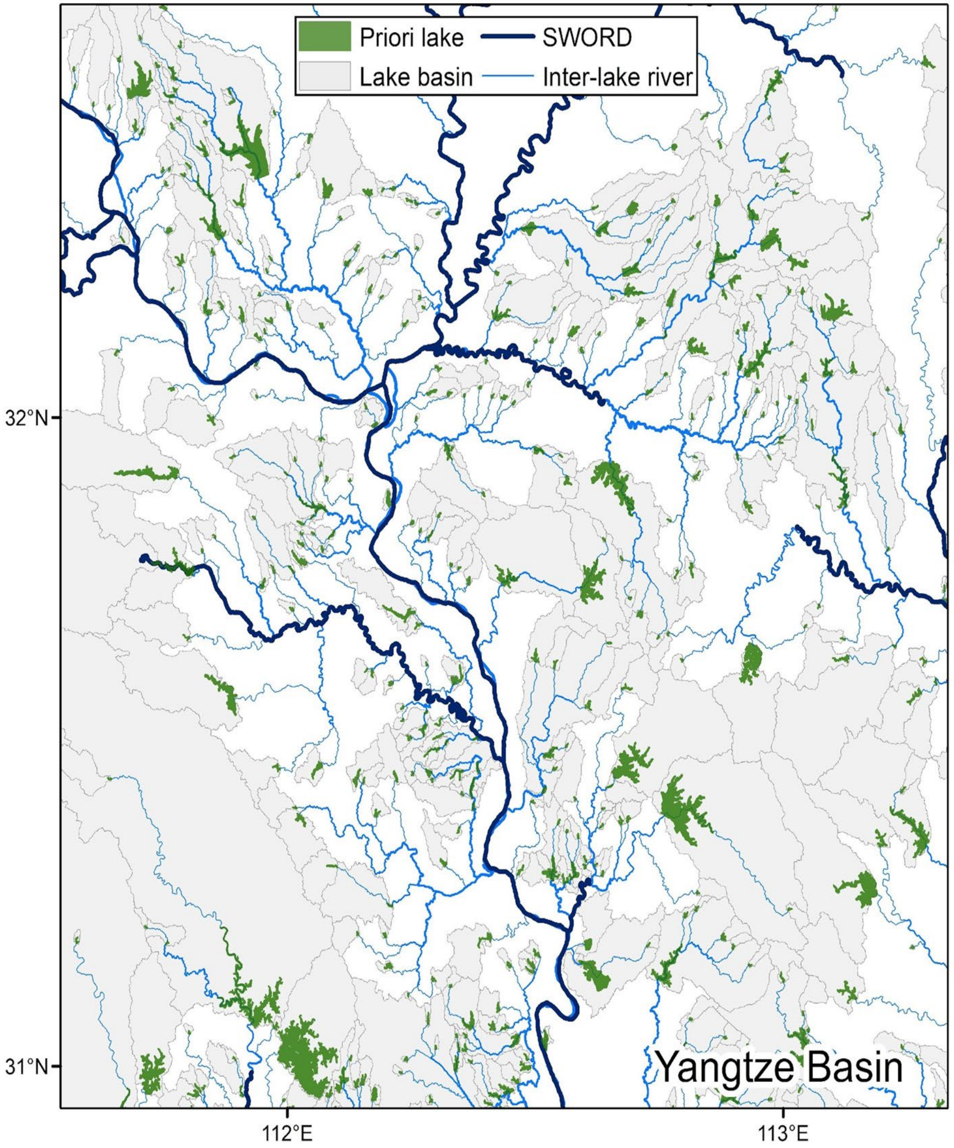
⇨ Comprehensive understanding of lake changes



~95% of lakes larger than 6ha over the TP will be measured using SWOT HR datasets, including small glacial lakes

Courtesy, G. Zhang, CAS

River and lakes connectivity



SWOT-visible lakes and reservoirs segment the global drainage system to 3+ million reaches.

More than 50% of the reaches are shorter than 1.5 km and more than 80% are shorter than 10 km.

Accumulatively, these reaches stretch ~10 million kilometers, at least 4.6 times longer than SWOT-visible river reaches (SWORD).

These results accentuate the roles of water stores in fragmenting river systems.

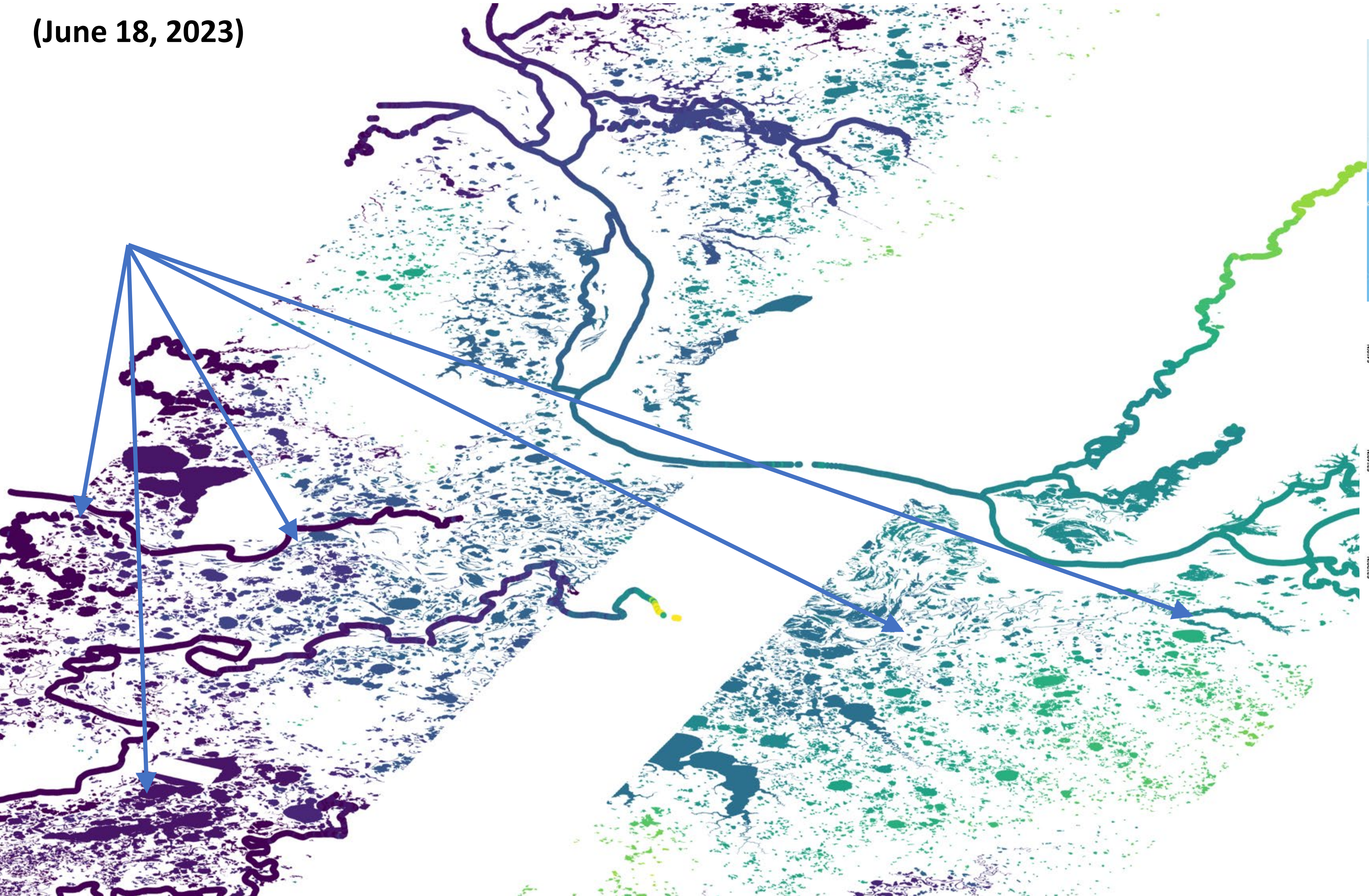
SWOT will teach us: how lake and reservoir storage changes can propagate downstream and modulate river discharge?

