Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)
Technische Universität München

Round Robin Assessment of Radar Altimeter LRM and SAR Retracking Algorithms for Significant Wave Height: A Coastal Point of View

Florian Schlembach[1],
Marcello Passaro[1], Graham Quartly[3], Francesco Nencioli[3], Andrey Kurekin[3], Guillaume Dodet[2], Jean-François Piollé[2], Fabrice Ardhuin[2], Christian Schwatke[1], Denise Dettmering[1], Florian Seitz[1], Paolo Cipollini[4], Craig Donlon[5]

[1] Technical University of Munich (DGFI-TUM), Munich, Germany
[2] Laboratoire d'Océanographie Physique et Spatiale (LOPS), CNRS, IRD, Ifremer, IUEM, Univ. Brest, Brest, France
[3] Plymouth Marine Laboratory (PML), Plymouth, UK
[4] Telespazio VEGA UK for ESA Climate Office, ESA-ECSAT, UK,
[5] European Space Agency, ESA-ESTEC/EOP-SME, The Netherlands

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Outline

1. Round Robin Assessment
2. Data
3. Methods
4. Results and Discussion
5. SeaState_cci Selection Process
6. Conclusion

1. Round Robin Assessment

- ESA SeaState Climate Change Initiative (CCI) Project
  - Main objective: Generation of a long-term multi-mission significant wave height (SWH) dataset
  - Reprocessing of satellite altimetry data of the past 25 years
  - With the focus on the coastal zone and high sea states (based on SeaState_cci users survey)

Round Robin Assessment
- Evaluation of novel retracking algorithms for LRM and SAR altimeters
- Two novel retrackers shall be selected

2. Data

Level-1 datasets for input

Mission / # of	Jason-3	Sentinel-3A
Half-orbits/pole-to-pole tracks	16	30
Cycles	73	17 (covering 13 months)
NetCDF files	1162	512
Type of waveforms	L1B	L1A/L1BS (incl. PLRM)

Reference used for validation

- In-situ buoy data (125 buoys for Jason-3, 170 buoys for S3A)
- 2x wave models: ERA5, ERA5-based hindcast (ERA5-h)

2. Data

Submitted Retracker Datasets

- 6 teams have participated (TUM, PML, CLS, UniBonn, Isardsat, UON). 11+8 retracked datasets were evaluated.

Retracking algorithms	Altimeter mode	Author	Denoising applied
MLE-3	LRM	-	No
MLE-4	LRM	-	No
Brown-Peaky	LRM	UON	No
WHALES	LRM	TUM	No
WHALES_adj	LRM	PML	Yes
WHALES_realPTR	LRM	PML	No
WHALES_realPTR_adj	LRM	PML	Yes
Adaptive	LRM	CLS	No
Adaptive_HFA	LRM	CLS	Yes
TALES	LRM	UniBonn	No
STARv2	LRM	UniBonn	Yes (implicitly)
		Total number	11
SAMOSA-2.5	DDA	SAMOSA-based	No
WHALES-SAR	DDA	TUM	No
DeDop-Waver	DDA	Isardsat	No
LR-RMC	DDA	CLS	No
LR-RMC_HFA	DDA	CLS	Yes
MLE-4-PLRM	PLRM	-	No
TALES-PLRM	PLRM	UniBonn	No
STARv2-PLRM	PLRM	UniBonn	Yes (implicitly)
		Total number	8

3. Methods

1. Outlier analysis
2. Noise analysis
3. Wave spectral variability
4. Comparison against wave models (ERA5 / ERA5-based hindcast)
5. Comparison against in-situ buoy data

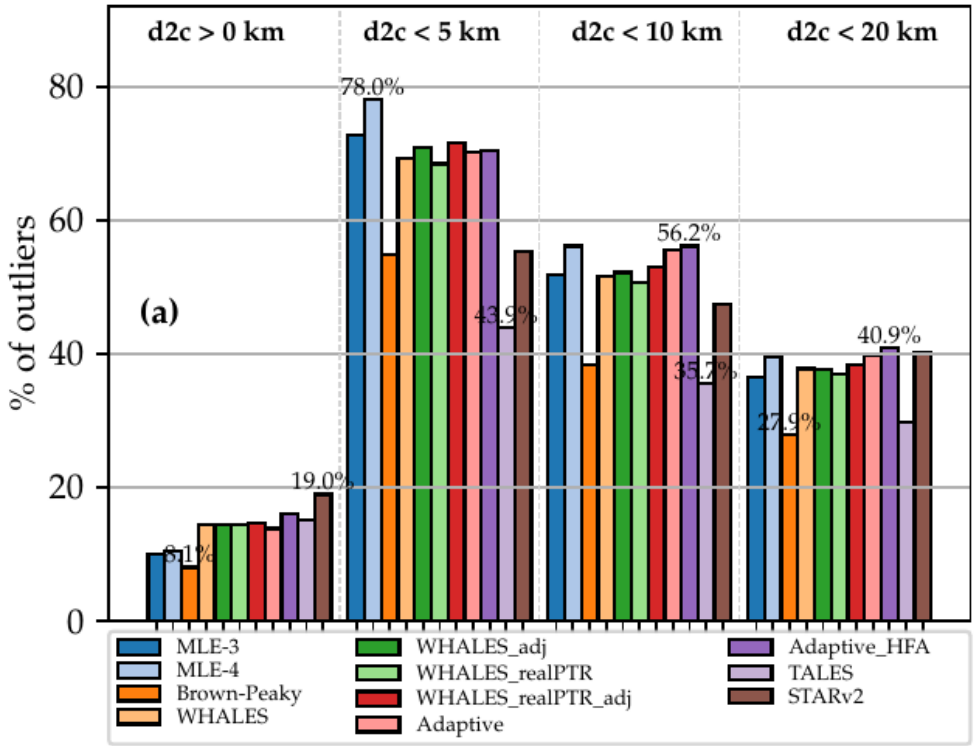
Distance-to-coast (dist2coast): Open-ocean: dist2coast > 20km, **coast**: dist2coast <= 20km

Sea states: low (0-2m), average (2-5m), high (>5m), very high (>10m)

