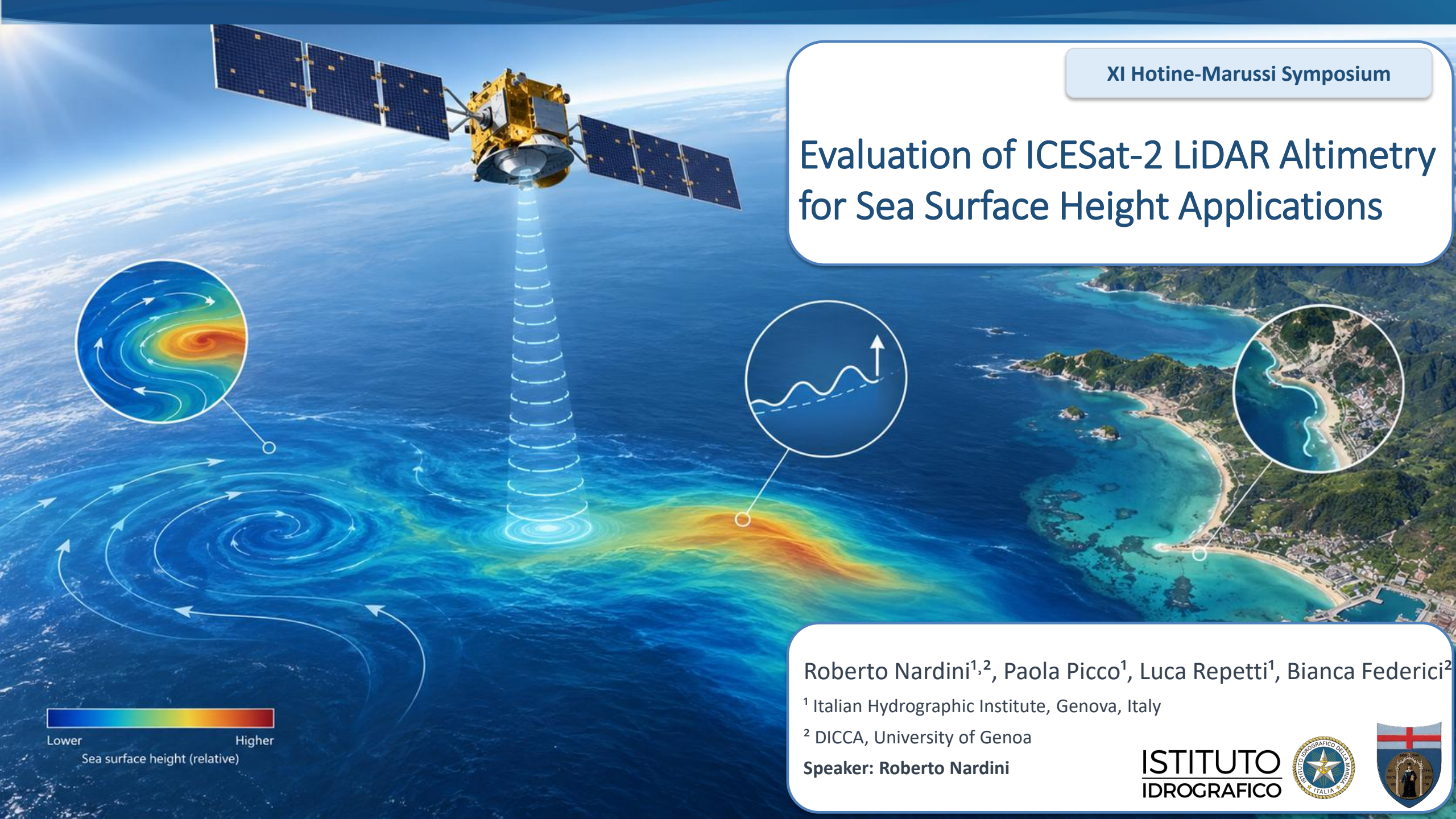


Evaluation of ICESat-2 LiDAR Altimetry for Sea Surface Height Applications



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Speaker: Roberto Nardini

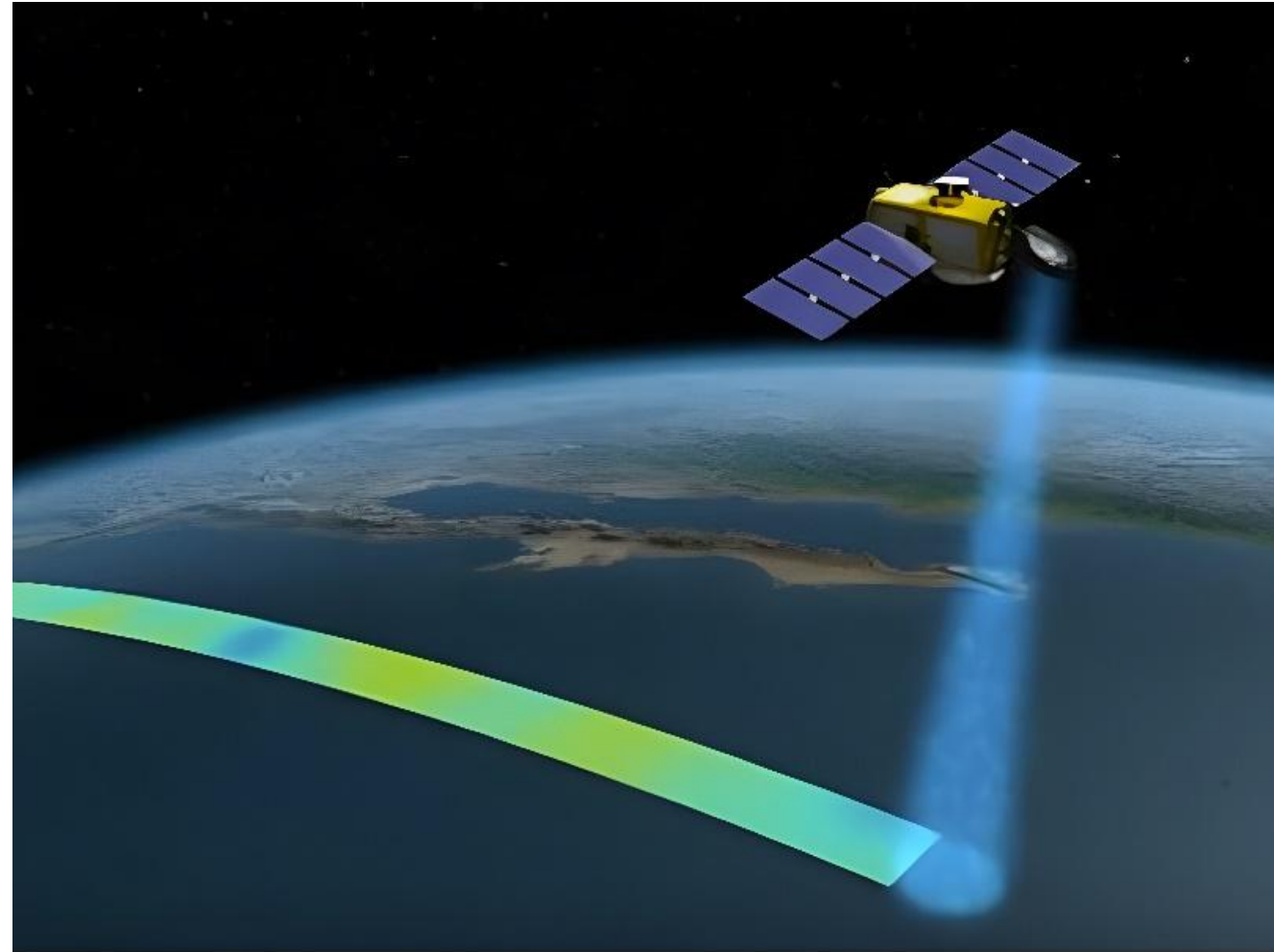
ISTITUTO
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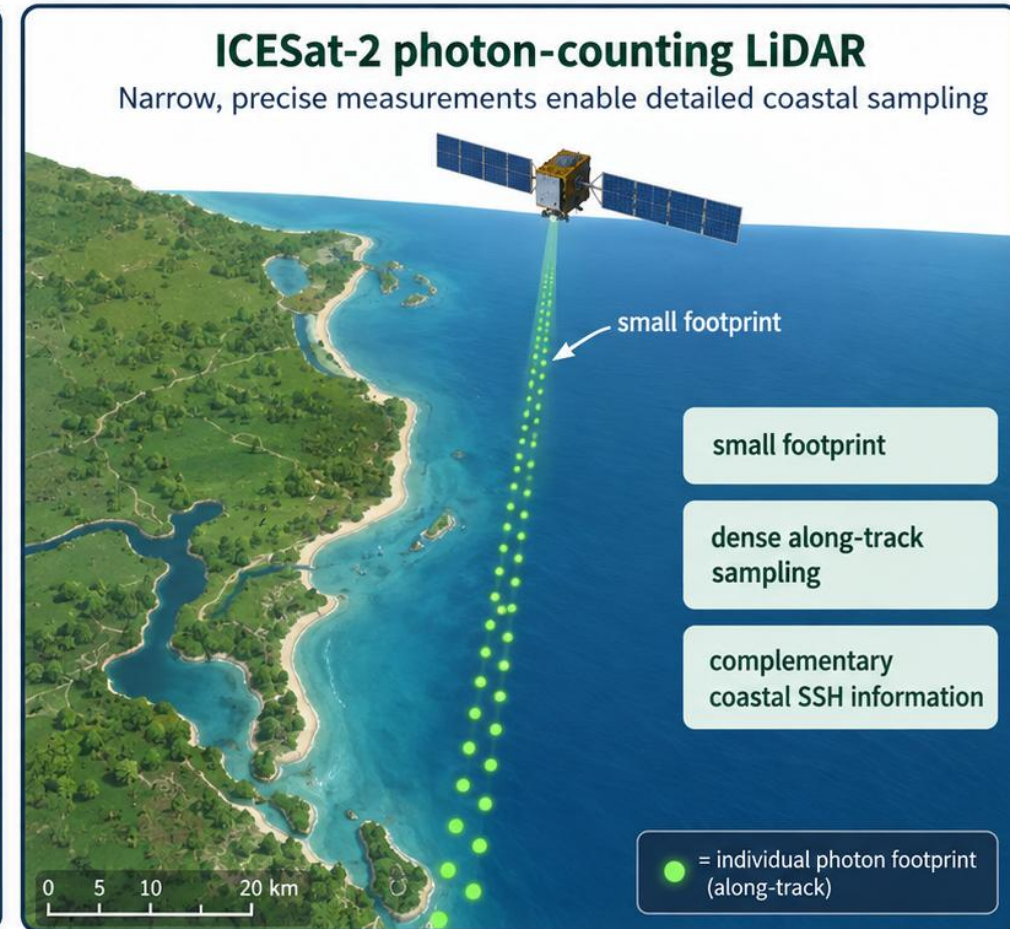
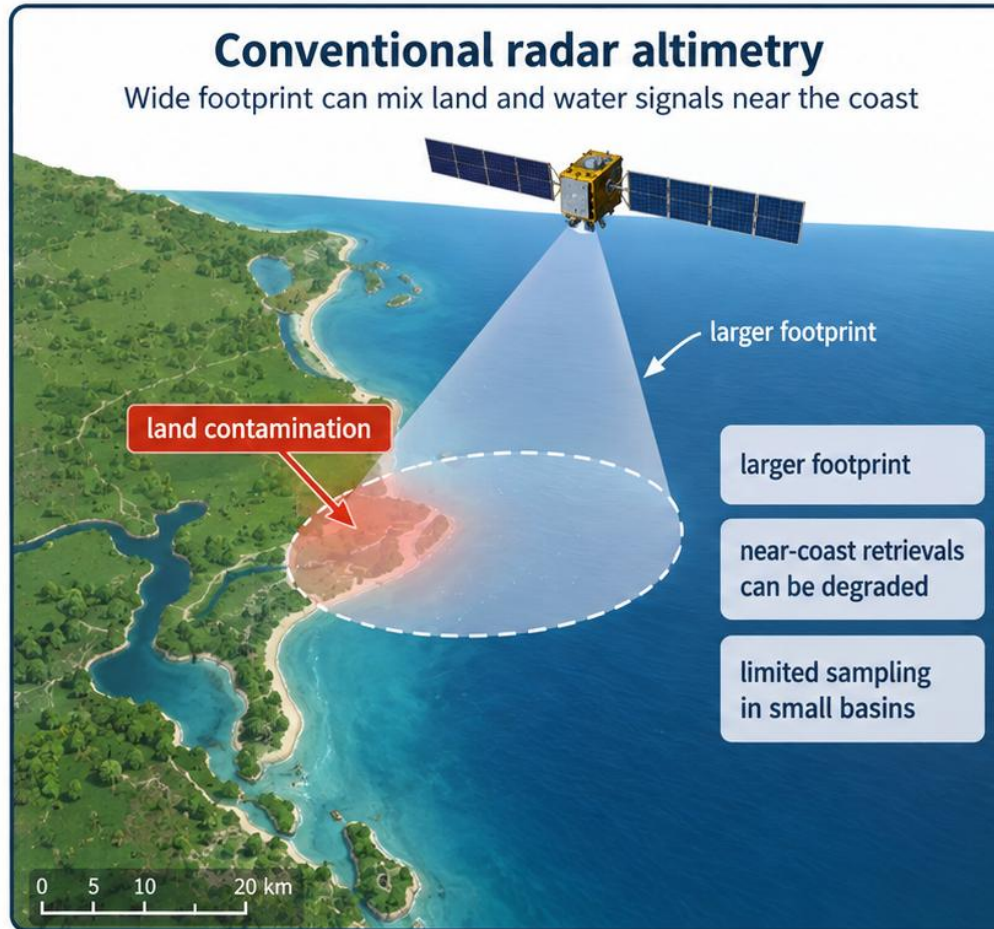
Satellite Altimetry Overview

- Satellite altimetry is a fundamental tool for studying sea surface topography and ocean circulation.
- Applications:
 - Ocean circulation
 - Sea level rise
 - Coastal monitoring
- Key features:
 - Global coverage
 - High accuracy
 - Long-term records

Global coverage • high accuracy • long records



Why ICESat-2 for Coastal and Semi-Enclosed Basins?