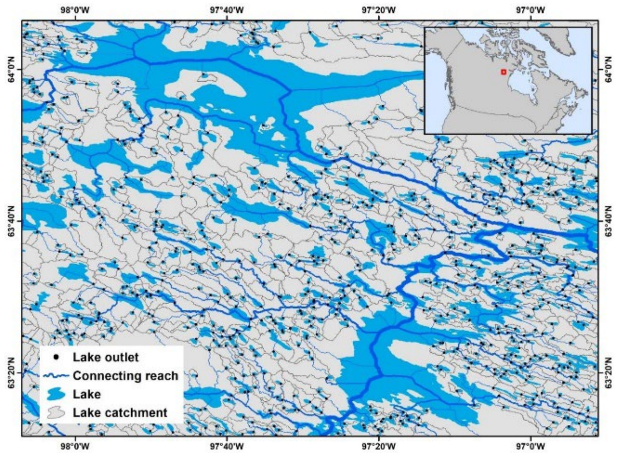
Courtesy, T. Pavelsky

SWOT observation of height over the Yukon river (Alaska),

(June 18, 2023)

SWOT example of 3-D images





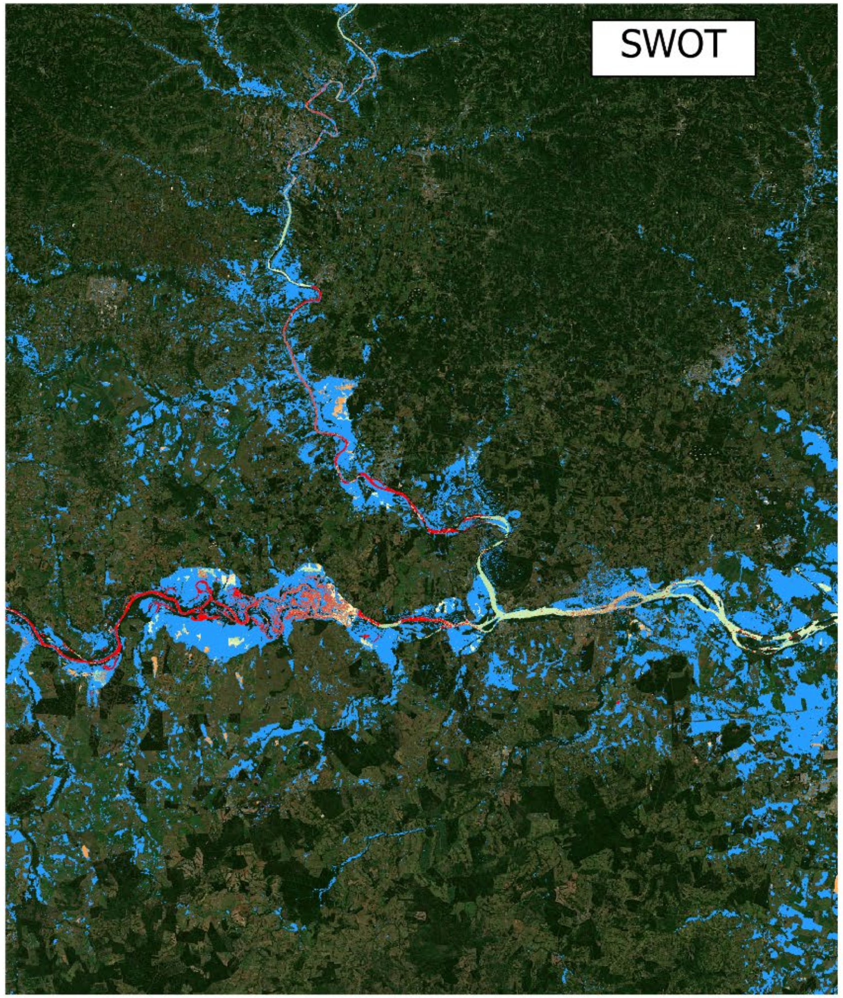
connectivity of lakes and rivers and impacts on discharge?

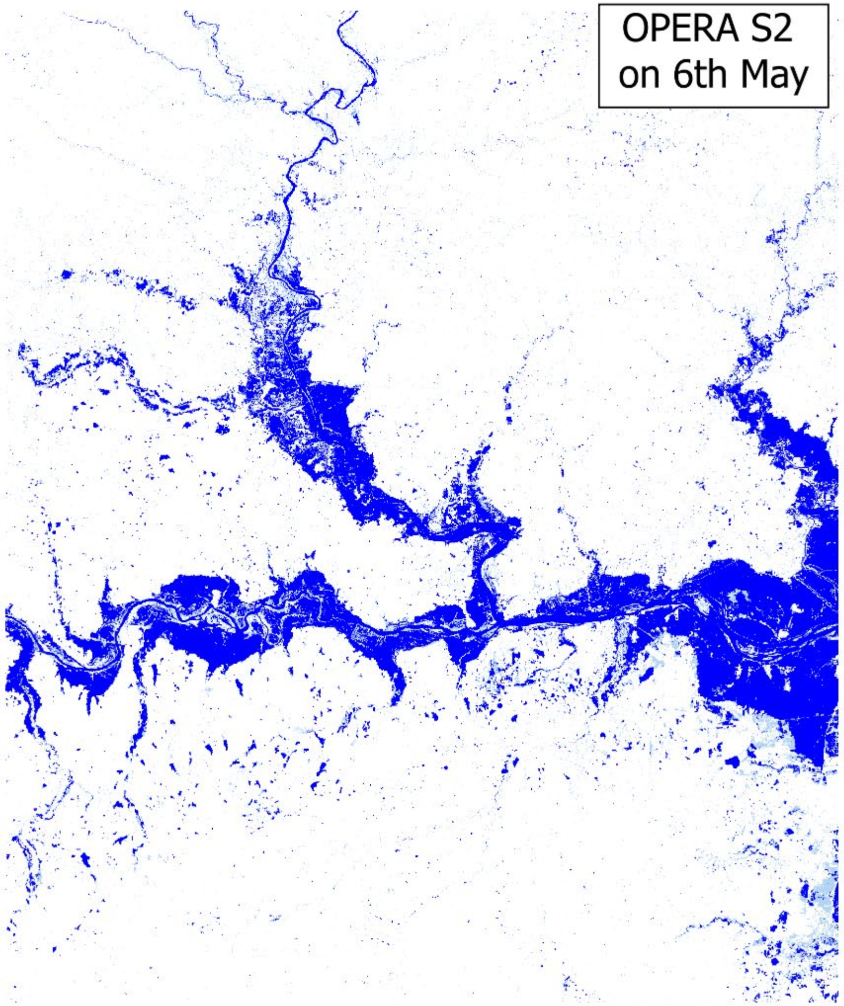
Water height

0 10 100 m

Swot water elevation measured during the flood event in Rio Grande do Sul (Brazil) in Spring 2024