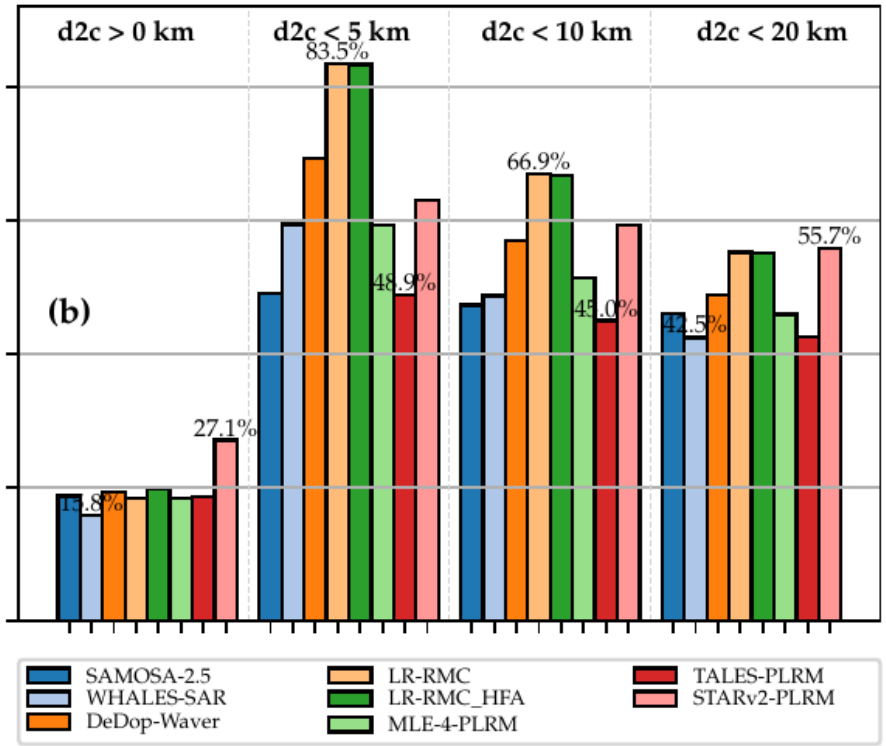
4.1 Results and Discussion – Outlier Analysis

- 3 types: invalid (SWH quality_flag), out_of_range ([-0.25, 25]m), median_absolute_deviation (mad)
- Total number of outliers:

LRM



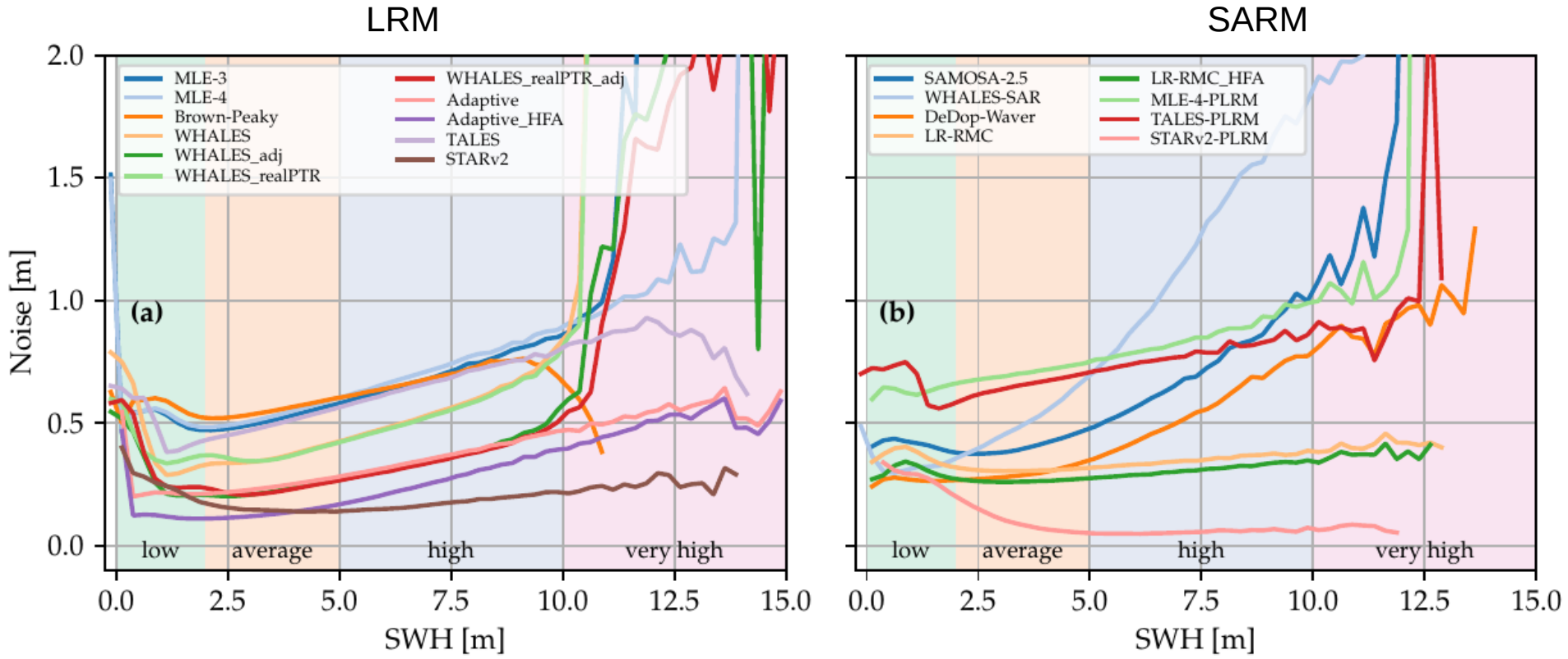
SARM



Number of outliers increases significantly when approaching coast
Retrackers with the least amount of outliers (open-ocean): Brown-Peaky (J3), WHALES-SAR (S3A)