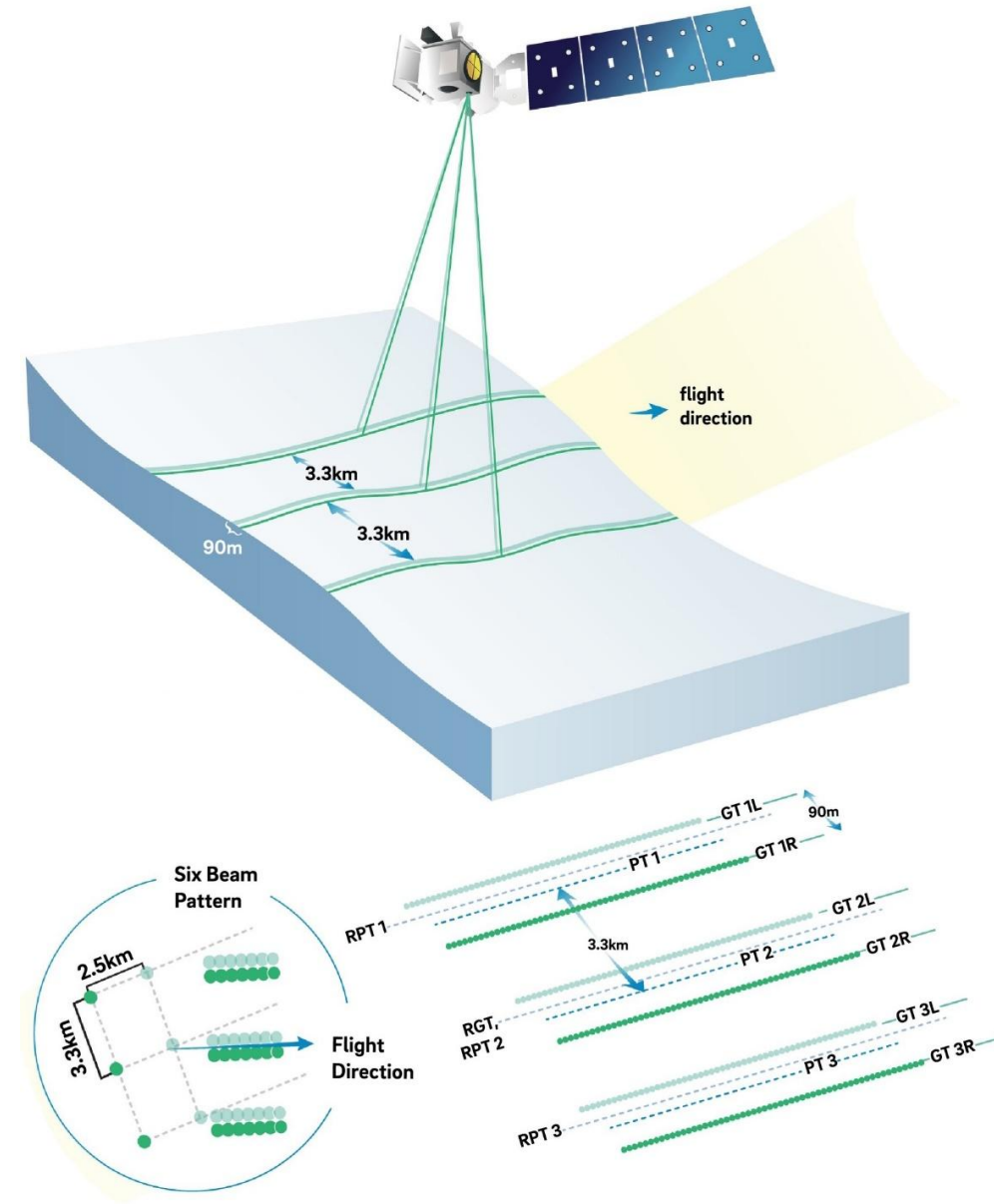


Complementary – not a replacement

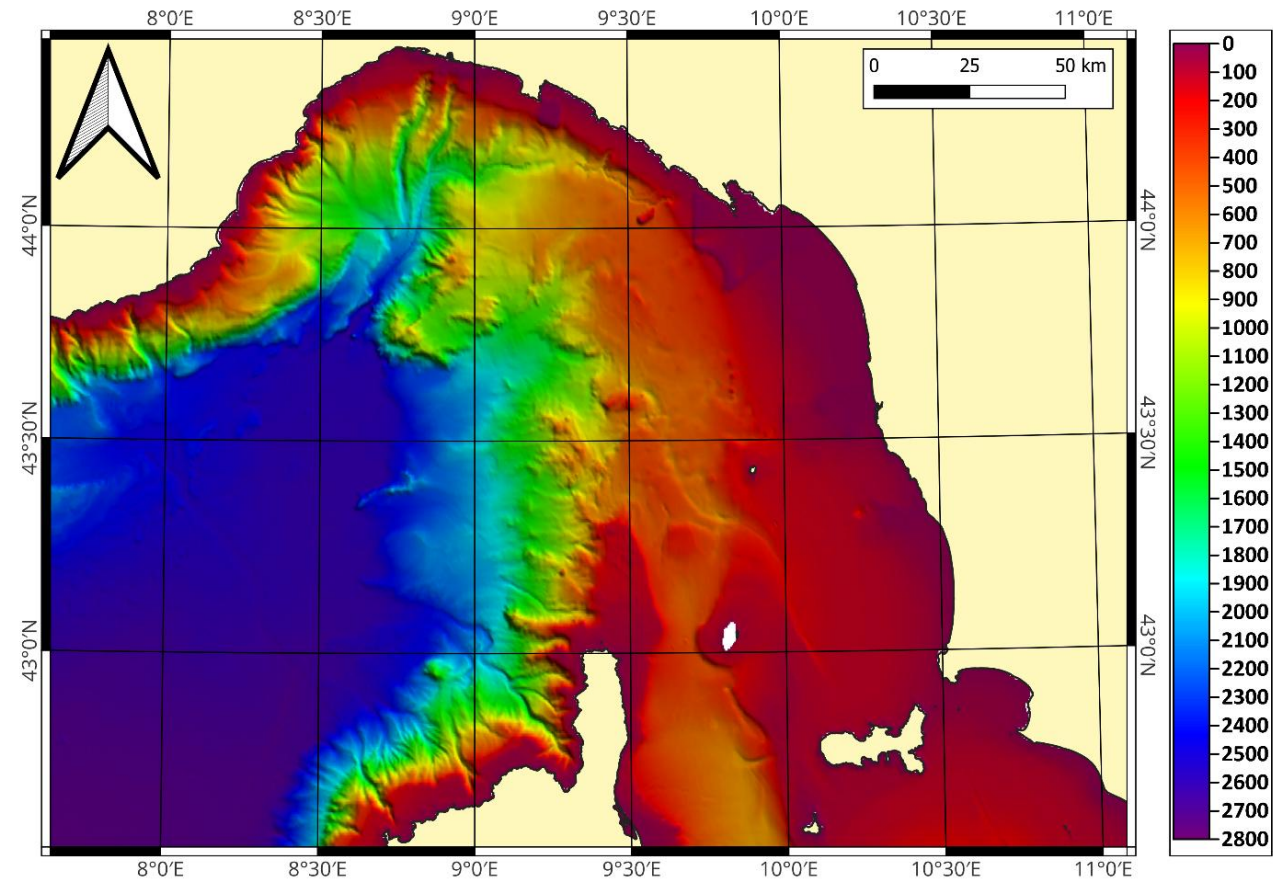
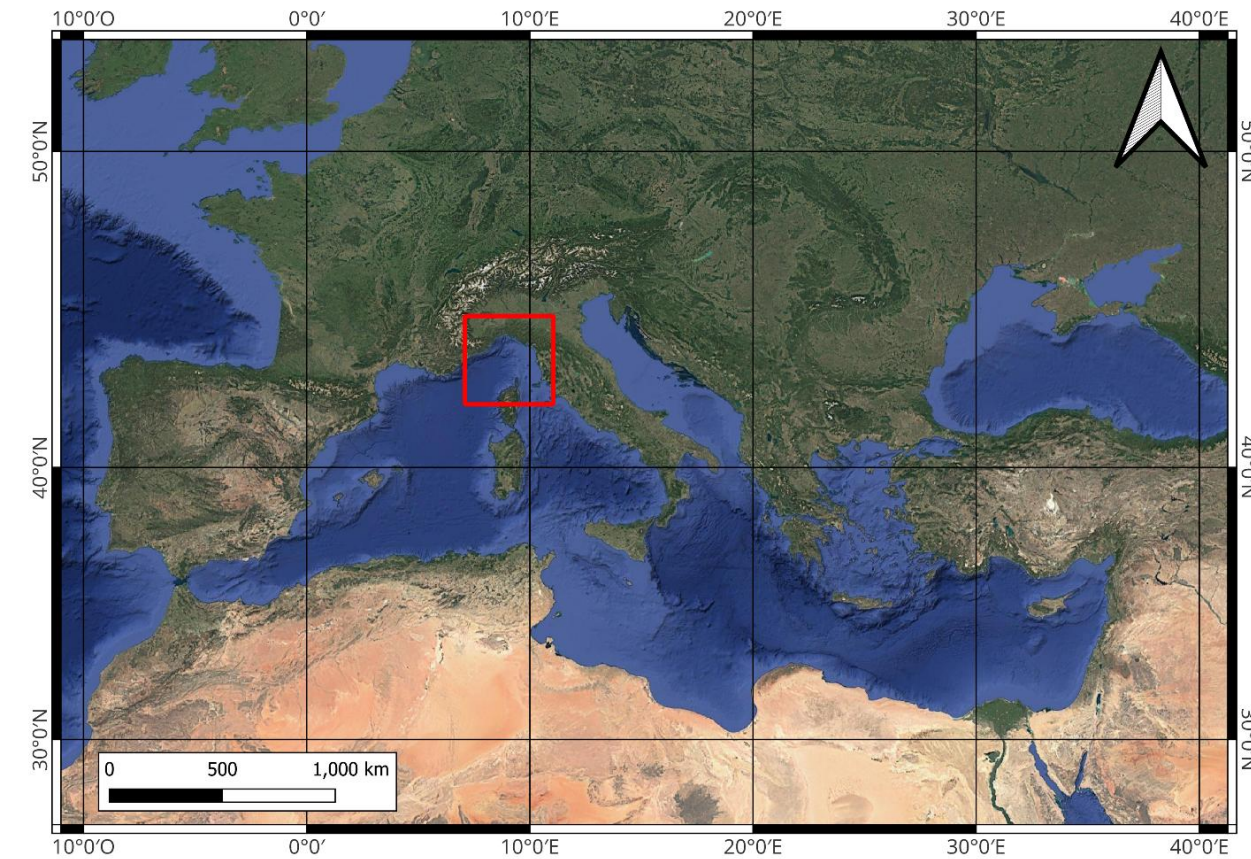
Different measurement principles, strengths, and spatial scales — together they provide a more complete picture of coastal and semi-enclosed basins.