CEDS 2024





SWOT DATA
DIFFERENCE OF WATER ELEVATION (m)
Between 14th of April and 6th of May

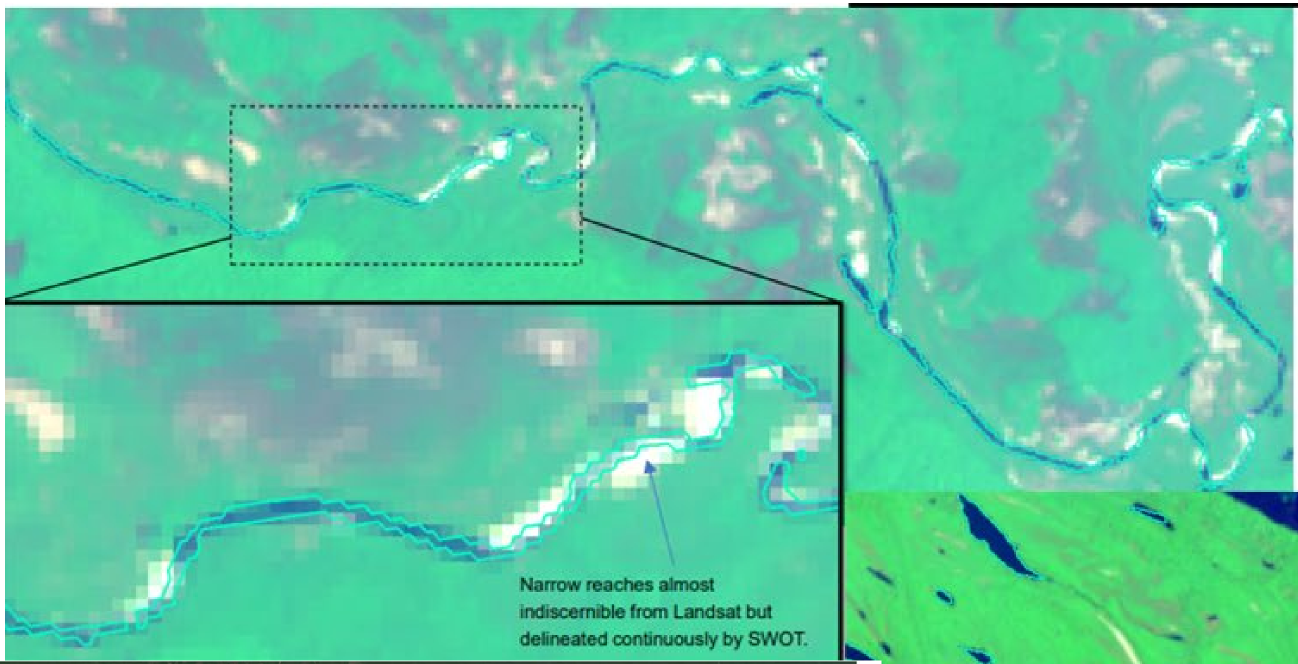
<= 1 | 1 - 2 | 2 - 3 | 3 - 3 | 3 - 4 | 4 - 5 | 5 - 6 | 6 - 7 | 7 - 8 | 8 - 8 | 8 - 9 | > 9

SWOT WATER EXTENT
on 6th of May

Pixel clouds were used with index 4 (open water) and filtering of outliers (20<wse<20m)
Opera image is showing the water mask over the same area and is used to validate SWOT detected water mask

Courtesy, Moreira

SWOT over the Amazon

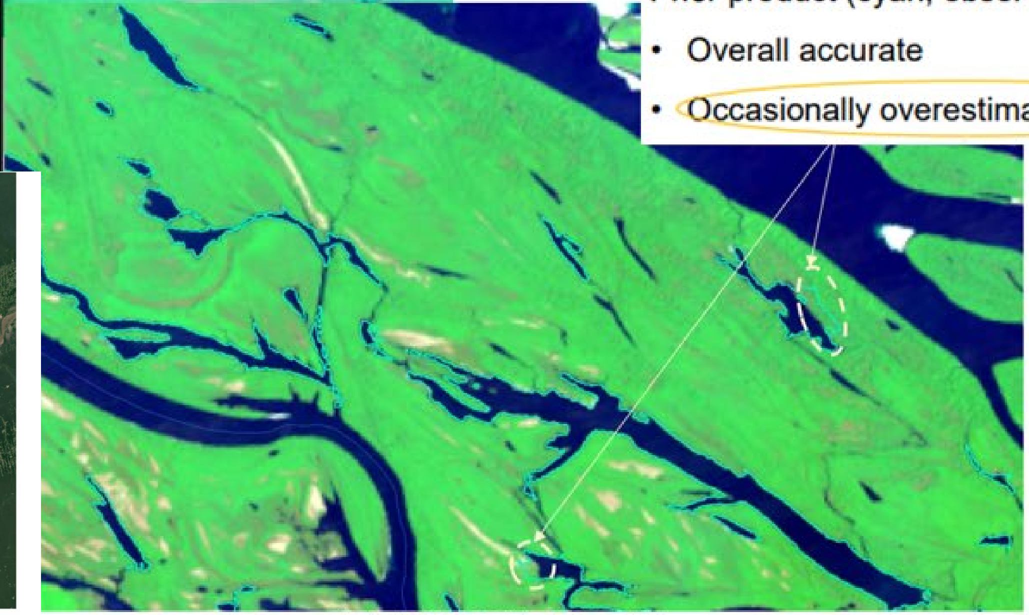


Landsat 8 (02/22/2024), bands 752 as RGB

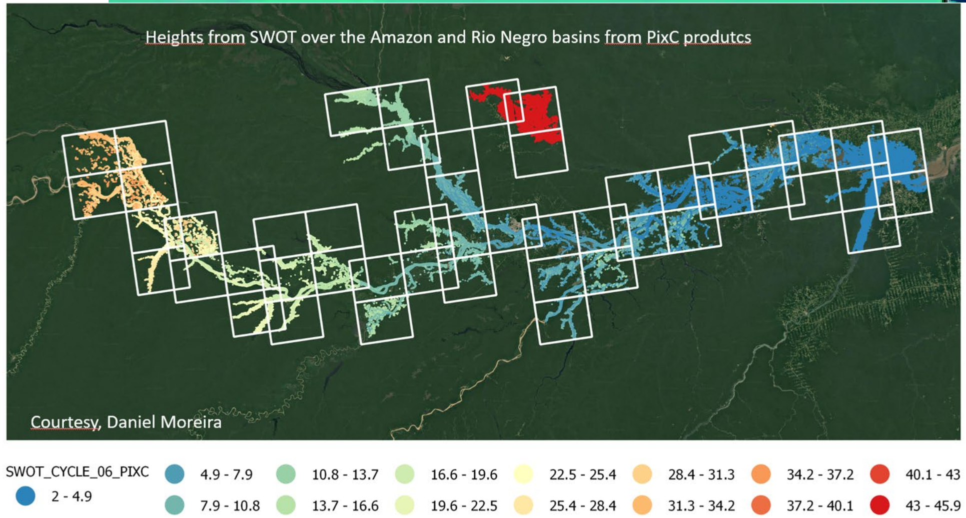
Unassigned observations (cyan polygons) capture quite a lot of the smaller headwater reaches in the Amazon basin.

Another closer look at the normal-quality *Prior* product (cyan, observed 02/14).

- Overall accurate
- Occasionally overestimated (wet soil?)