4.2 Results and Discussion – Noise Analysis

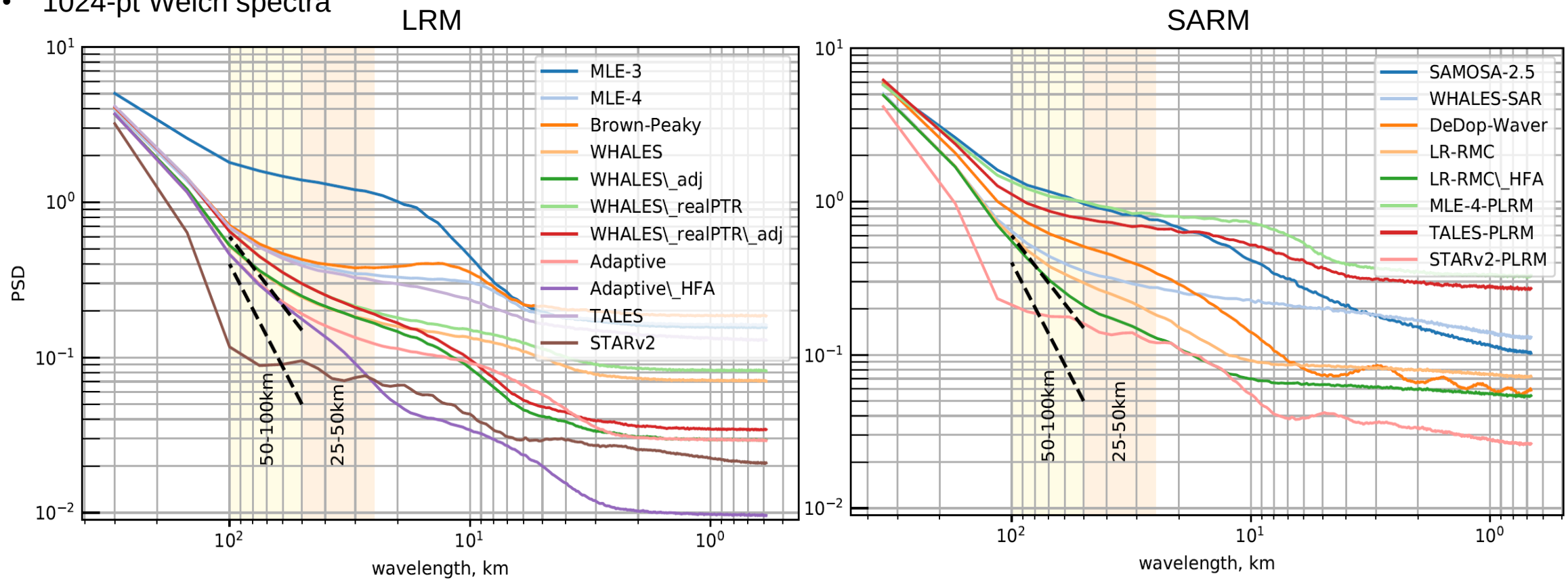
- Instrinsic noise: Standard deviation of a 20-Hz measurement



Best noise characteristic: LRM: Adaptive, STARv2; SARM: LR-RMC

4.3 Results and Discussion – Wave Spectral Variability

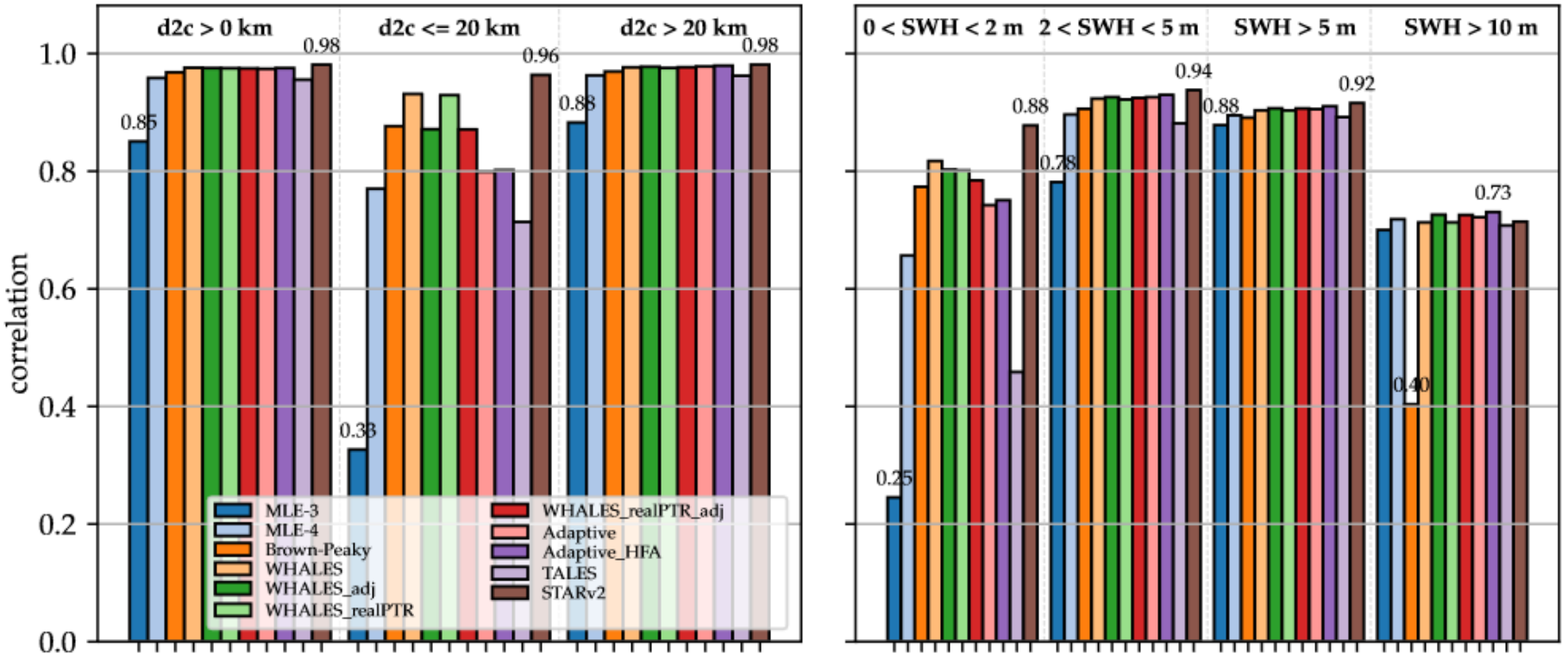
- 1024-pt Welch spectra



Best: **LRM**: Adaptive, STARv2; **SARM**: LR-RMC, STARv2-PLRM, **but** STARv2 might miss signal energy @50-100km