ICESat-2

- Launch: 15 September 2018 (NASA)
- Original goal: Estimation of volume change of polar ice sheet
- Equipment: spaceborn photon counting LIDAR (ATLAS)
- 6 Laser Beams: 3 pairs (Weak/Strong) distanced 3.3 km
- Pulse Repetition Rate: 10 kHz
- Wavelength: 532 nm (Green) that can penetrate water
- 91-day revisit time over the same ground point
- 70 cm along-track photon sampling

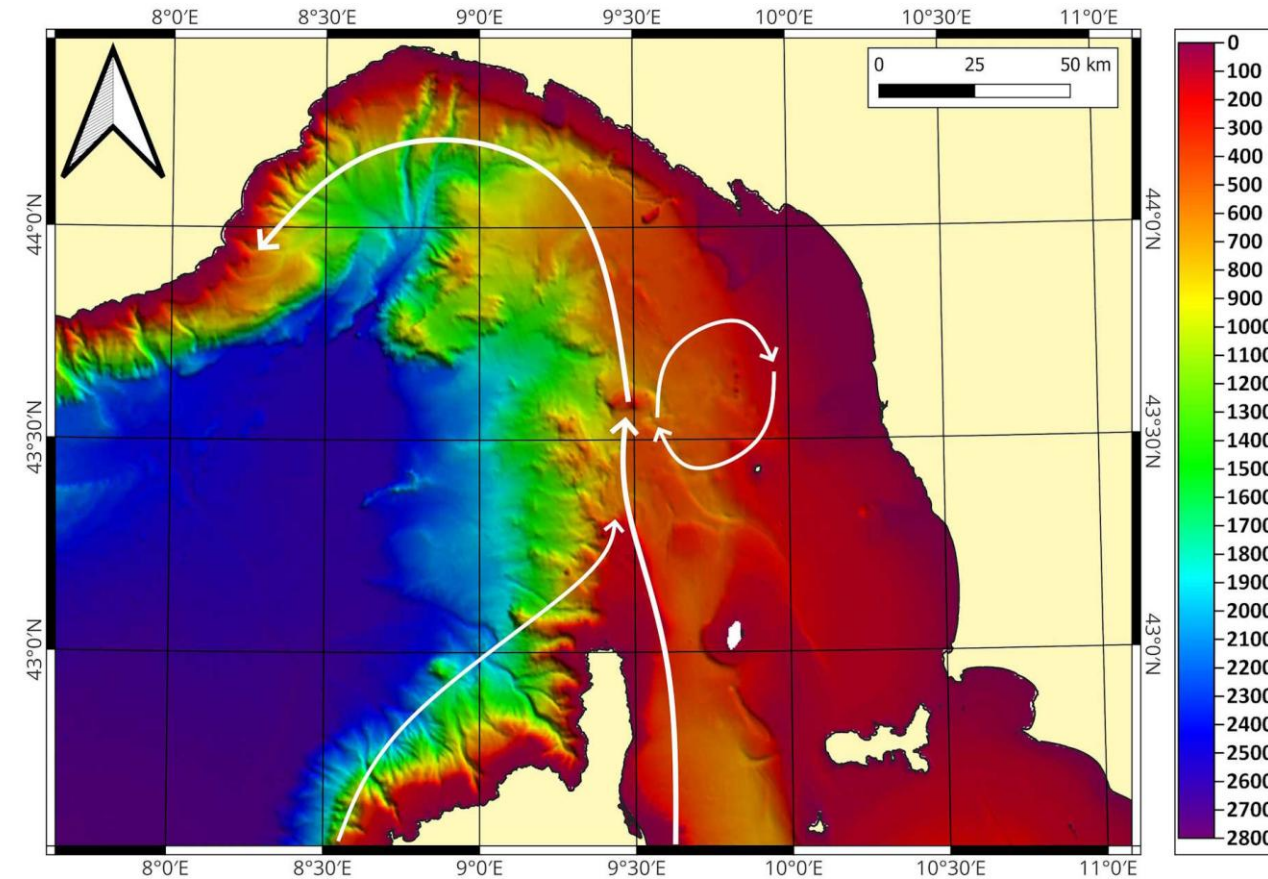


CASE STUDY: LIGURIAN SEA



Oceanographic Context

- Northwestern Mediterranean basin.
- Deep and steep in the western area (nearly 3000 m), shallower in the eastern part.
- Two deep canyons near Genoa and another one parallel oriented toward east.
- Cyclonic circulation (both surface and intermediate waters).
- An anticyclone is present in the southeastward Ligurian Sea, stronger in summer.



Study Objectives

- 1 Assess ICESat-2 potential for Sea Surface Height (SSH) estimation
- 2 Develop a reproducible processing workflow for a reliable SSH dataset
- 3 Compare seasonal variability with the Genoa tide gauge and Jason/X-TRACK radar altimetry.
- 4 Reduce manual QC by implementing automated sea-state screening

ICESat-2 Dataset: Coverage and Data Volume

3973

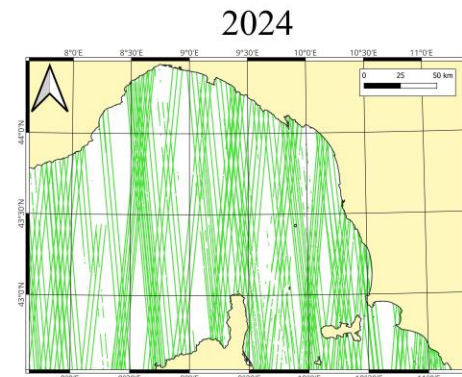
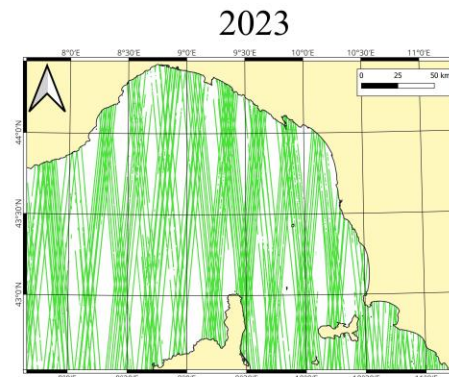
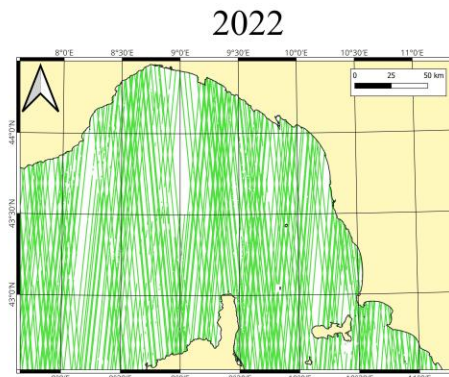
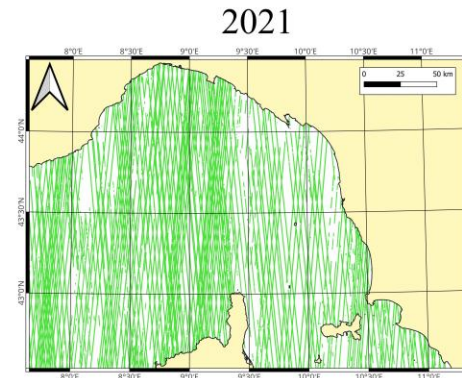
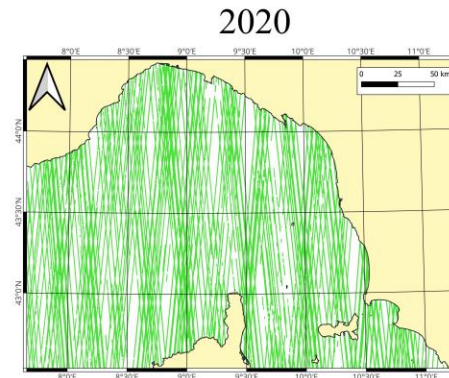
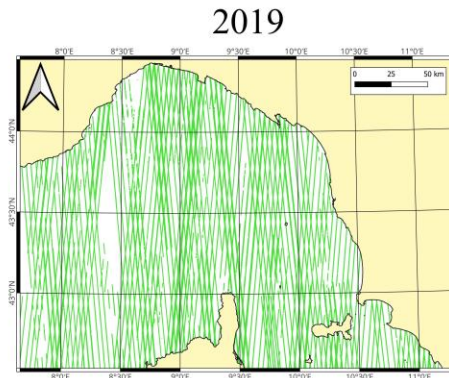
tracks selected

2875

valid after processing

16 Oct 2018 → Dec 2024

- All available Ligurian Sea acquisitions were initially considered.
- Coverage remains spatially and seasonally heterogeneous after quality control.



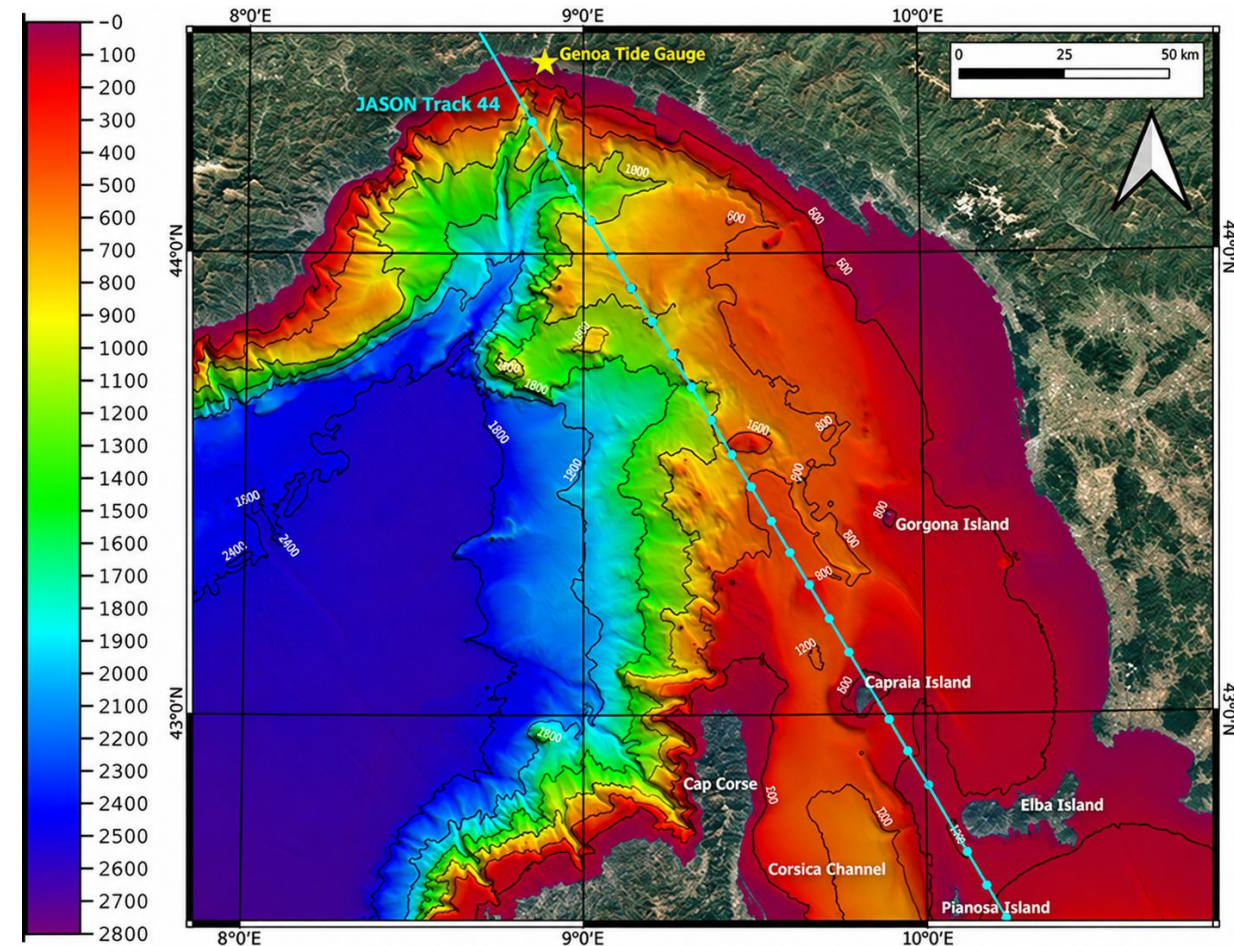
Independent Reference Data

GENOA TIDE GAUGE

- Old Port of Genoa
- Floating-gauge data used
- Instrument accuracy: 2 mm
- Sampling: 1 min → daily / seasonal means
- Period: Jan 2018 – Dec 2024