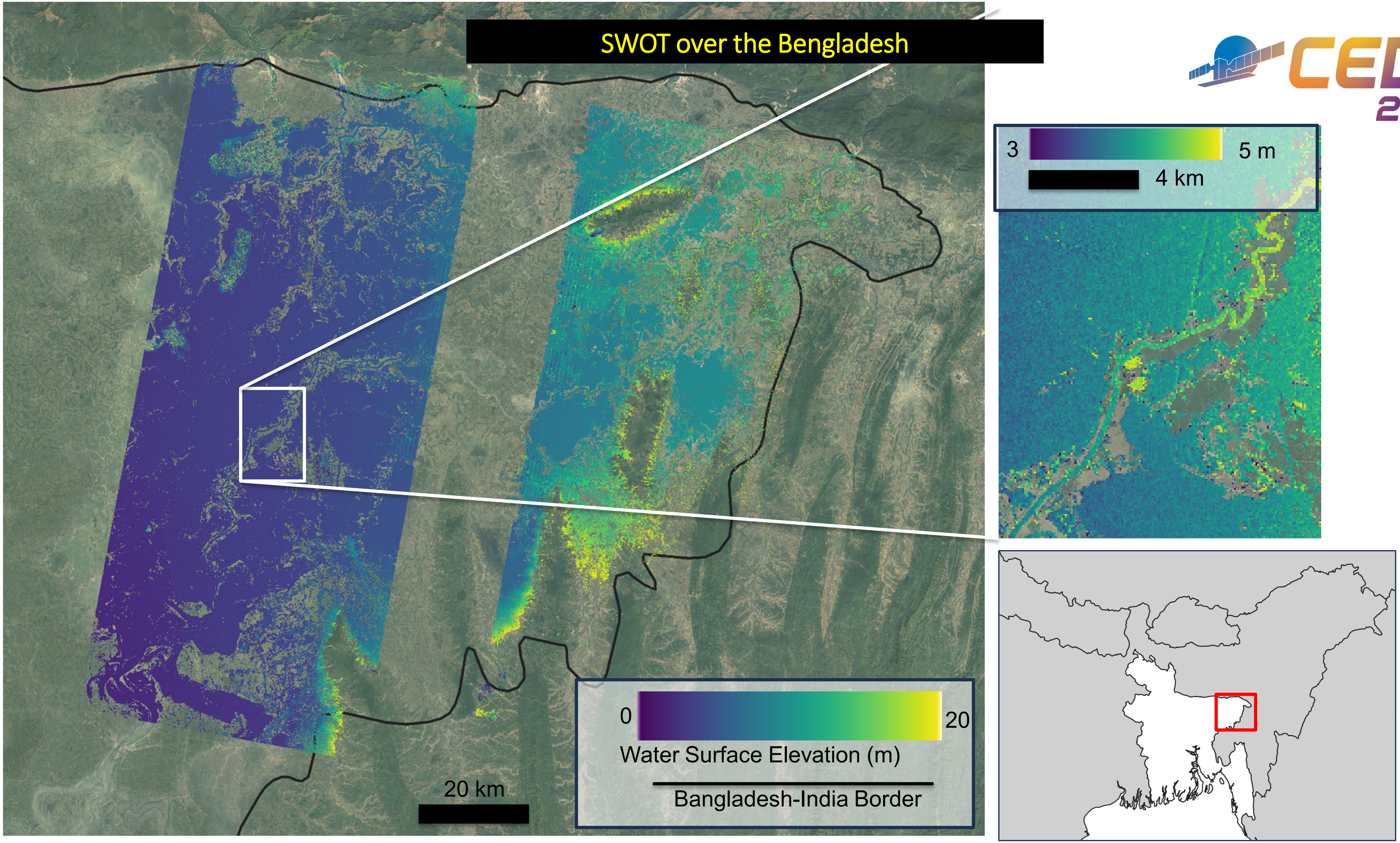


Landsat 8 (02/22/2024), bands 752 as RGB



Courtesy, Wang, Moreira

SWOT over the Bengladesh



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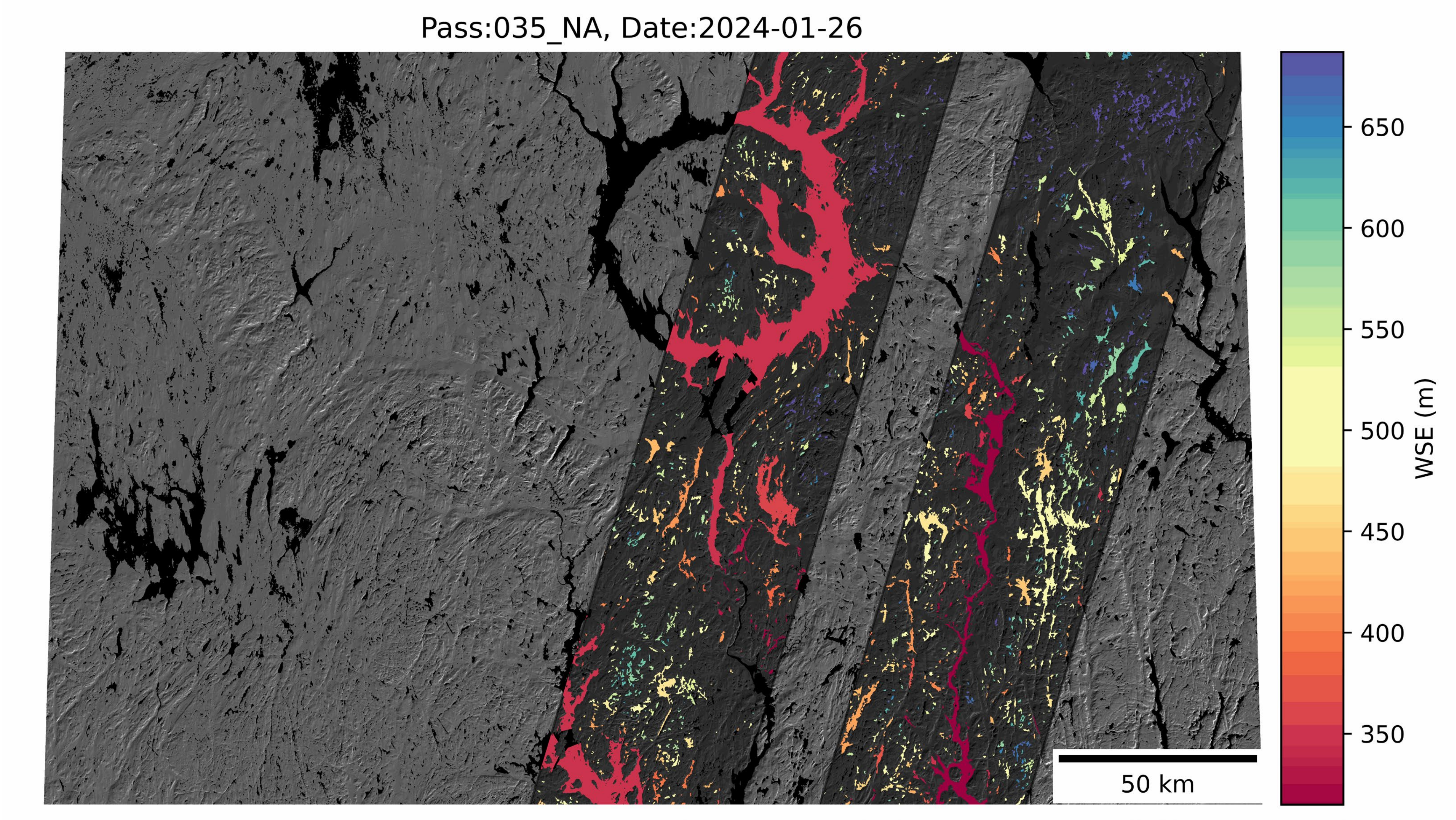
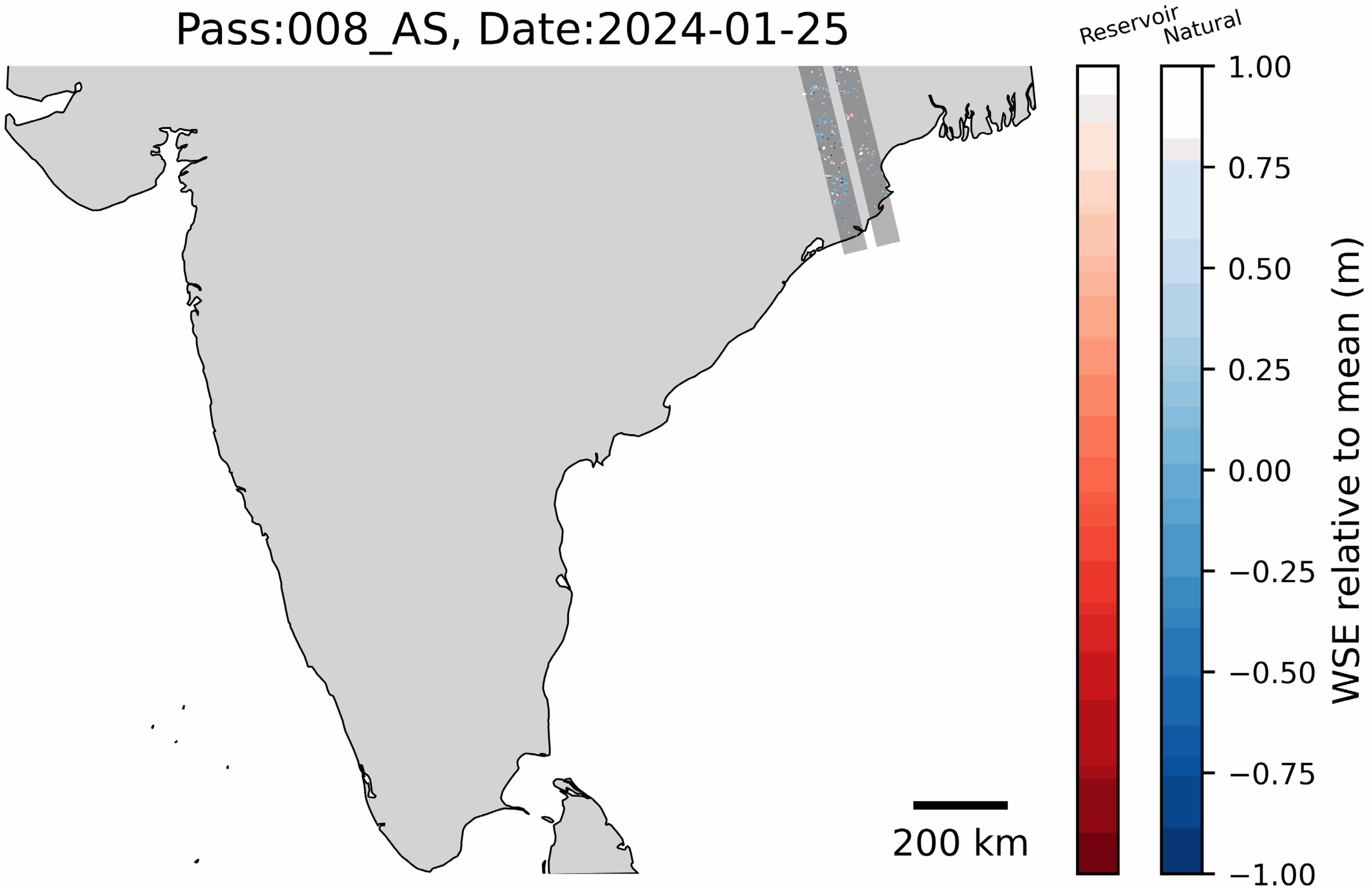
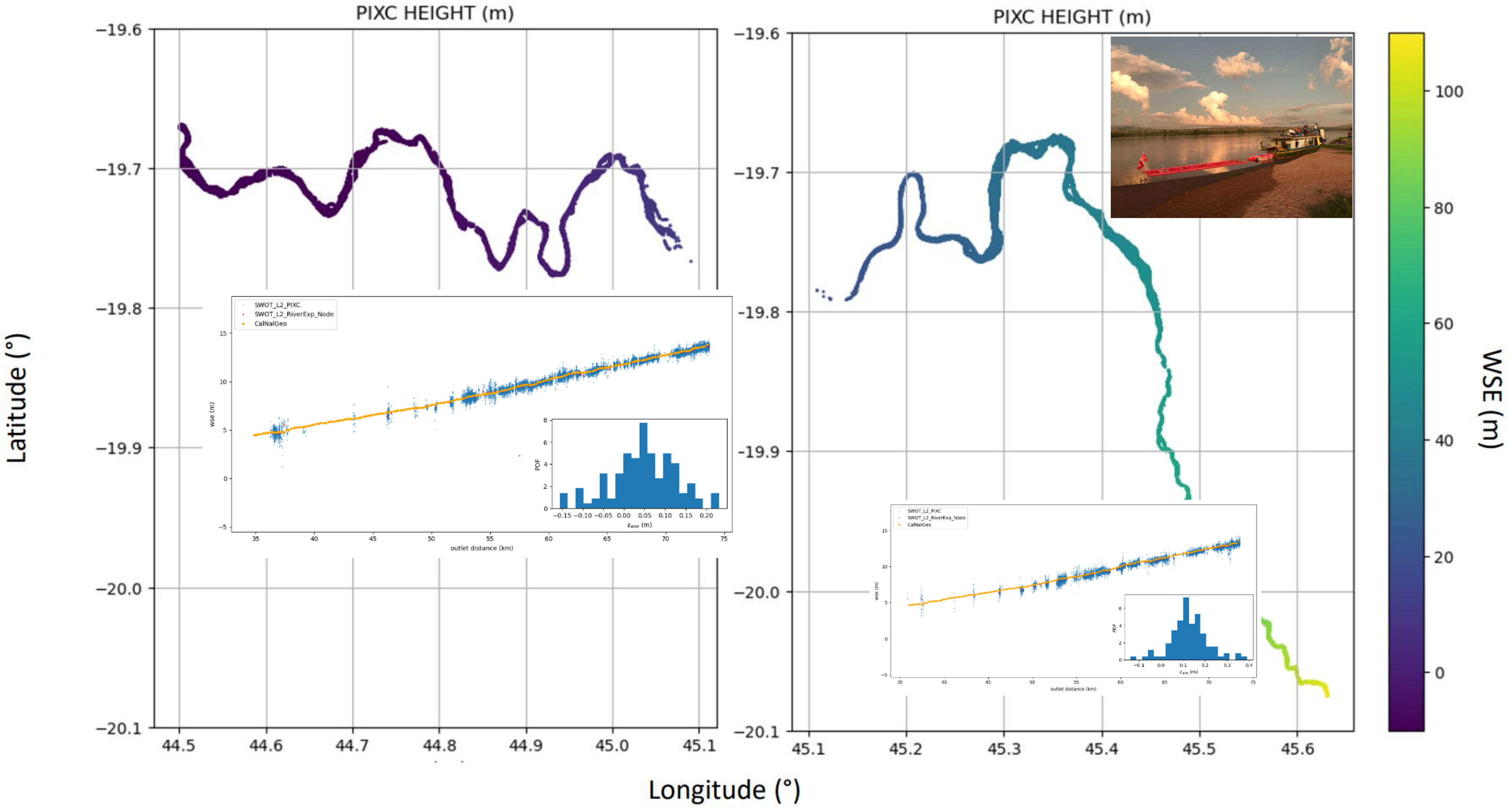
SWOT over the Quebec