4.4 Results and Discussion – Comparison with ERA5-h Wave Model (J3)

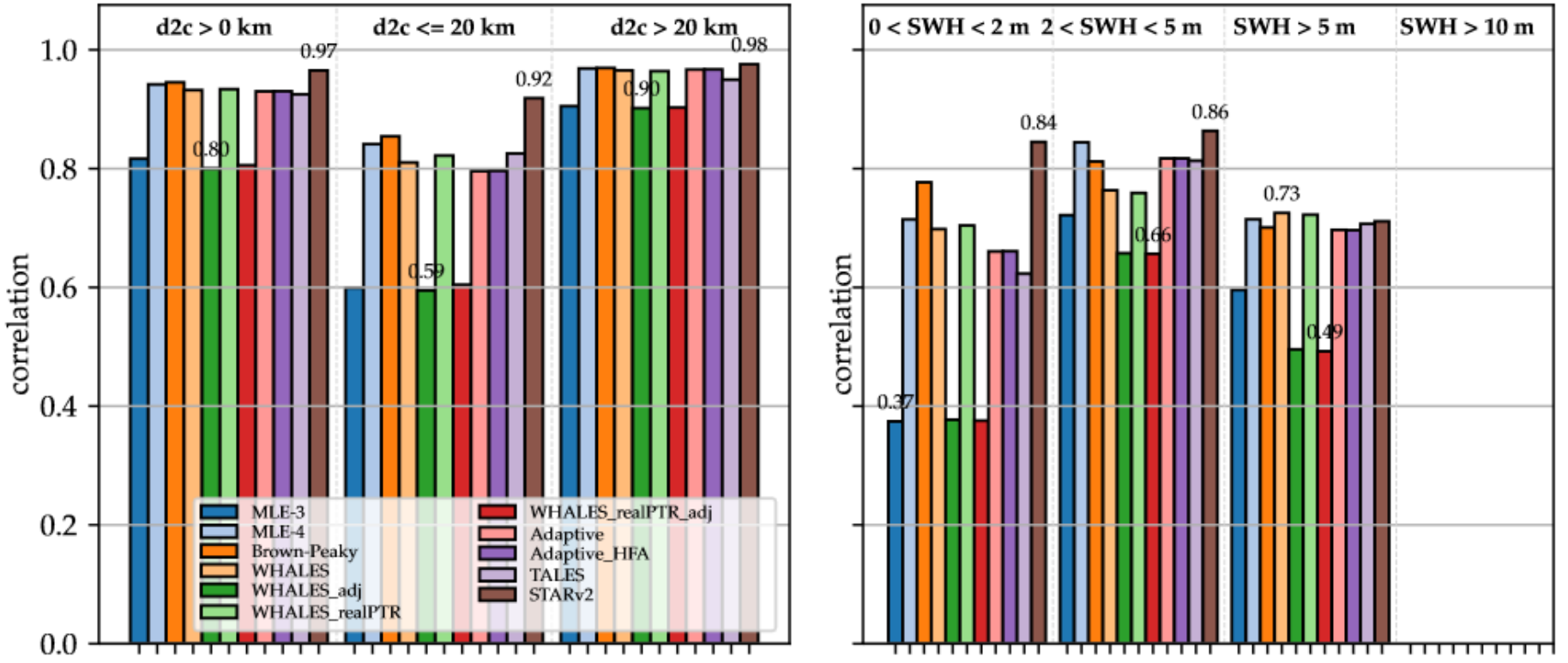
- Correlation, **Jason-3**:



Dist2coast: Good correlation in overall and open-ocean, degraded correlation in coast
SWH: decreased correlation in higher sea states