JASON / X-TRACK

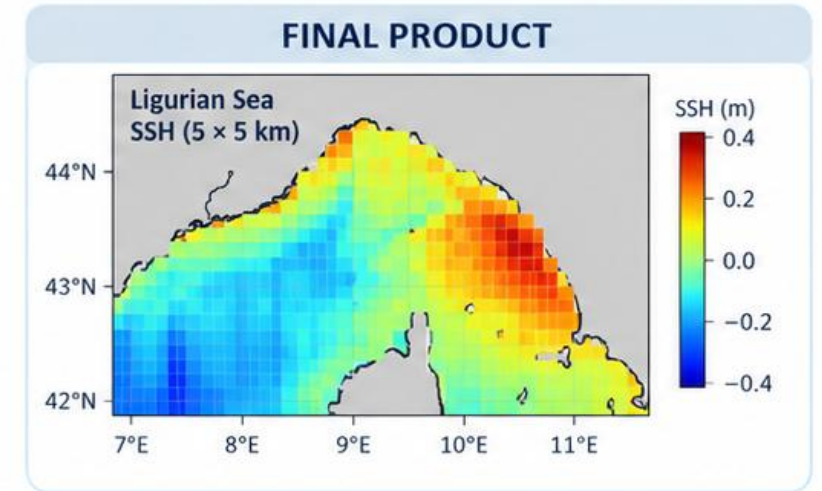
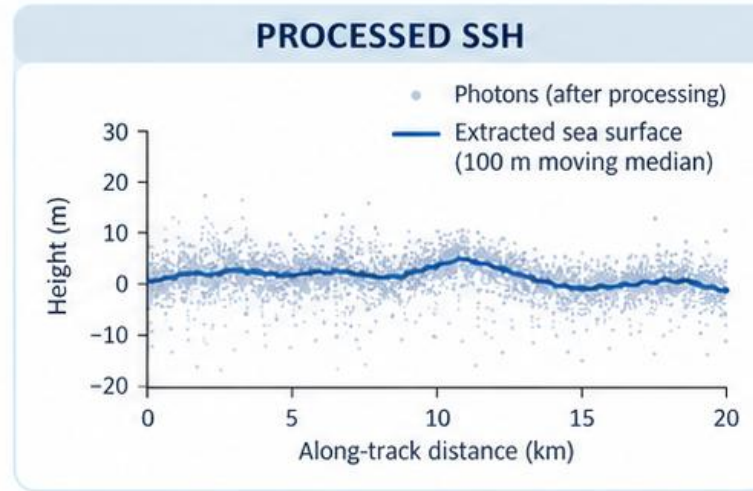
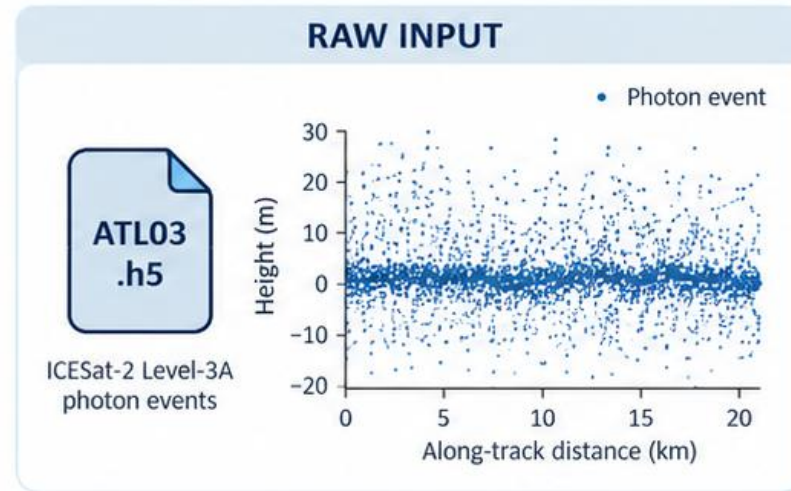
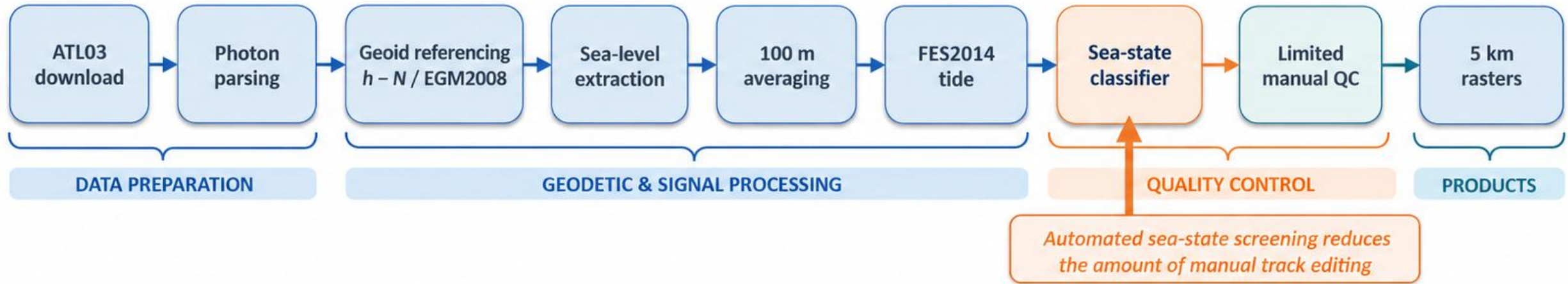
- X-TRACK L2P Sea Level Anomaly (SLA)
- Reference ground track #044 across the Ligurian Sea
- TOPEX/Jason-1/2/3 time series: 1993–2022
- ~10-day repeat cycle; ~6 km along-track spacing
- ~150 km transect from the Corsica Channel toward Genoa



Independent references: Genoa tide gauge for temporal variability + Jason/X-TRACK for along-track seasonal SLA

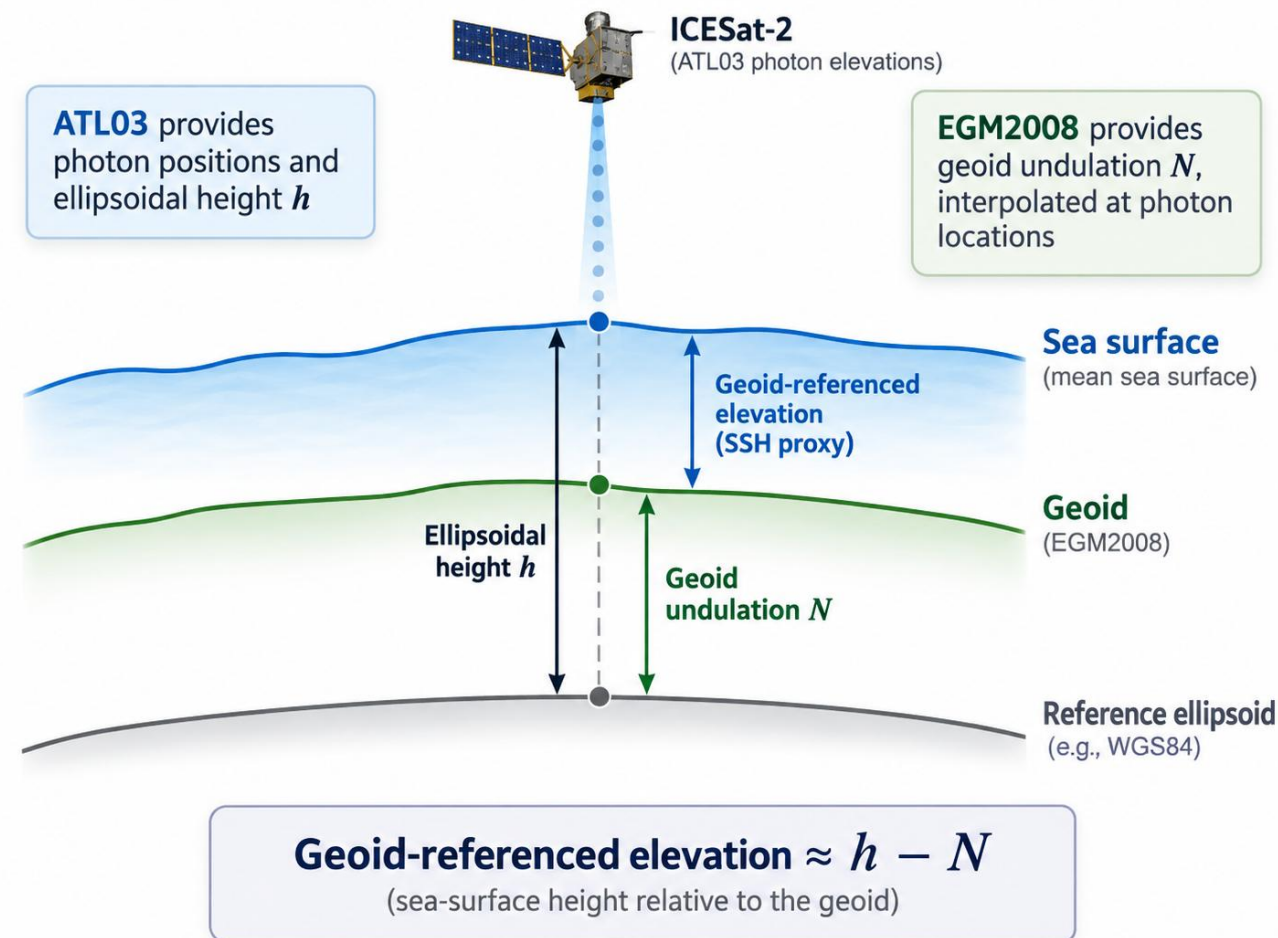
Processing Workflow

From raw photon events to quality-controlled regional SSH products

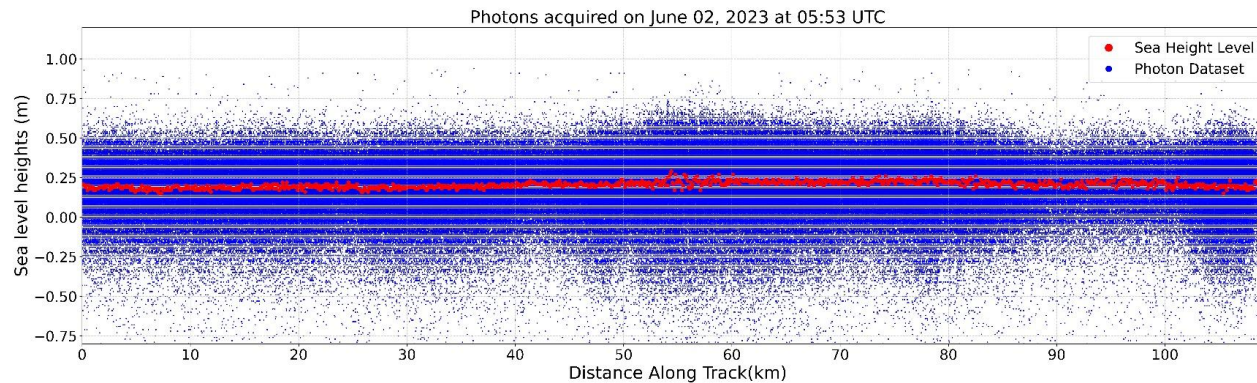


ATL03 Parsing and Reference Surfaces

- ATL03 provides geolocated photon events for all six beams.
- For each photon: time, latitude, longitude and ellipsoidal height h are extracted.
- EGM2008 geoid undulation N is taken from the grid included in the product and interpolated at photon locations.



Sea-Level Extraction and 100 m Spatial Averaging



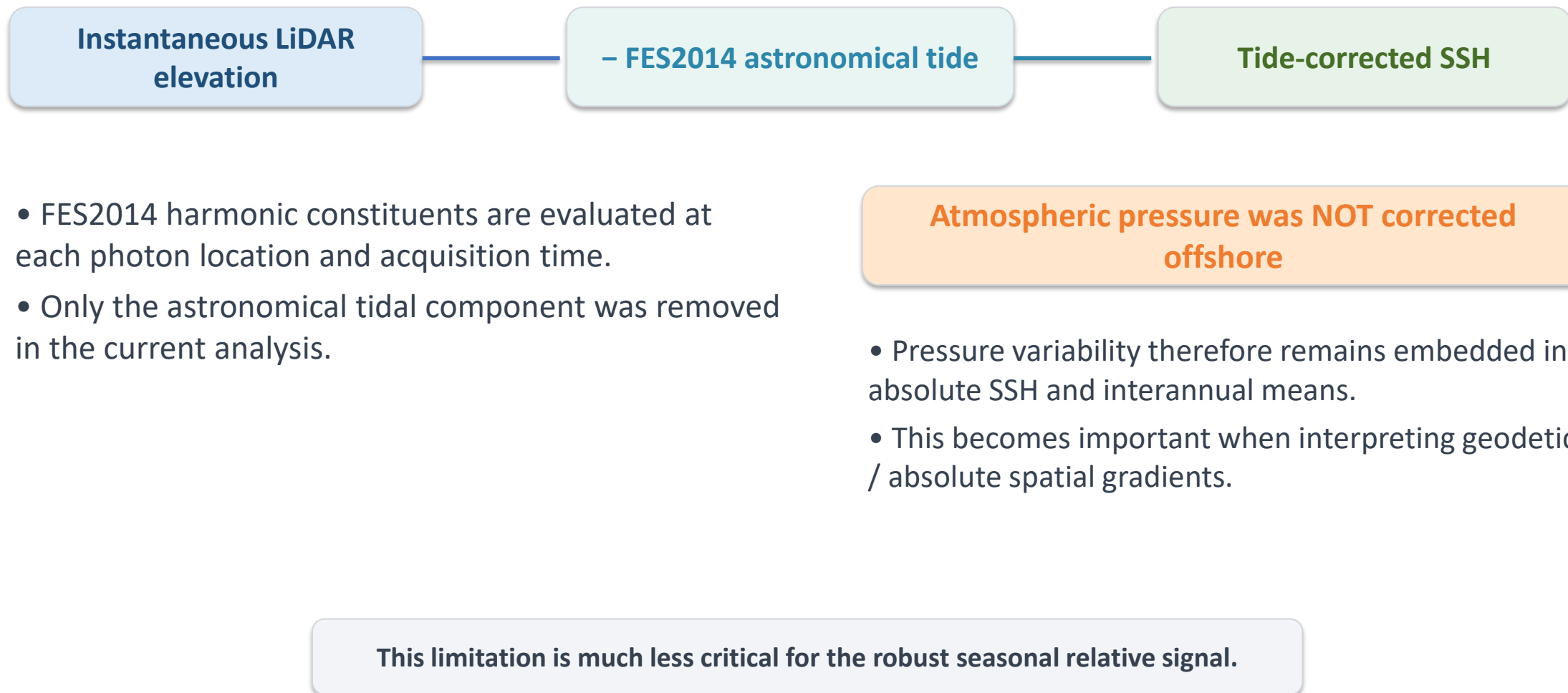
- Moving-median algorithm isolates the sea-surface signal from the photon cloud.
- Extracted sea-level points are spatially averaged in 100 m windows.
- Averaging reduces short-scale wave variability while preserving the along-track SSH signal.