Distribution of SWOT observation over India



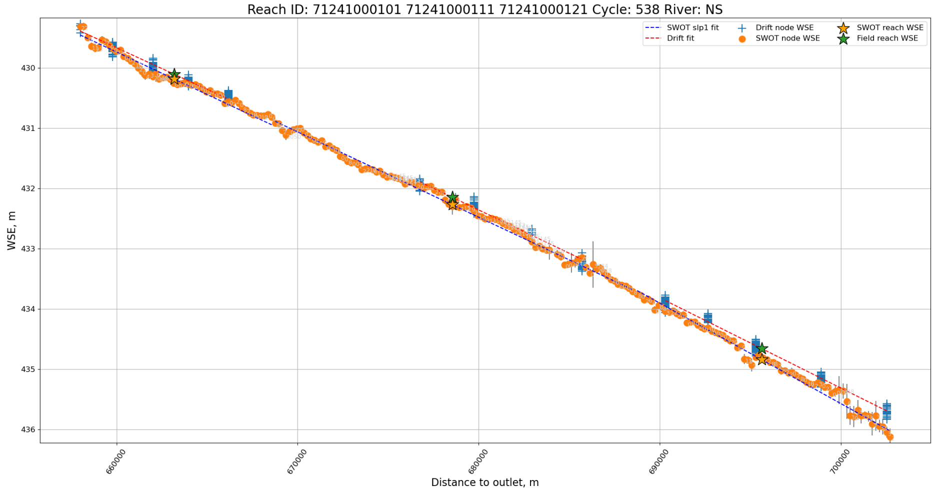
SWOT over a tropical river: Tsiribihina, Madagascar, C/V using GNSS height profiles



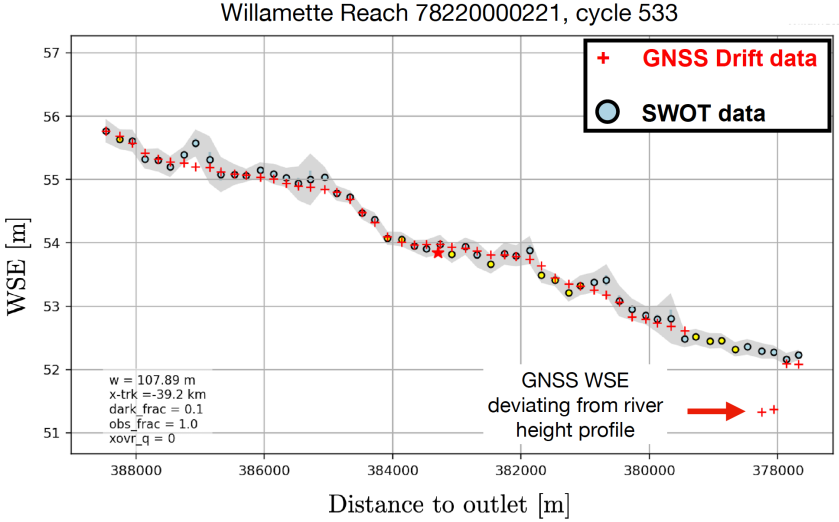
Moreira, Larnier, Garambois, Cretaux et al., in prep