4.4 Results and Discussion – Comparison with In-situ Buoy Data (J3)

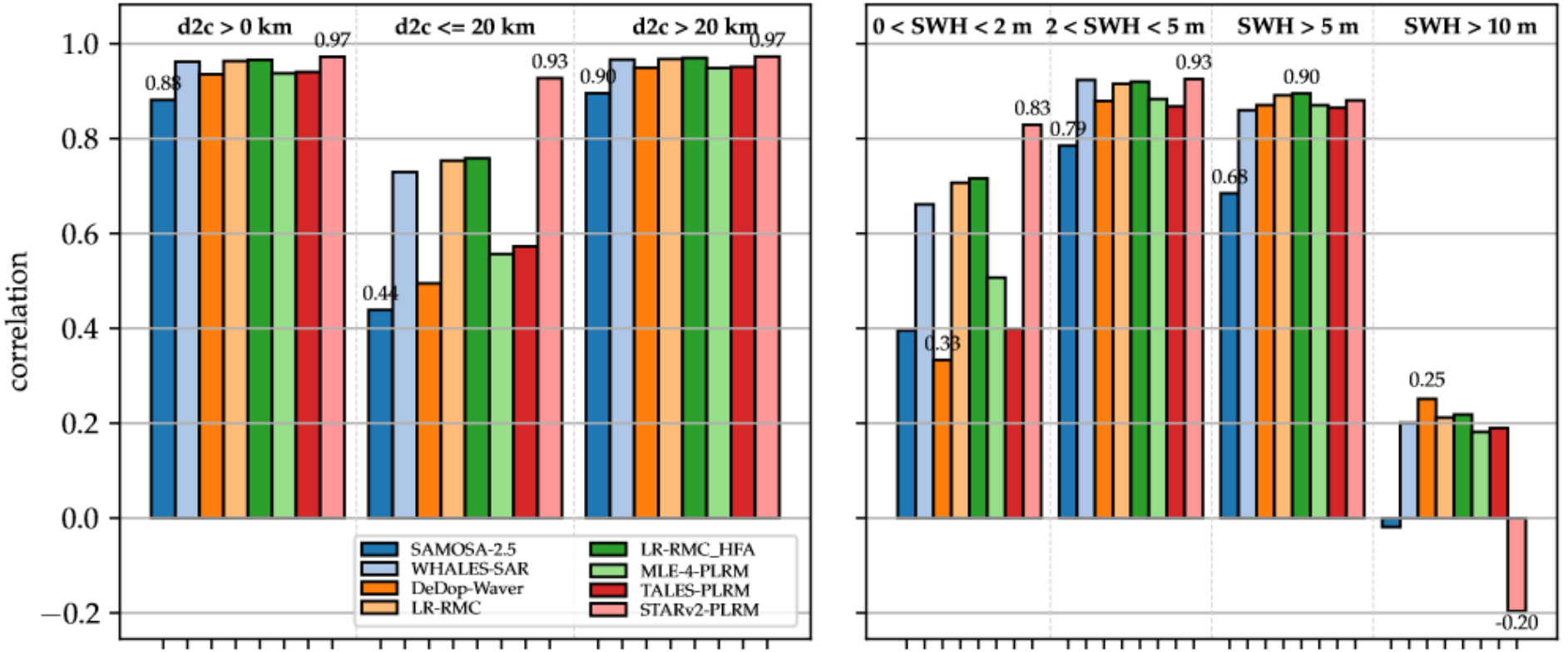
- Correlation: **Jason-3**



In general decreased correlation values in the coastal zone

4.5 Results and Discussion – Comparison with ERA5-h Wave Model (S3A)

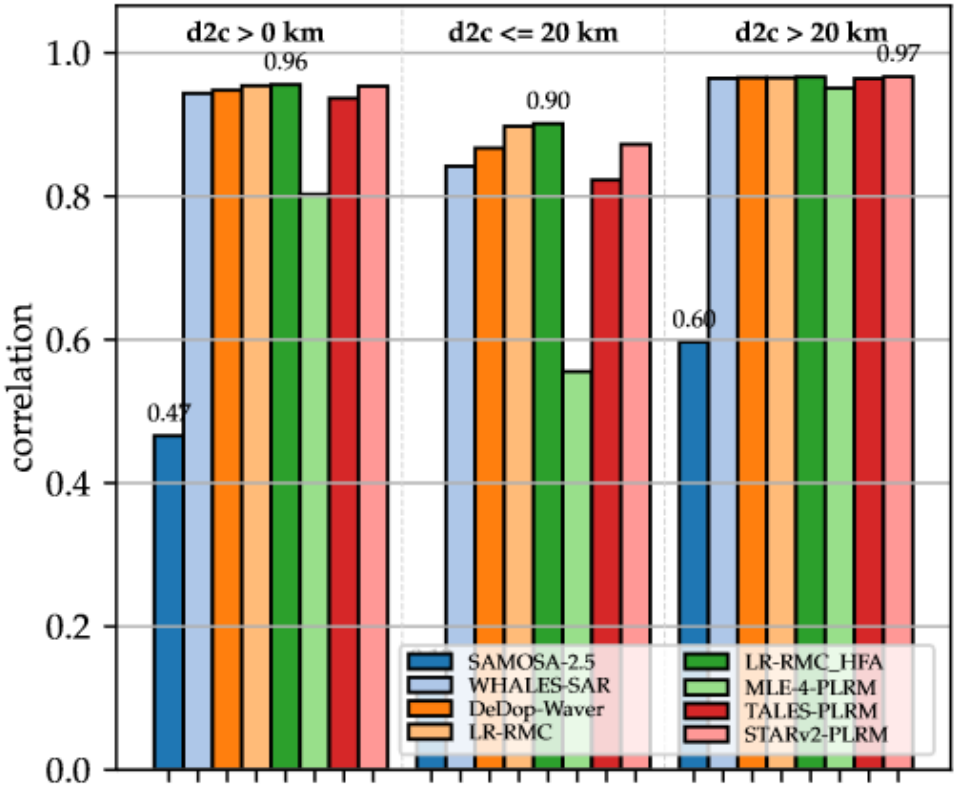
- Correlation: **Sentinel-3A**

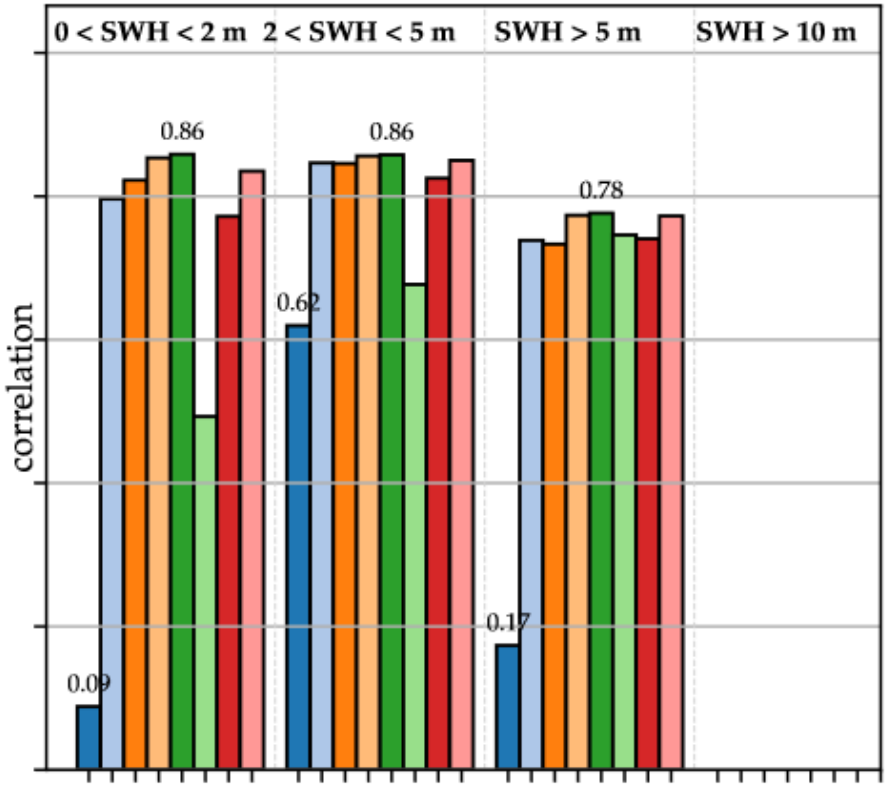


Dist2coast: Good correlation in overall and open-ocean, degraded correlation in coast
SWH: decreased correlation in very high sea states

4.5 Results and Discussion – Comparison with In-situ Buoy Data (S3A)

- Correlation: **Sentinel-3A**





Dist2coast: Good correlation in overall and open-ocean, degraded correlation in coast
SWH: decreased correlation in very high sea states

5. SeaState_cci Selection Process

Definition of weights for different criteria, based on the project‘s objective and a user survey:

- **Qualitative**: The retracker must exhibit a minimum spectral level of → STARv2 was thus excluded

0.2 m^2/(cycles/km) @100km, 0.05 m^2/(cycles/km) @50km ([1] Quilfen and Chapron, 2019)

- **Quantitative**:

Weighting factor	Criteria
0.3	Accuracy against wave models for global areas (SDD)
0.3	Accuracy against coastal buoys (SDD)
0.1	Accuracy against wave models for high sea states (SDD)
0.1	Accuracy against wave models for very high sea states (SDD)
0.1	Intrinsic noise (SD)
0.1	Intrinsic noise for the coastal zone (SD)

Accordingly, the following retrackers’ were selected:

rank \ mode	LRM	DDA
1.	Adaptive	LR-RMC
2.	WHALES	WHALES-SAR

6. Conclusion

- The general performance strongly depends on the user needs‘
- **Significant improvements** as compared to **standard retrackers** MLE-4, SAMOSA-based for open-ocean and coast

Low and high sea states

- **Performance** is still an issue (S3A correlation against ERA5-h model @SWH>10m: less than 0.25)

Coastal zone

- **Significant differences** in **performance** for the retrackers
- **Significantly decreased** number of valid measurements w.r.t. open-ocean (98% to 50%)
- **Performance** has improved significantly w.r.t. baseline solution (correlation of S3A retrackers: 0.15 to 0.90)

- Python framework for reproducing the validation results is available on request: florian.schlembach@tum.de
- Results will be published soon

BACKUP

3. Methods

Metrics for Analysis performed

Type of analysis	In charge of
Outliers	TUM
Noise	TUM
Comparison with in-situ	PML
Comparison with wave models	TUM
Wave spectral variability	PML

*

- Distance-to-coast
  - Definition: It is defined as the distance of each 20-Hz point from the nearest coast
    - **Open-ocean**: dist2coast > 20km, **coast**: dist2coast <= 20km
  - Resolution: 0.01°-grid
  - From PacIOOS, see http://www.pacioos.hawaii.edu/metadata/dist2coast_1deg_ocean.html

3.1 Methods – Outlier Analysis

Types of outliers

1. **invalid**
   - The SWH value is already a NaN value
   - The qual_flag is marks this sample as bad (1)
2. **Out_of_range:**
   - Sample is out of range [-0.25, 25]m
3. **Median absolute deviation (mad):**
   - Per-sample: SWH – median_closest_20 > (3 * MAD_closest_20 * 1.4826)

Evaluated metrics
- Total number of outliers
- Number of outliers in the coastal zone (<20km, <10km, <5km)

Implemented method
- Evaluated 20-Hz SWH data → per netCDF file → 1 report per file
- Individual outlier reports (per netCDF) file are summed up

3.2 Methods – Noise Analysis

Definition of noise: A noise value is defined as the standard deviation of the 20-Hz SWH within a 1-Hz distance.