Photon cloud

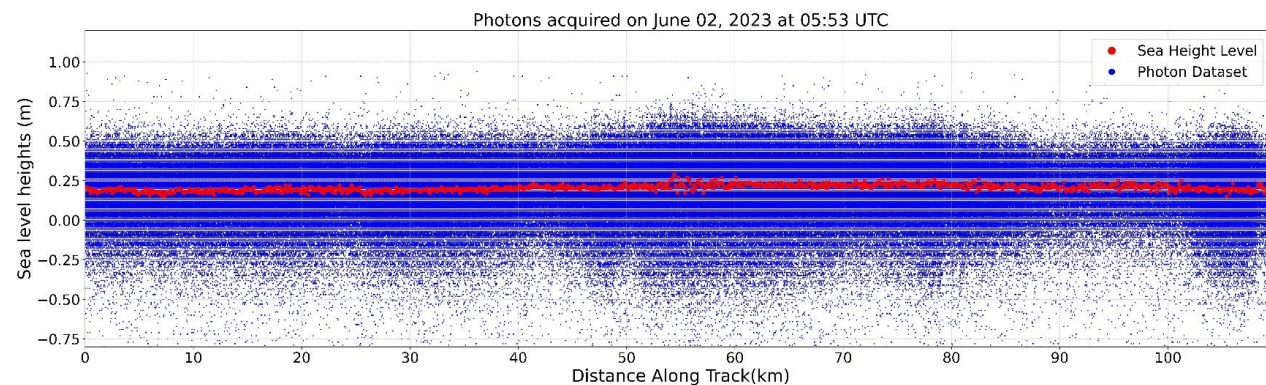
Moving median

100 m mean

Tidal Correction and Remaining Atmospheric Signal

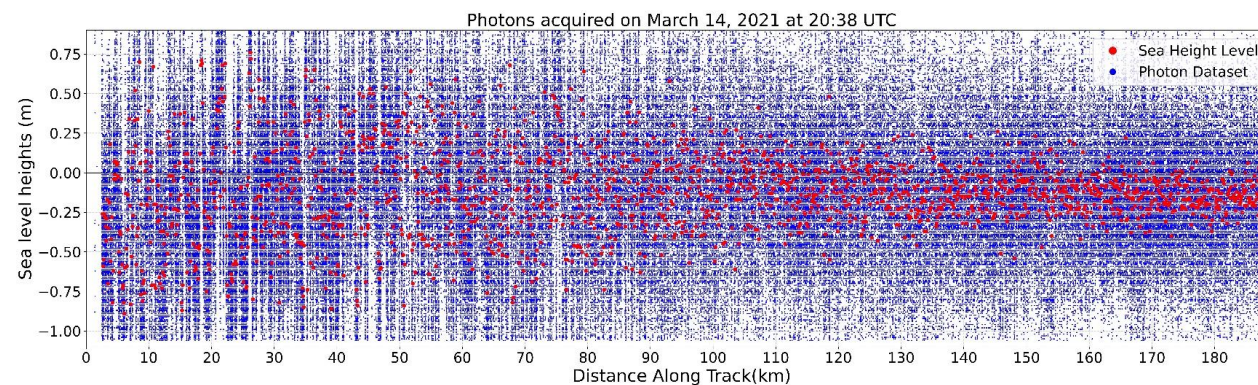


ICESat-2 Profiles: Good-Quality Conditions

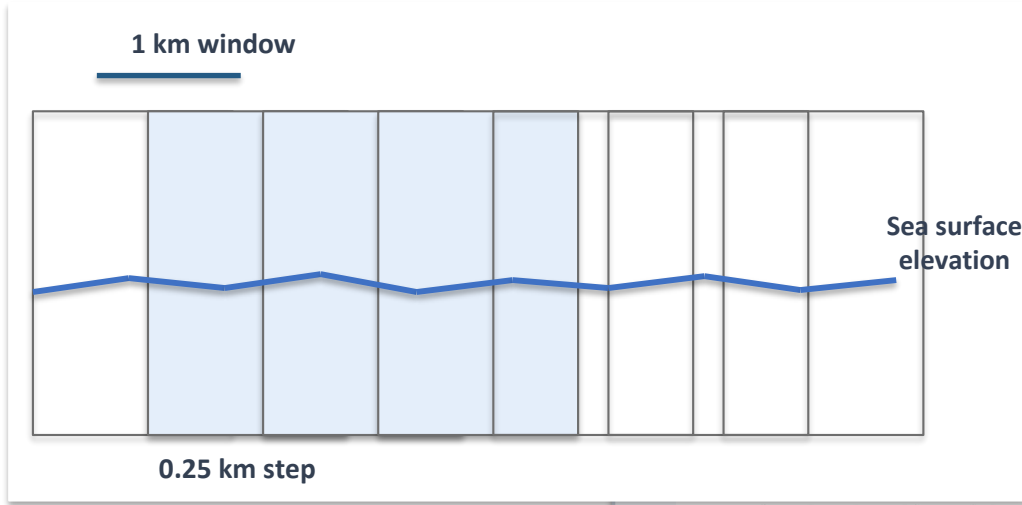


A — calm sea conditions along the track
Total SD 0.16 m | SSH SD 0.03 m

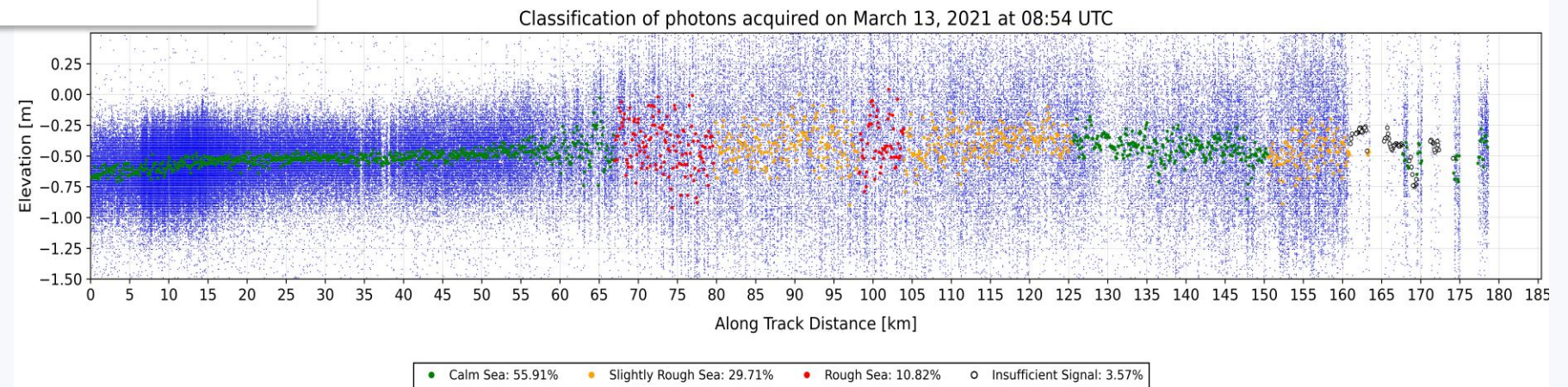
B — rough conditions along the track
Total SD 0.45 m | SSH SD 0.26 m