SWOT Profile of ~45 km of the North Saskatchewan River

Water Surface Elevation



Distance Along River

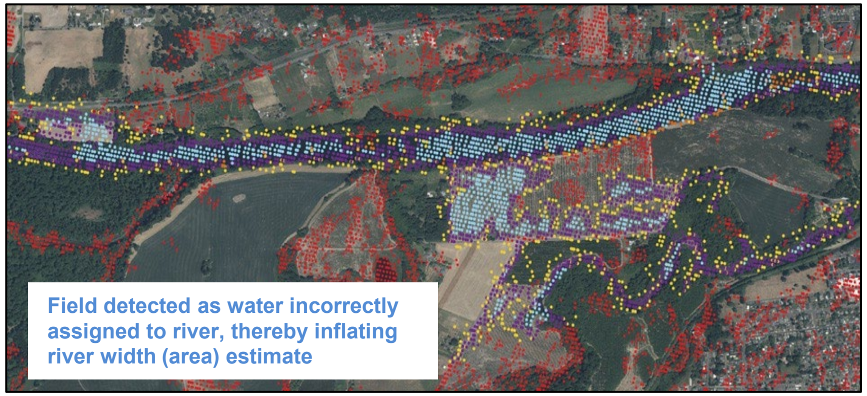


Water detection’s issues with SWOT

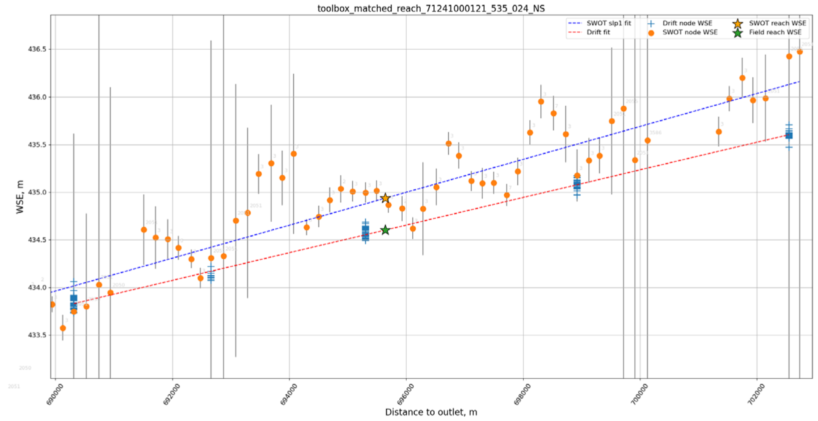
Problem #1: Bright Land

Classification

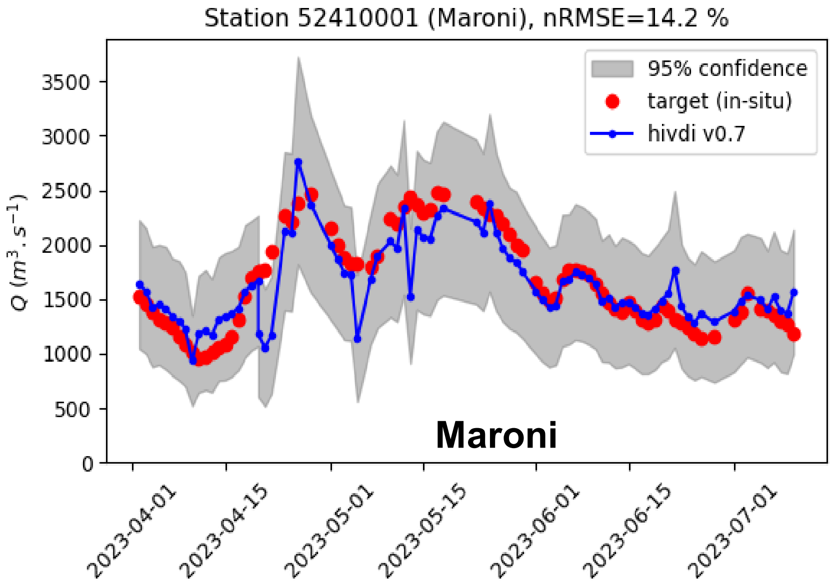
- No data
- Land
- Land near water
- Water near land
- Open water
- Dark water
- Low-coherence water near land
- Open low-coherence water

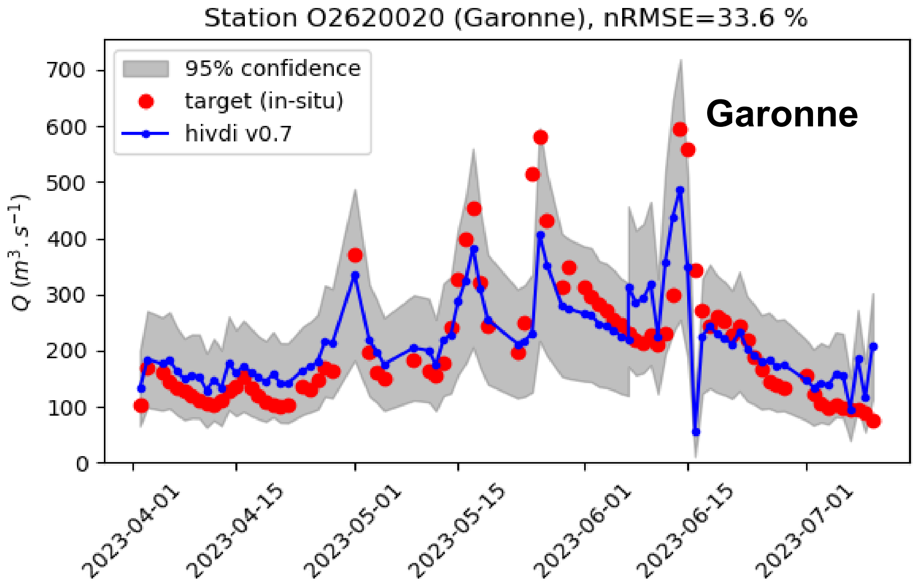


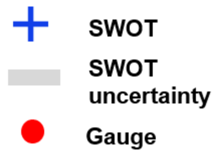
Problem #2: Dark water



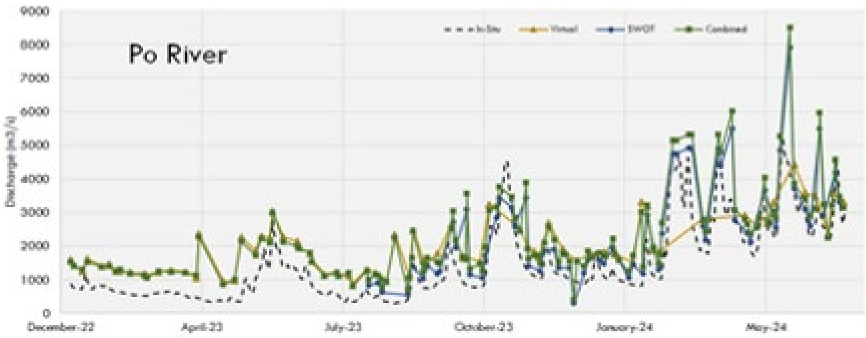
Preliminary SWOT Estimates of River Discharge







Preliminary results of SWOT discharge are promising, but we have lots of work left to do to understand SWOT's capabilities and limitations in this area.