Evaluated metrics

- Median of all noise values: as a fct. of distance-to-coast (open ocean and coast)
- Median of all noise values: as a fct of sea state **and** distance-to-coast (open ocean and coast)
  - Low sea state: 0m < SWH < 2 m
  - Average sea state: 2m < SWH < 5 m
  - High sea state: SWH > 5 m
  - Very high sea state: SWH > 10 m
- Additionally: median noise values vs. SWH range (0.25 m resolution)

Implemented method

- Full 20-Hz dataset is reduced to 1-Hz dataset
  - SWH (median), lat/lon (median), dist2coast(median)

3.3 Methods – Wave Spectral Analysis

The along-track spectra of the SWH is computed for open-ocean segments.

Evaluated metrics
- Power spectral density (PSD) of the along-track data
- Mean spectral power for spatial scale between 100-50 km and 50-25 km

Implemented method
- Welch spectra
  - 1024-points segments
  - Using a Hann-window
  - 50% overlap of the segments
  - Only segments with at least 95% of valid data is used
  - Missing data is filled with linearly interpolated data

3.4 Methods – Comparison against Wave Model

Model grid points and altimetry will be coupled by considering the median of the SWH 20-Hz measurements from altimetry within the grid point.

Evaluated metrics

Retracker dataset vs. Wave model (both ERA5 and ERA5-h)

- Correlation
- Slope of linear fit
- Standard deviation of differences (SDD)
- Median bias of differences

Implemented method

- Full 20-Hz dataset is reduced to 1-Hz dataset
- The full 1-Hz dataset is analysed using linear regression
- Values that are out-of-range [-0.25, 25]m are set NaN

3.5 Methods – Comparison against In-situ Buoy Data

The closest 51 20-Hz along-track altimetry points will be coupled with the buoy records.

Evaluated metrics

Retracker dataset vs. in-situ buoy data

- Correlation
- Slope of linear fit
- Standard deviation of differences (SDD)
- Median bias of differences

Implemented method

- Distance between buoys and along-track < 50 km
- Time difference between the buoy data record and along-track points < 30 min
- 51 closest 20-Hz points are considered
- 2 h (3-point) moving average filter is applied to buoy data
- Three-sigma outliers, out_of_range outliers are excluded

3.4 Methods – Reading the Datasets

- An 20-Hz SWH value is set NaN if
  - The SWH value is already a NaN value
  - The qual_flag vector is flagged as bad (1)
  - The sea_ice vector of referenced L2 dataset is flagged (1) (exception S3 temporarily)
  - All values around 0.0 with tolerance 1e-4 (to avoid retrackers' "forced absolute zeros")
- Distance-to-coast is computed according corresponding lat/lon values based on PacIOOS' 0.01° grid

3.5 Methods – 1-Hz Reduction

Required for

- Noise analysis
  - A noise value is defined as 1-Hz data (1 noise value – stddev of 20 points)
- Comparison with model
  - Models‘ resolution is based on 1-Hz grid data
  - System memory constraints to perform a full 20-Hz correlation analysis

Method

- Lattidude/longitude
  - 20-Hz lat/lon → median(lat/lon) → 1-Hz lat/lon
- SWH
  - Take only median if at least 17 values are non-NaN → otherwise set SWH=NaN
  - 20-Hz lat/lon → at_least_17_non_nans(median(SWH)) → 1-Hz SWH

3.6 Methods - Retracker Validation Framework

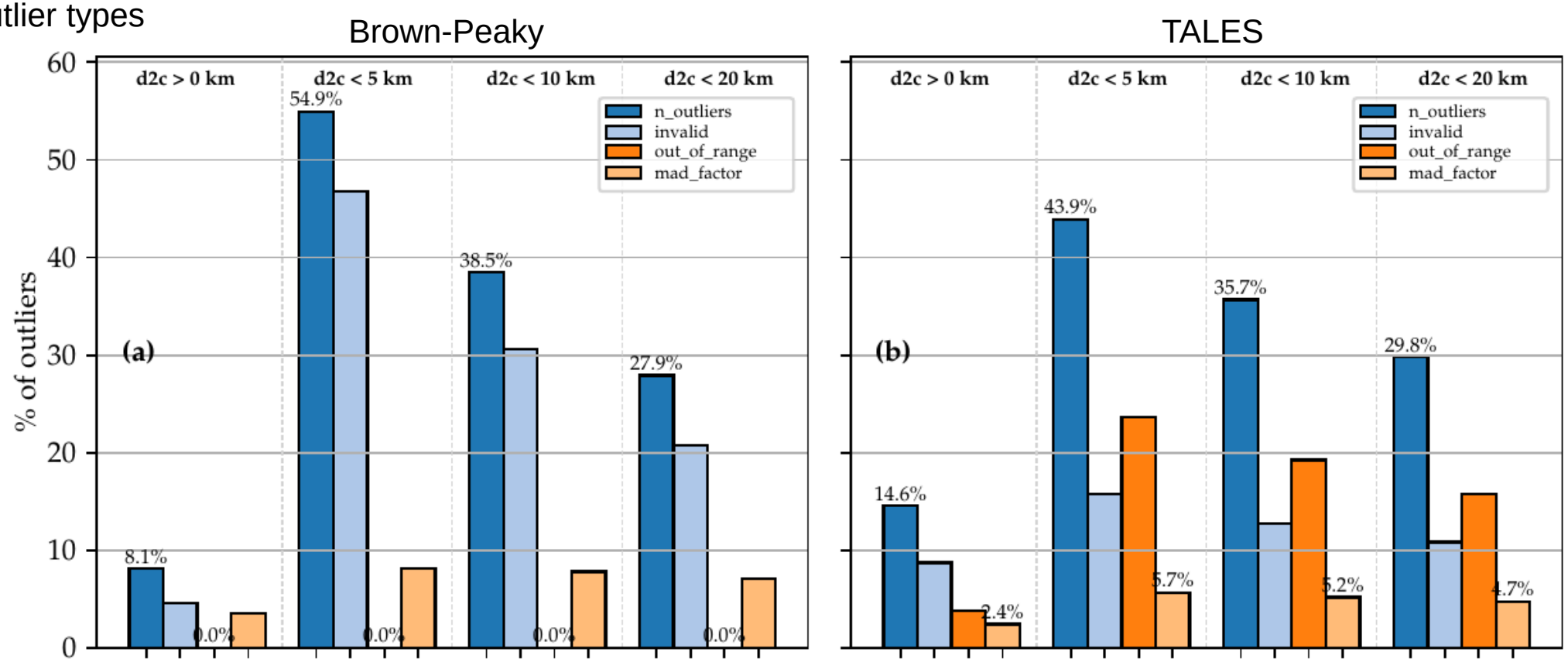
Retracker validation (retrackval) framework