Automated Sea-State Classification



Real Ligurian Sea classified output



1 km windows
0.25 km step

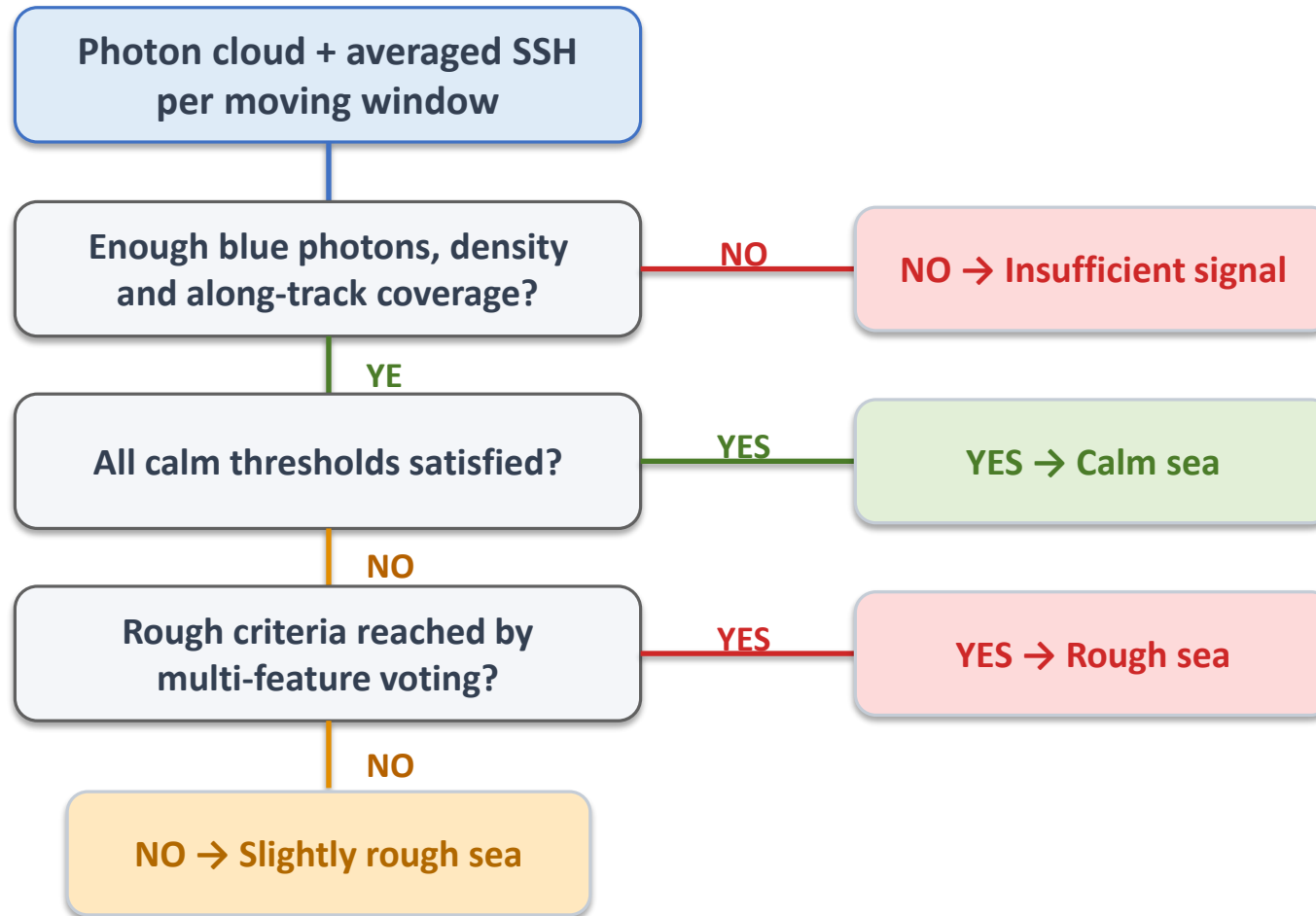
CALM SEA

INTERMEDIATE SEA

ROUGH SEA

INSUFFICIENT SIGNAL

Classification Logic



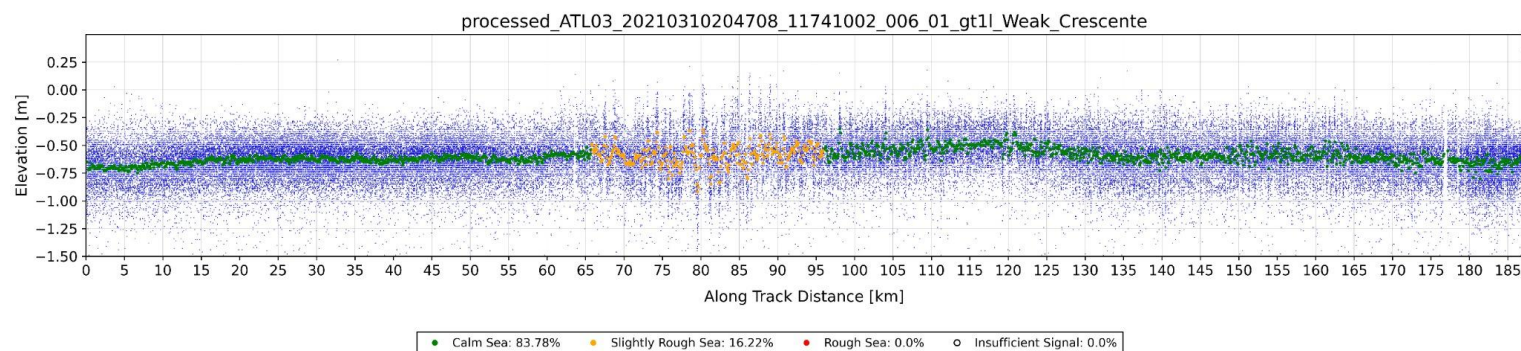
Beam-specific post-processing

- Beam-specific thresholds.
- Several indicators of dispersion and instability are combined.
- Rolling-median features for Strong / Weak beams.

Overlapping windows → point-wise class assignment

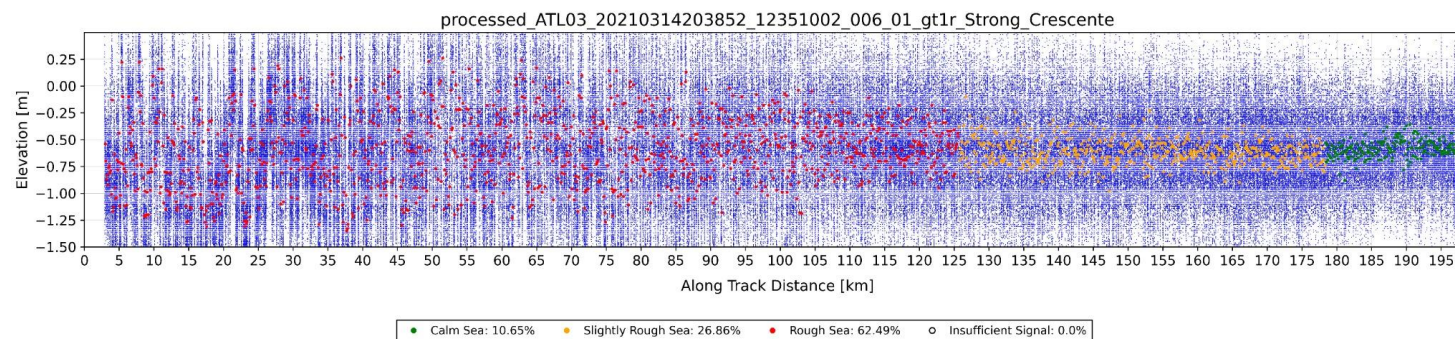
- Each averaged SSH point can belong to multiple windows.
- Conservative priority rule: Insufficient > Rough > Slightly rough > Calm.
- Beam-level percentages summarize the four classes.

ICESat-2 Profiles: Classification examples

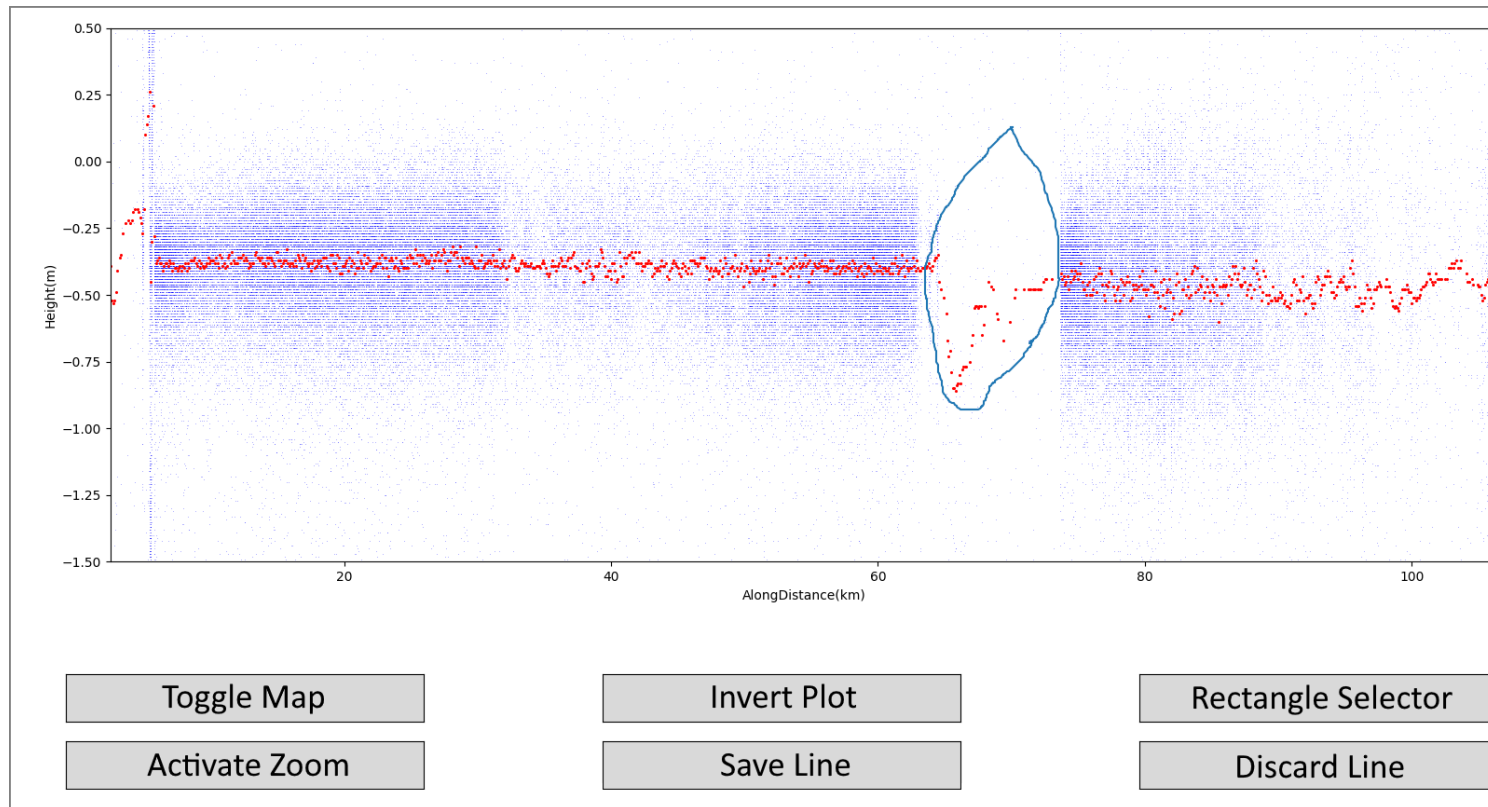


83.78% calm
16.22% slightly rough

10.65% calm
26.86% slightly rough
62.49% rough



Final Manual Review: Still Necessary

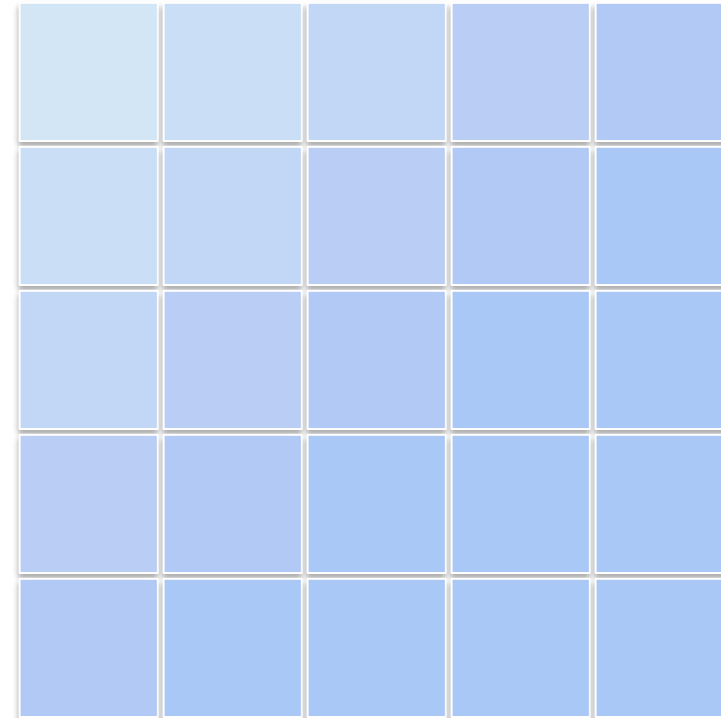


- Automated classification removes most routine screening.
- Some local misclassifications and isolated outliers still remain.
- A light final manual review is retained before rasterization.
- Expert control is preserved, with much less operator time.

Classifier first → light manual QC last

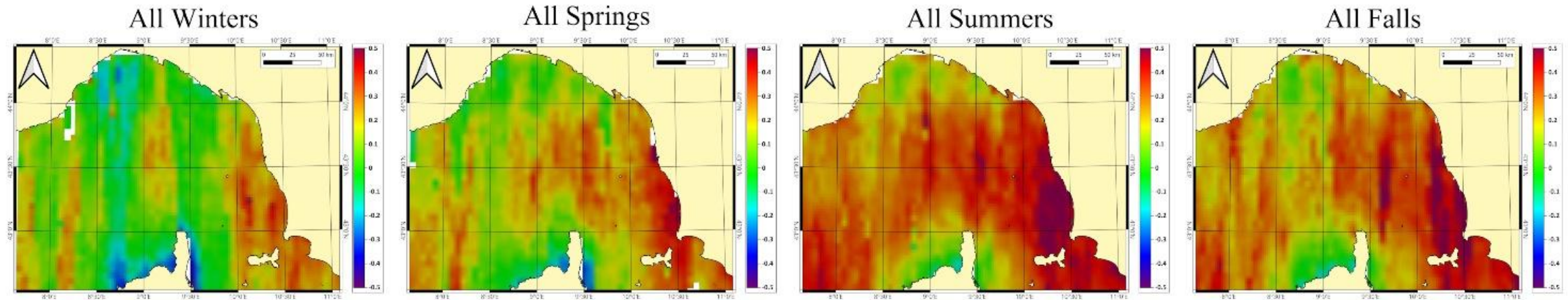
Raster Generation

- Aggregate corrected SSH points into GeoTIFF raster surfaces.
- Spatial resolution: 5×5 km.
- Quality weighting inversely related to SSH standard deviation: calm / low-dispersion observations contribute more.
- Products:
 - a) seasonal maps,
 - b) multi-year seasonal means,
 - c) annual means.