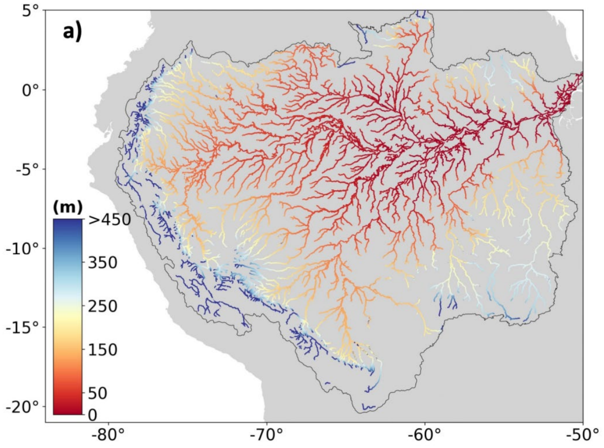


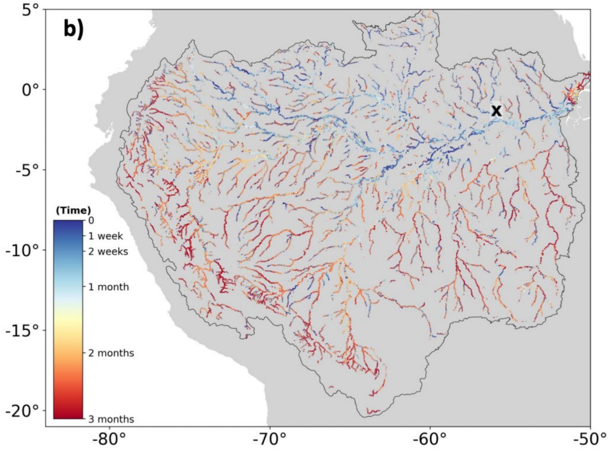
Discharge estimation using SICFLOW using SWOT and multi-mission data, on the Po River.

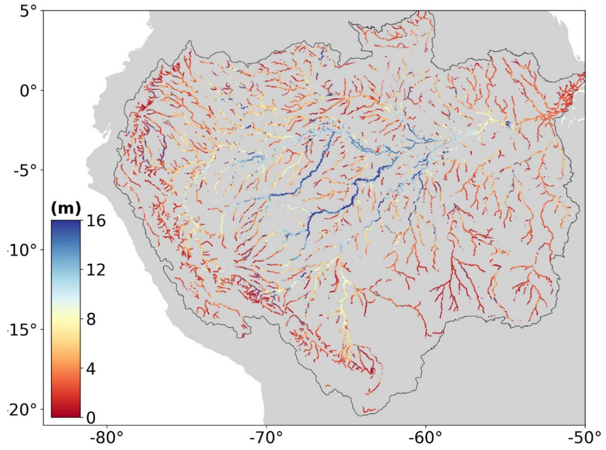
Courtesy K. Larnier, P-A. Garambois, J. Monnier, P-O Malaterre, H. Oubanas

Widespread and Exceptional Reduction in River Water Levels Across the Amazon Basin during the 2023 Extreme Drought Revealed by Satellite Altimetry and SWOT

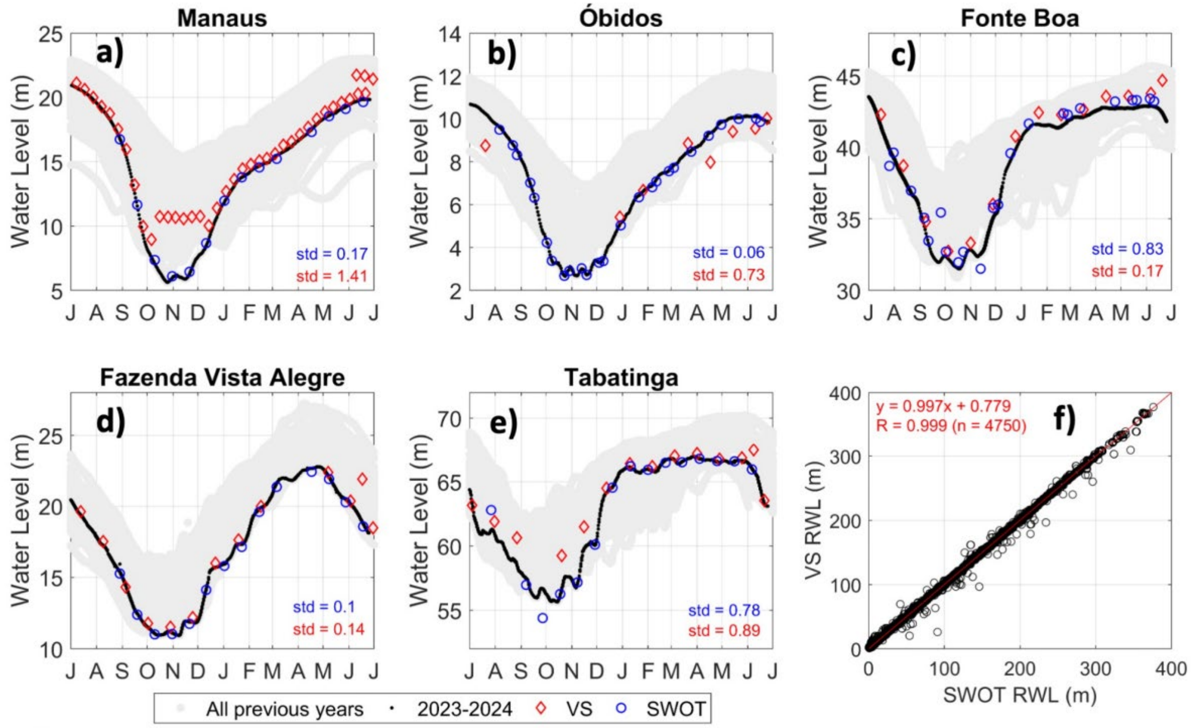
CEDS 2024







a) Minimum River Water Levels recorded from SWOT in 2023. b) Time difference between the minimum RWL at each SWOT node and that at Obidos station. c) annual amplitude of water level recorded from SWOT during the first year of data