- Fully-automated scripts, written in Python 3.x
- Features
  - Python package
  - Python dependencies are managed using a conda environment
  - Unit-tests
  - Platform-independent
- Git repository includes all submitted datasets (using large file storage)
- Easy-to-use: About 10 commands → assessment can be reproduced

- Computational effort: outlier + noise + comparison against model + wave spectra variability
  - 19 retracked datasets: about 15 hours (on 35 parallel threads @ 2.20 GHz)

4.1 Results and Discussion – Outlier Analysis

- Outlier types

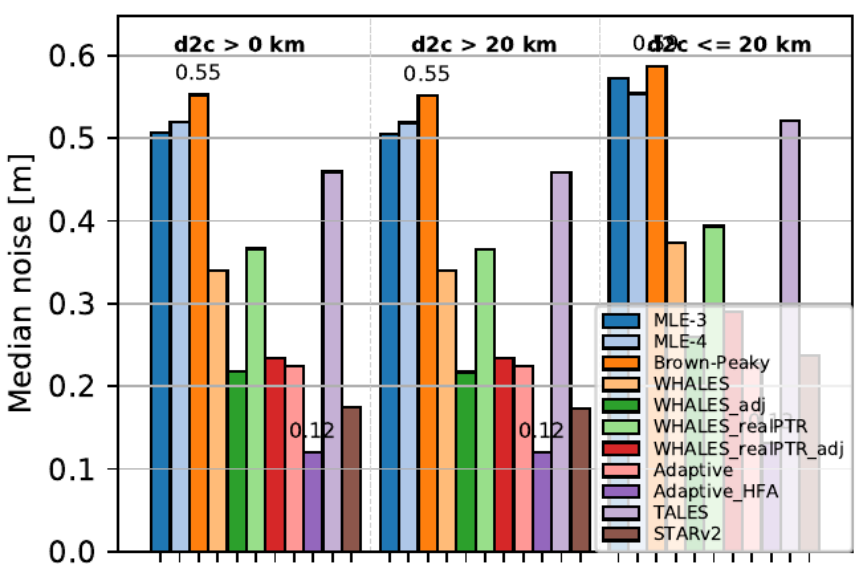


Dominant type of outliers are of type invalid (increasing with a decreased dist2coast), mad_factor ~ constant

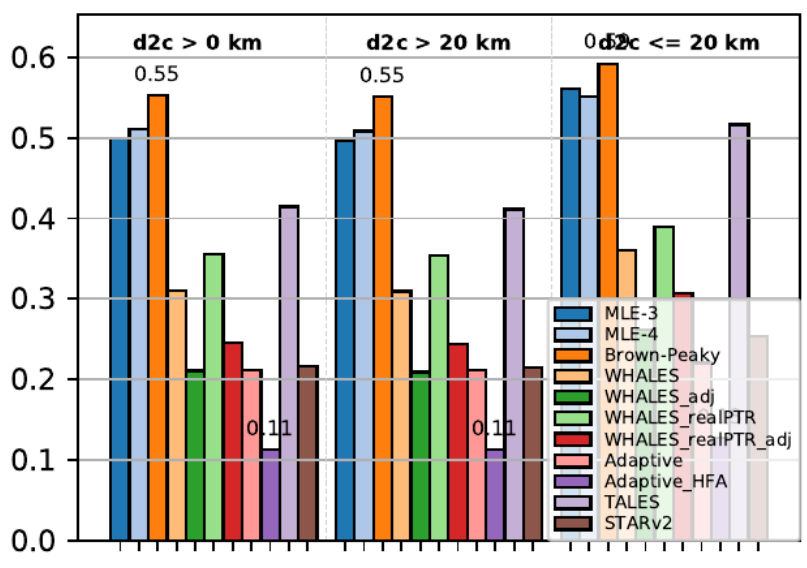
4.2 Results and Discussion – Noise Analysis (Jason-3)