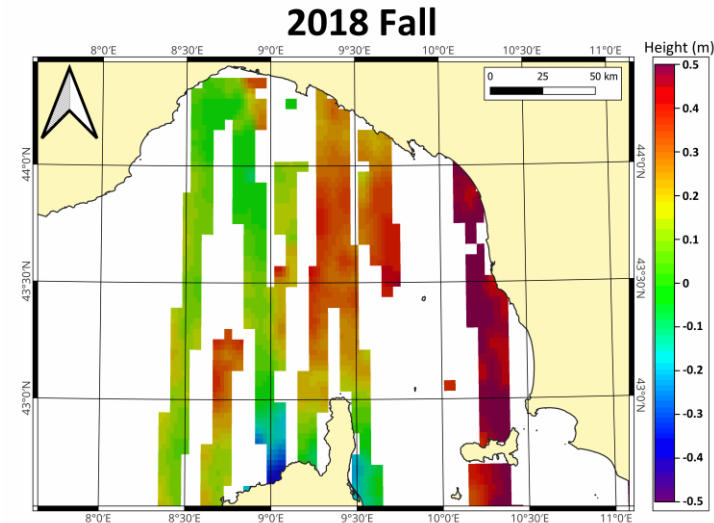
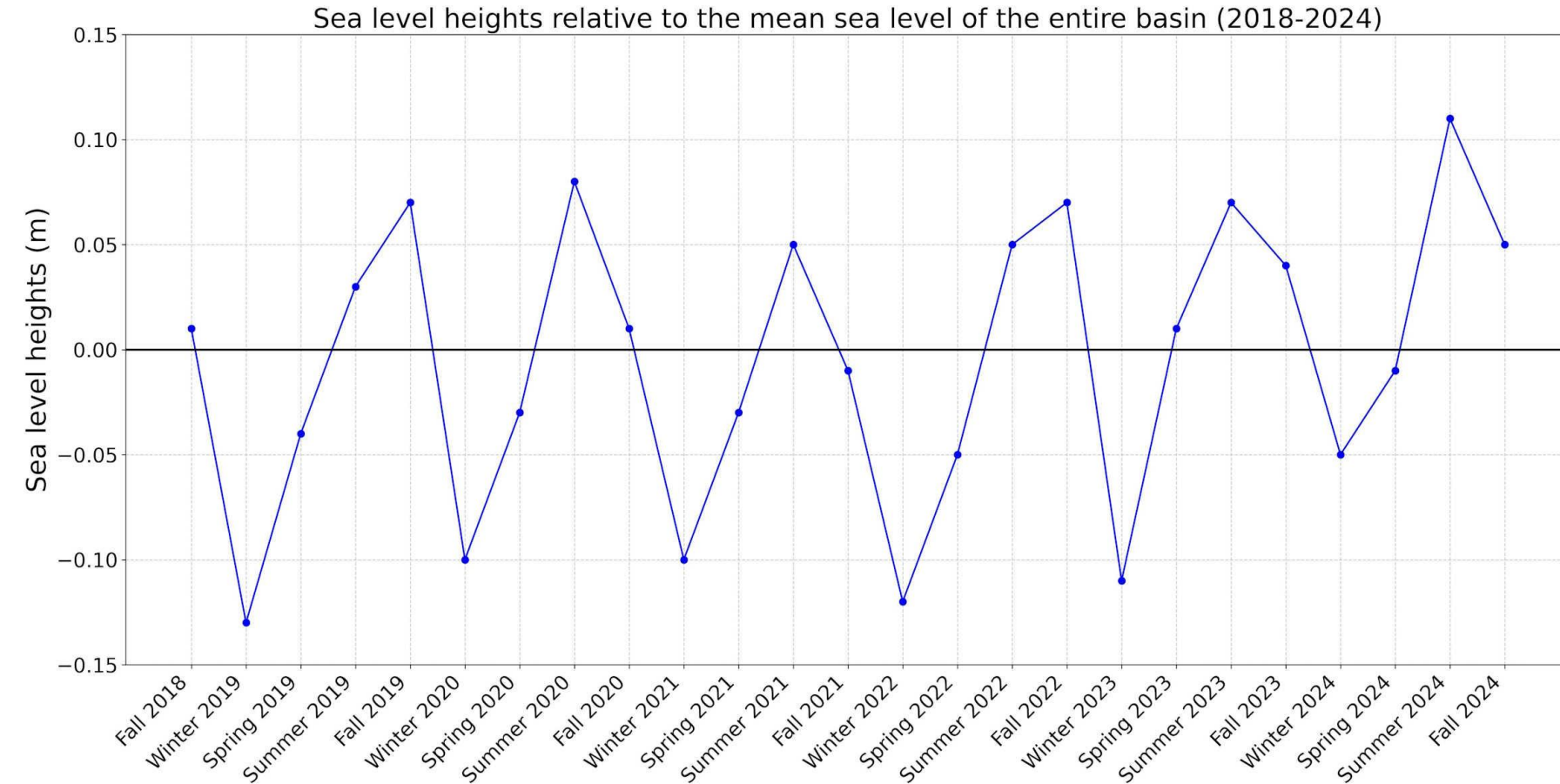
**weighted mean
per 5 km pixel**

RESULTS: Seasonal SSH Maps



- Multi-year seasonal surfaces preserve the expected lower winter SSH and higher summer/fall SSH.
- Spatial coverage is not uniform and depends strongly on meteo-marine conditions; winter/spring contain more gaps.

RESULTS: Temporal SSH Variability



12–20 cm

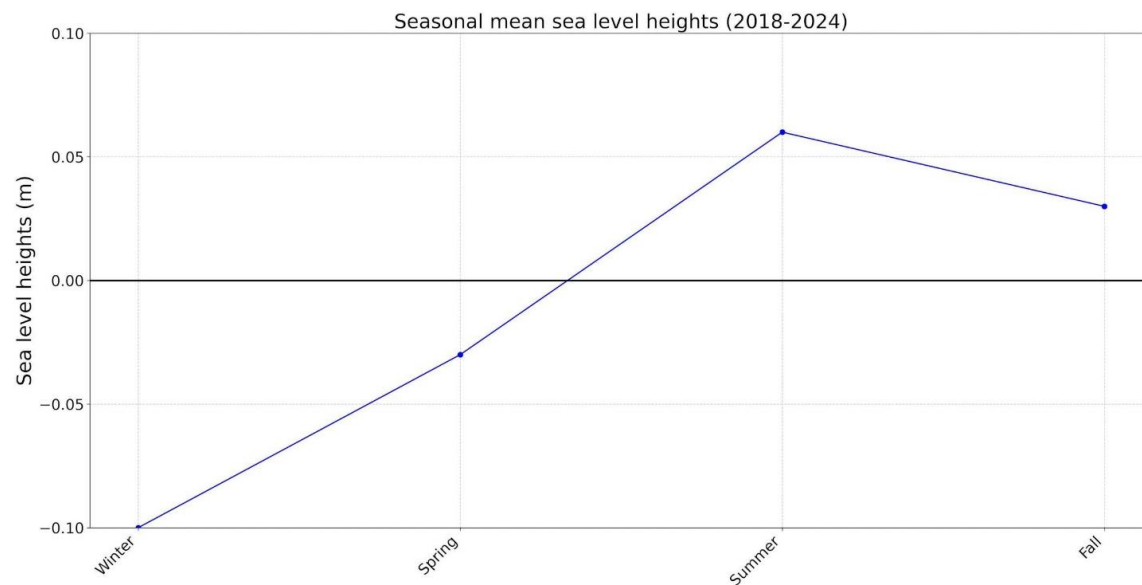
seasonal amplitude across years

13 cm

mean seasonal SD

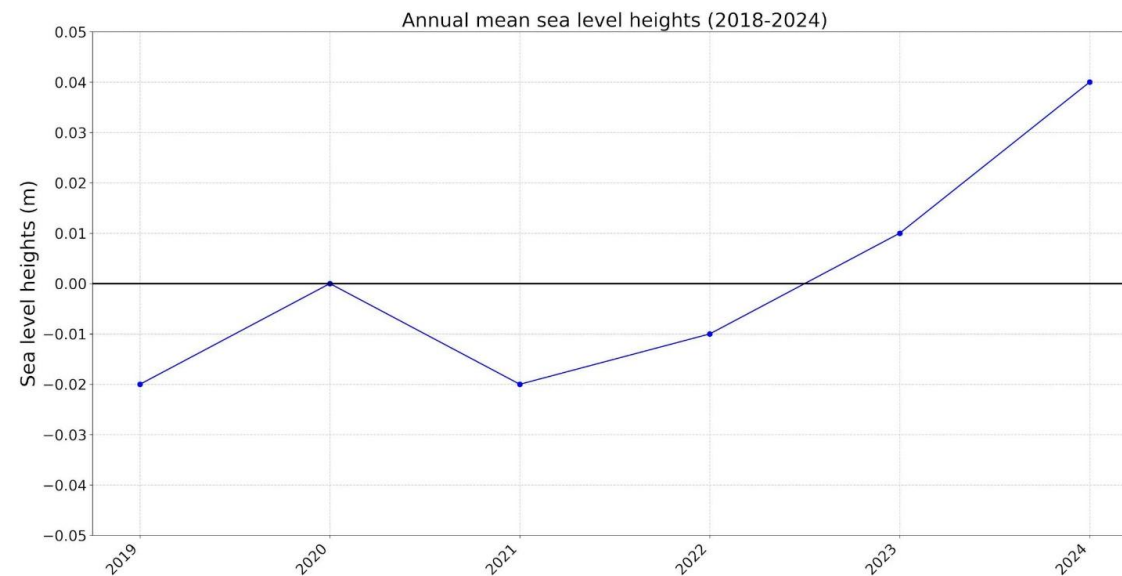
**SD ~9 cm in summer
vs ~19 cm in winter**

RESULTS: Multi-year Seasonal and Annual Means



16 cm

multi-year winter → summer difference

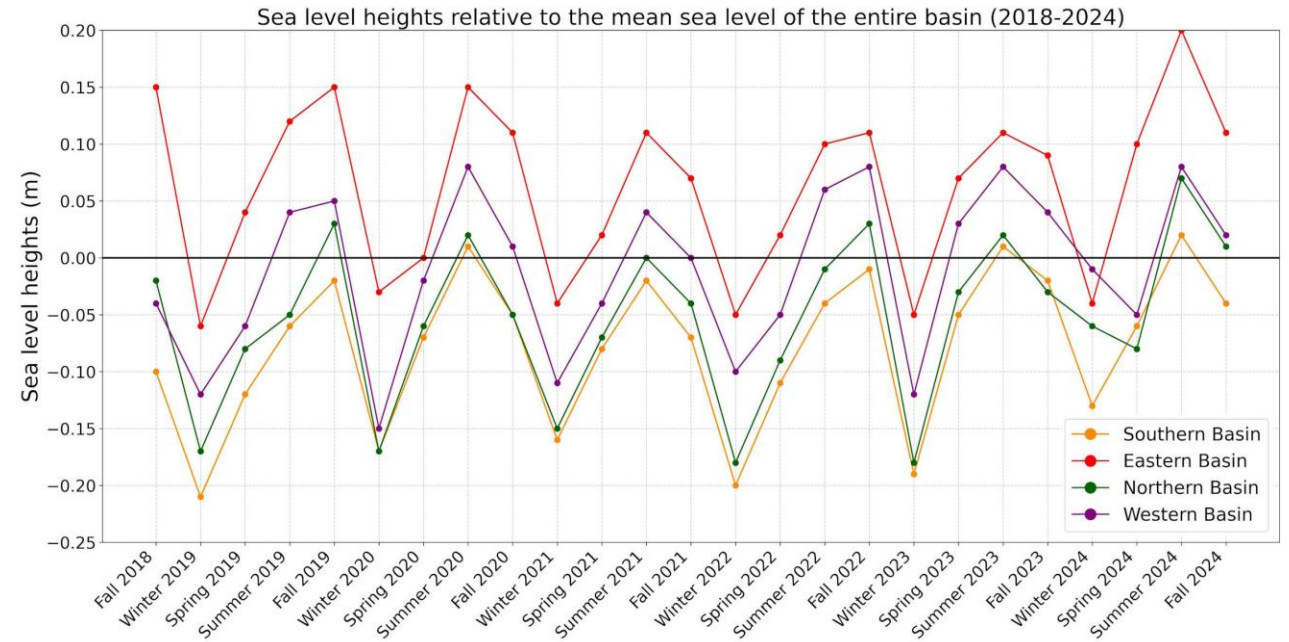
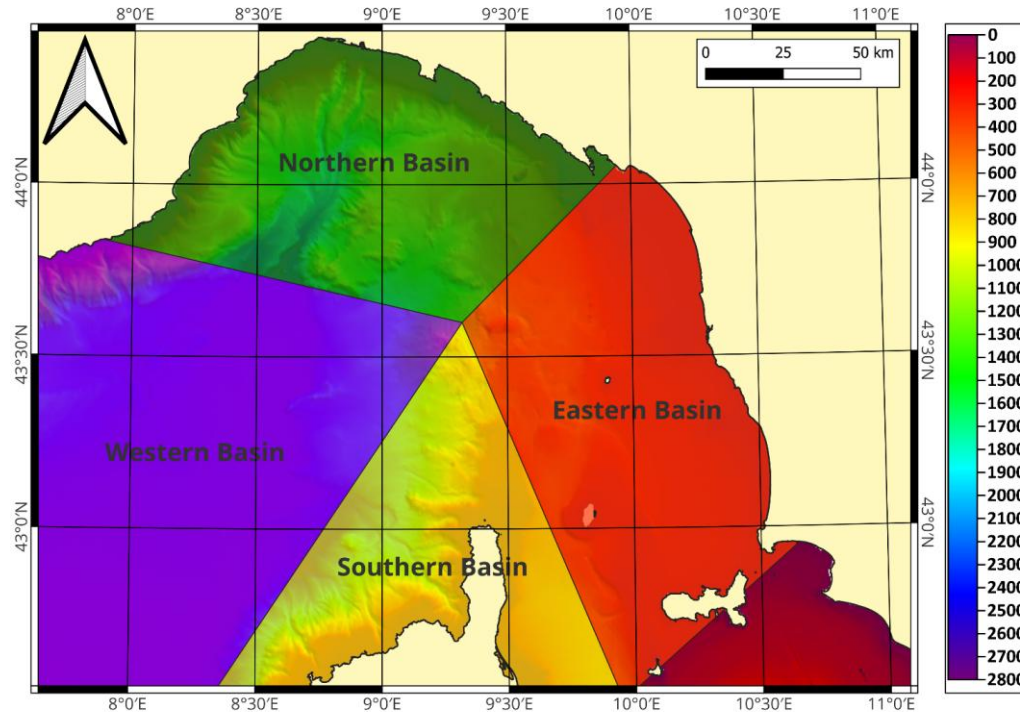