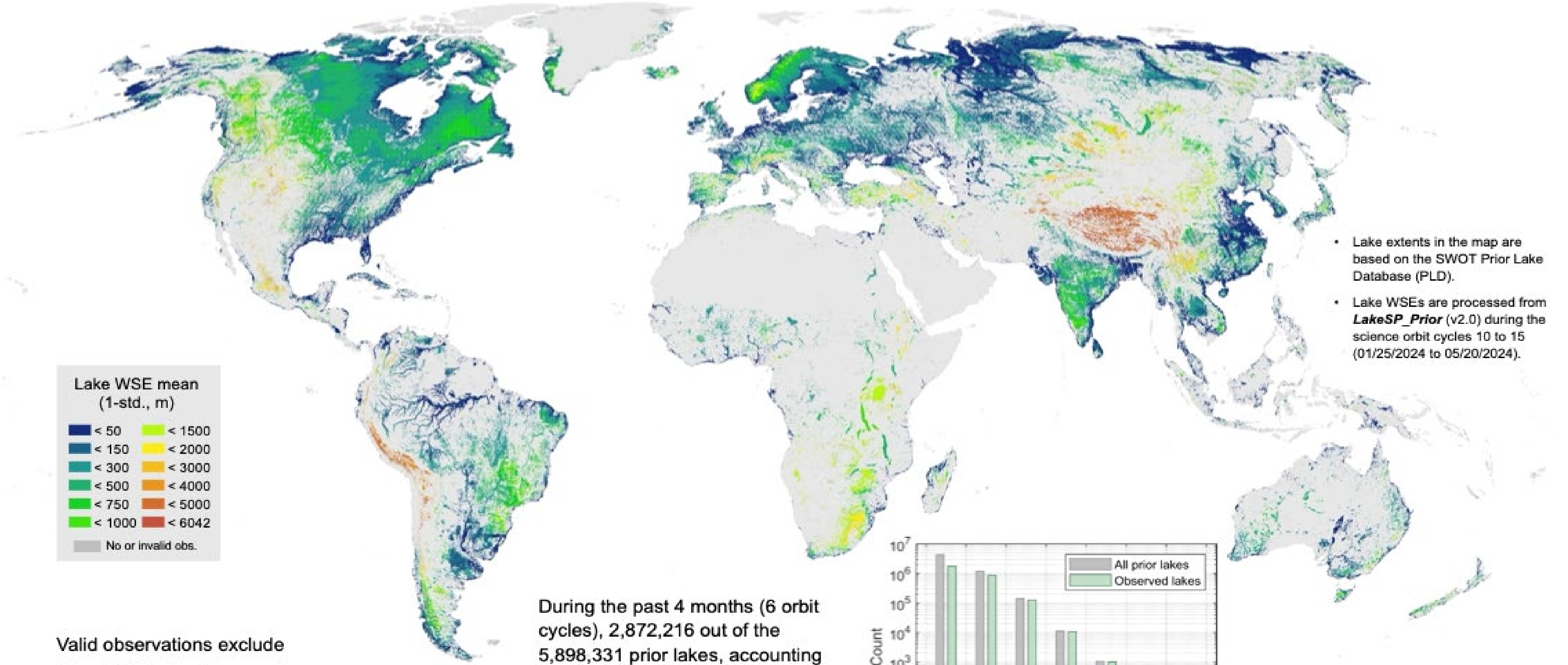


a-e) July to June annual variations (light grey lines) of daily River Water Levels at 276 five gauging stations from 1970 to 2022. The dotted black line is for July 2023 to June 2024, along with River Water Level estimates from nadir altimetry at Virtual stations (red diamond) and from SWOT (blue circle). f) Scatterplot between River Water Level estimates from Virtual Stations and SWOT during the drought period (October and November 2023, 4,750 manuscript submitted to Geophysical Research Letters)

Moreira, Papa et al., 2024

Global lake survey from SWOT (1/2)

SWOT-measured **mean water surface elevation** on global lakes during January to May 2024

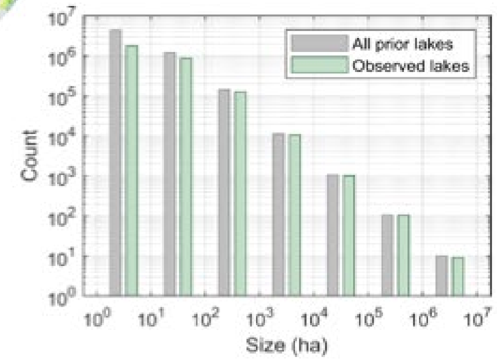


- Lake extents in the map are based on the SWOT Prior Lake Database (PLD).
- Lake WSEs are processed from ***LakeSP_Prior*** (v2.0) during the science orbit cycles 10 to 15 (01/25/2024 to 05/20/2024).

Valid observations exclude

1) statistical outliers, and
2) off-nominal measurements.

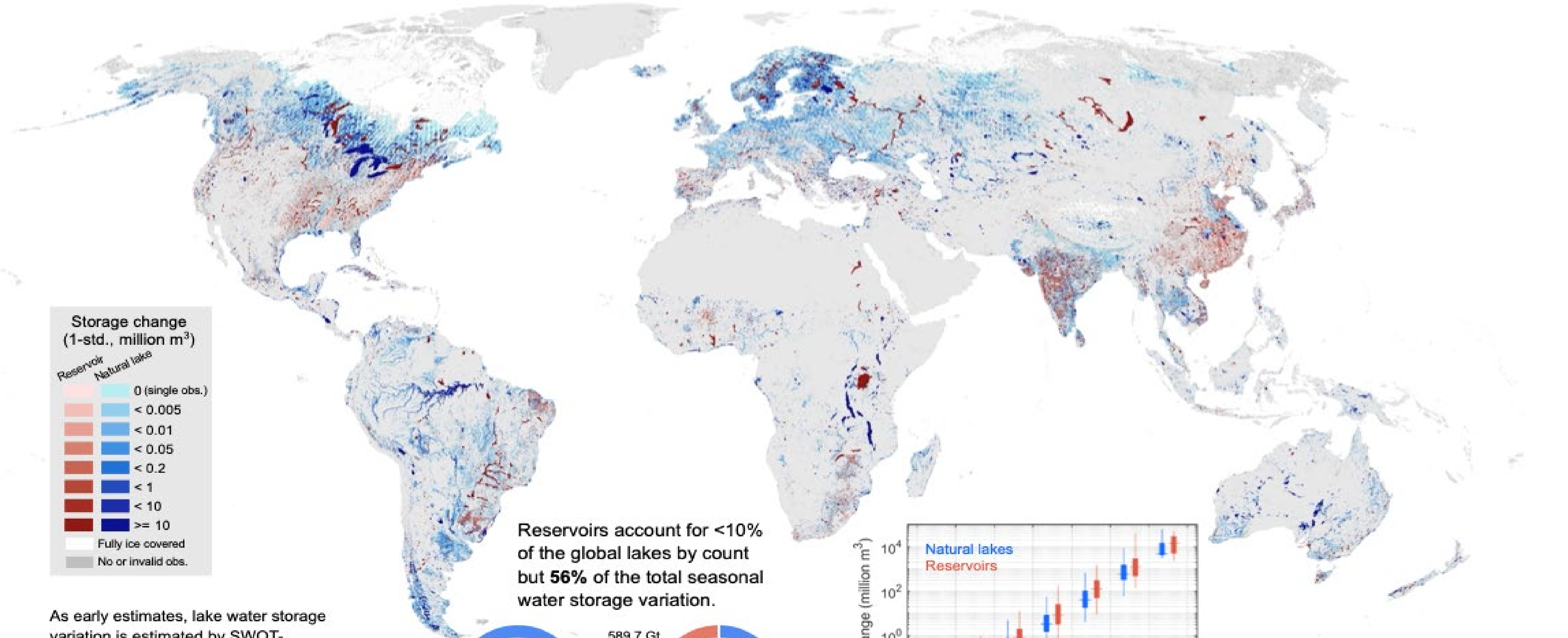
During the past 4 months (6 orbit cycles), 2,872,216 out of the 5,898,331 prior lakes, accounting for **89% of the global lake area** with a minimum size of 1 ha, were observed with at least one valid measurement by SWOT.



Jida Wang (U of Illinois), et al.

Global lake survey from SWOT (2/2)

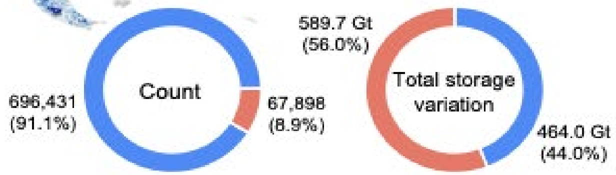
A first look at global **lake storage changes** from SWOT (January to May 2024)



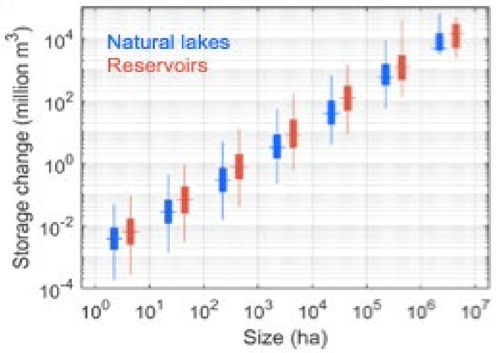
As early estimates, lake water storage variation is estimated by SWOT-measured WSE variation multiplied by the static prior lake area.

More accurate, realistic results will become available with the accumulation of SWOT data.

Reservoirs account for <10% of the global lakes by count but **56%** of the total seasonal water storage variation.



Lakes with only one measurement are excluded from change statistics.



Reservoirs experience ~70–220% **more seasonal storage variation** than natural lakes due to direct human water management.

Jida Wang (U of Illinois), et al.

SWOT – An ambitious and challenging mission

SWOT is addressing various questions in hydrology

It required a significant international effort in the preparation of the mission, and now have a high number of applications in different research areas

Preliminary results look very promising for measuring water surface elevations and inundation extents in rivers and lakes (and oceans).

It provides first global estimation of storage changes and river discharge

It contributes to the understanding of the role of continental water in global water cycle and climate change.

It provides dense coverage of ungauged basins, for surveying the role of continental water in water cycle and climate change, with many potential applications (scientific and societal) in Africa in particular

We still have a long way to go to fully understand SWOT's capabilities.

CEDS 2024

eventos.cmm.uchile.cl/ceds2024

Global Gateway

UNIVERSIDAD DE CHILE

fcfm FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS UNIVERSIDAD DE CHILE

CMM Center for Mathematical Modeling

Copernicus LAC Chile

Thank you for your attention