3 cm

largest annual mean difference (2023–2024)

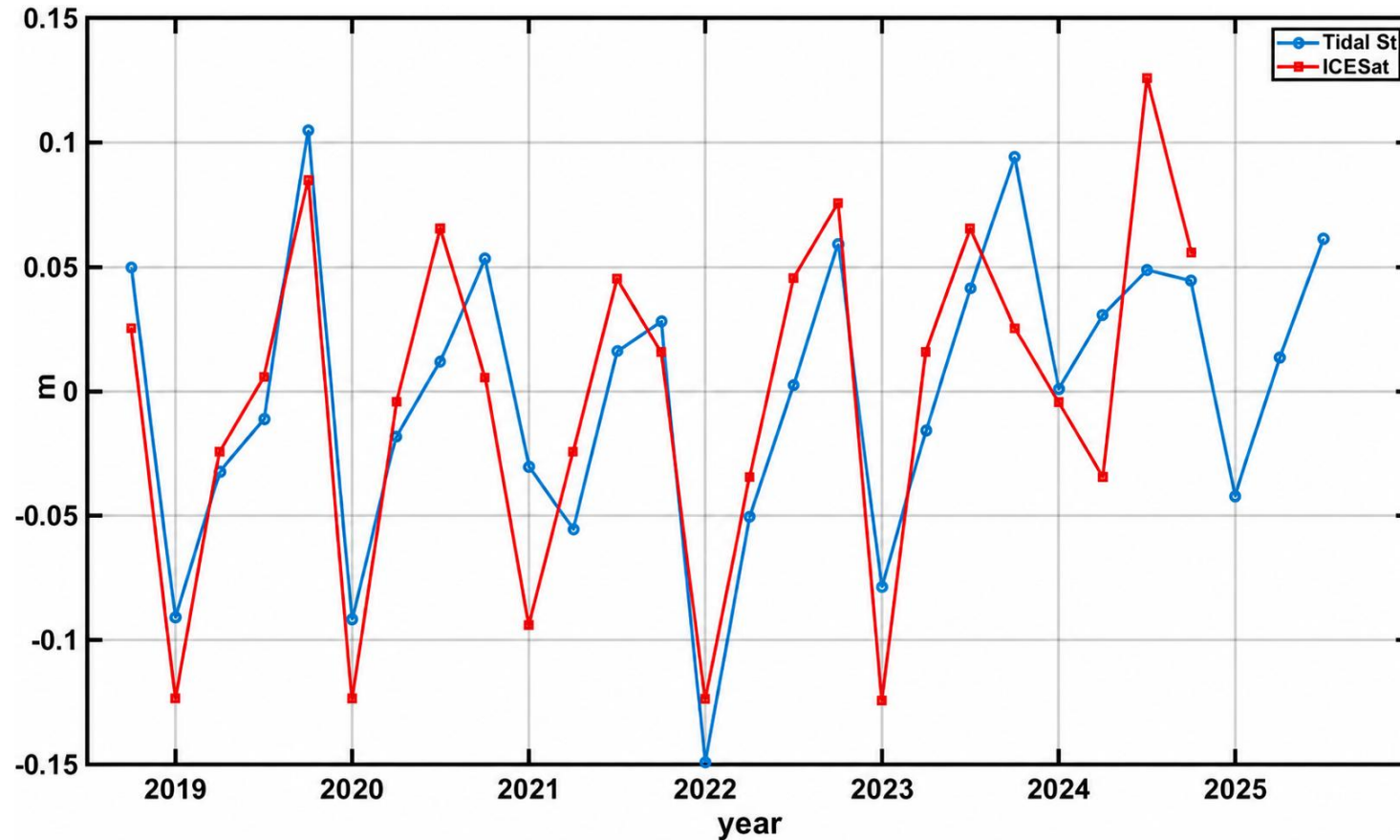
Six years are not sufficient to infer a robust long-term sea-level trend.

Spatial Patterns and Sub-Basin Comparison



- Four sub-areas were defined from morphology, oceanographic setting and map patterns.
- Temporal evolution is highly correlated among sub-basins; most differences appear as local mean offsets.
- The strongest divergence occurs in winter/spring 2024, when spatial coverage is also particularly poor.

REFERENCE COMPARISON : Genoa Tide Gauge



0.82
correlation

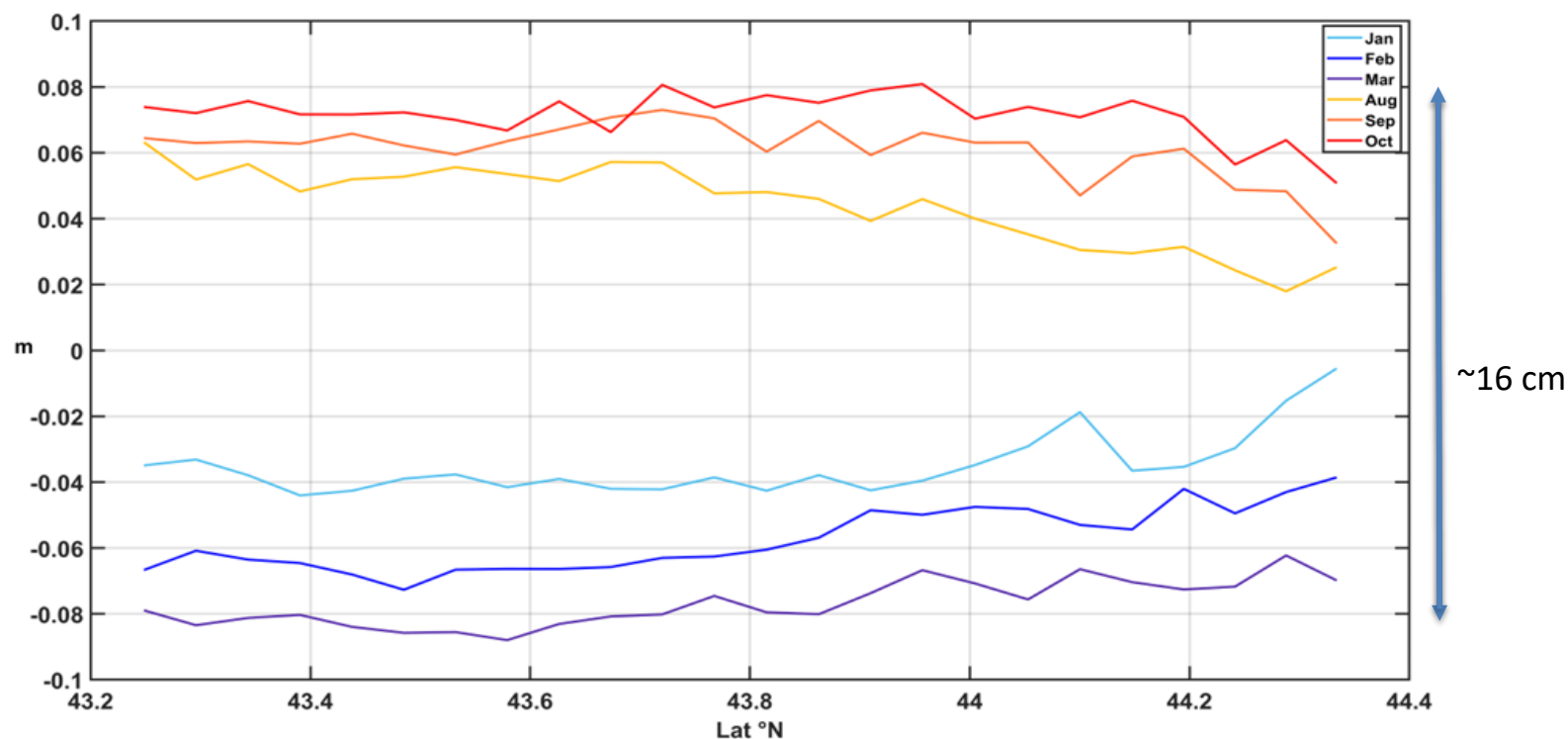
0.04 m
RMSE

Strong agreement in seasonal
temporal variability

Comparison uses the Northern Ligurian sub-basin; tide-gauge record is a coastal point observation.

REFERENCE COMPARISON: JASON / X-TRACK

Monthly mean SLA profiles from X-TRACK data-set over the period 1993-2022



SLA — Sea Level Anomaly:
variation relative to a
reference mean sea surface.

- Monthly mean SLA profiles along Jason track #044 (1993-2022).
- Winter and summer profiles show a clear seasonal separation: the maximum difference reaches ~16 cm.
- The seasonal amplitude is therefore of the same order of magnitude as ICESat-2.

Independent radar altimetry reproduces a seasonal sea-level signal comparable in magnitude to that retrieved from ICESat-2.

Conclusions

ICESat-2 captures a clear seasonal sea-level cycle in the Ligurian Sea

STRENGTHS

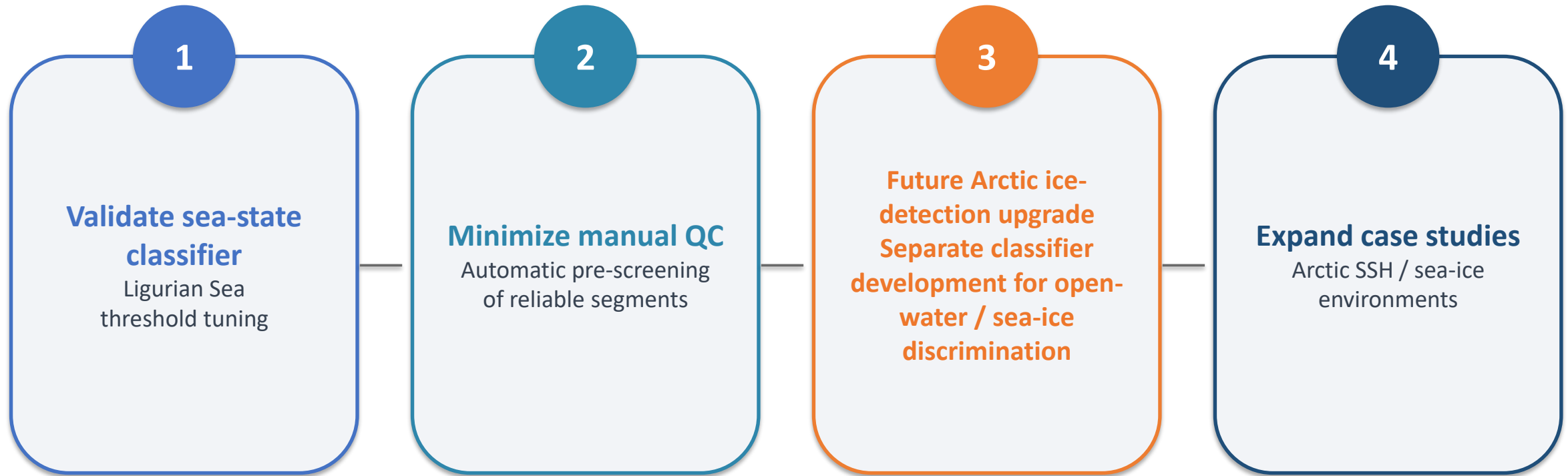
- Clear seasonal SSH variability over 2018–2024.
- Strong tide-gauge agreement: $r = 0.82$; $RMSE = 0.04$ m.
- Seasonal amplitude comparable to Jason/X-TRACK (~16 cm).
- Dense along-track sampling and segment-level QC are valuable at regional scale.

CURRENT LIMITATIONS

- Spatial and seasonal coverage remains heterogeneous.
- Rough seas, clouds and coastal effects can degrade some tracks.
- Lack of offshore atmospheric pressure data → dedicated measurements are needed for improved SSH correction
- Absolute spatial SSH patterns are less robust than relative seasonal variability.

ICESat-2 is a promising complementary source for relative and seasonal SSH in coastal and semi-enclosed basins.

Future Developments: From Automated QC to Arctic Ice Detection



Thank you!

Questions?

XI Hotine-Marussi Symposium