- Median noise

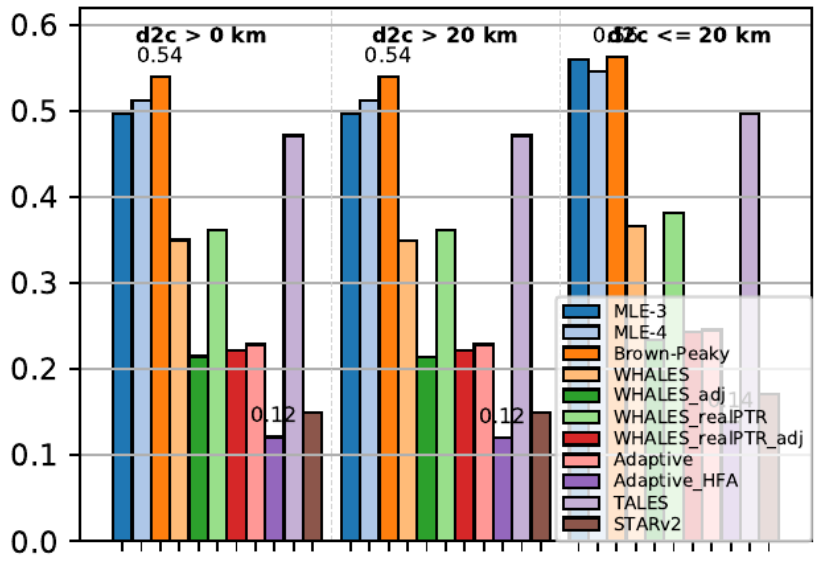
Full SWH range



Low sea state: 0m < SWH < 2 m



Average sea state: 2 < SWH < 5 m

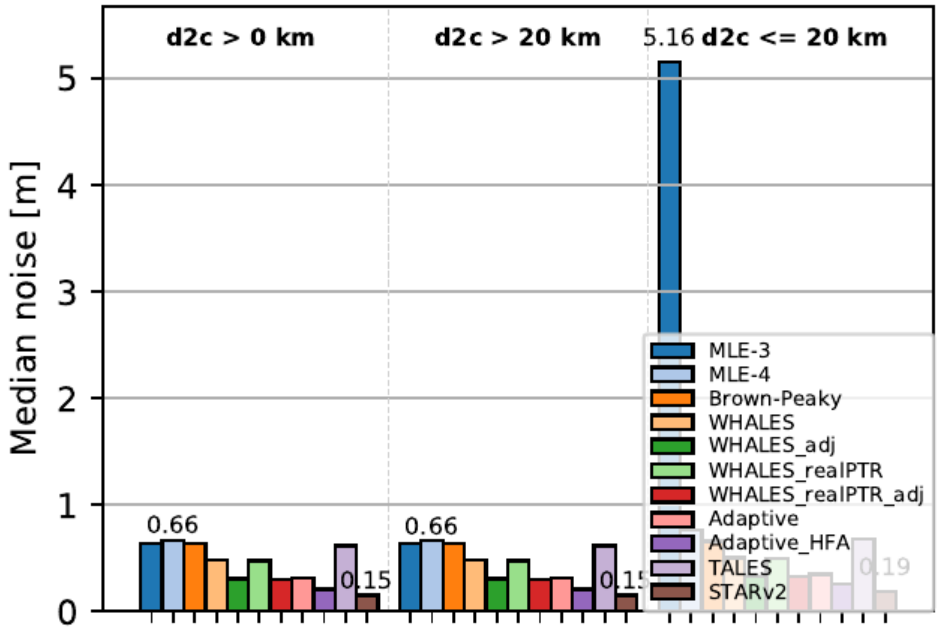


Adaptive (STARv2) has the best (second best) noise characteristic in **overall, low, average sea states**
→ minor dependency in open-ocean vs. coast in low and average sea state

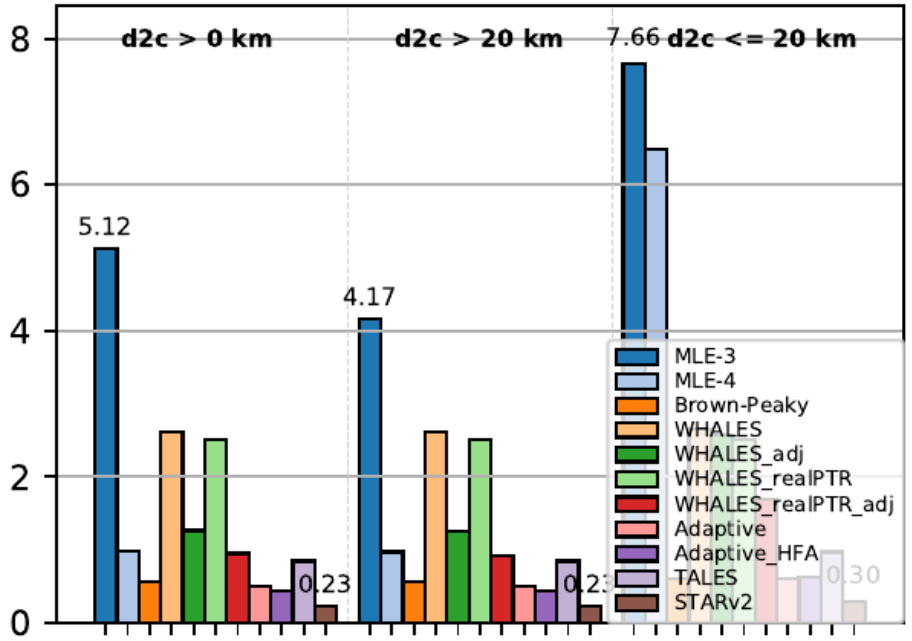
4.2 Results and Discussion – Noise Analysis (Jason-3)

- Median noise

High sea state: SWH > 5 m



Very high sea state: SWH > 10 m

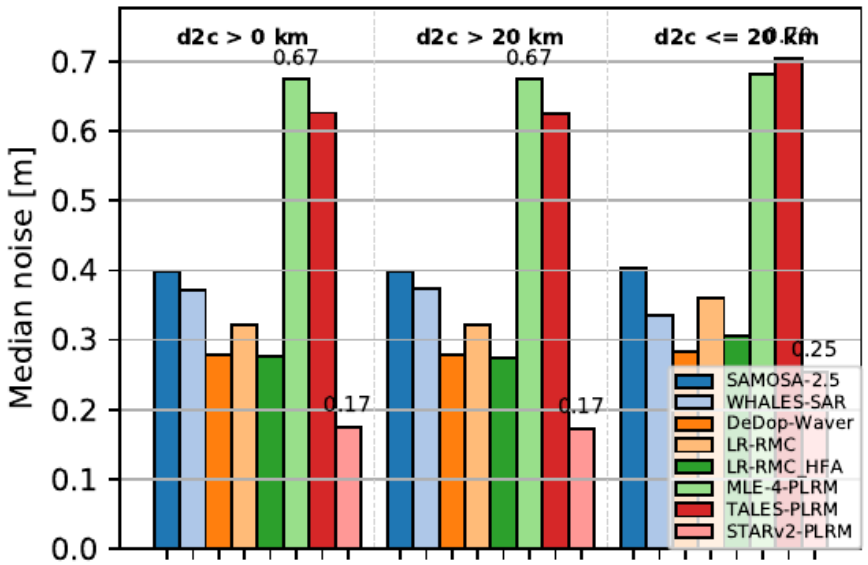


STARv2 is best in **high, very high** sea states
High noise level: **coast** + high/very high SWH

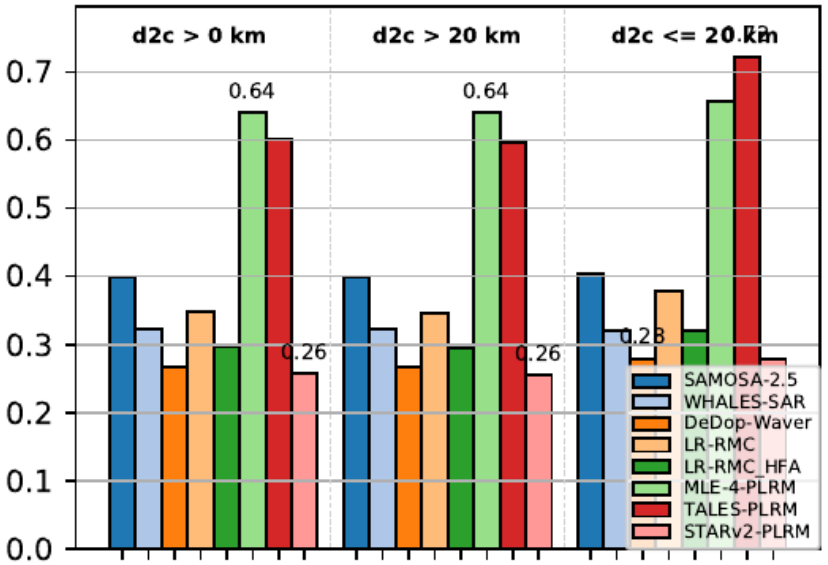
4.2 Results and Discussion – Noise Analysis (Sentinel-3A)

- Median noise

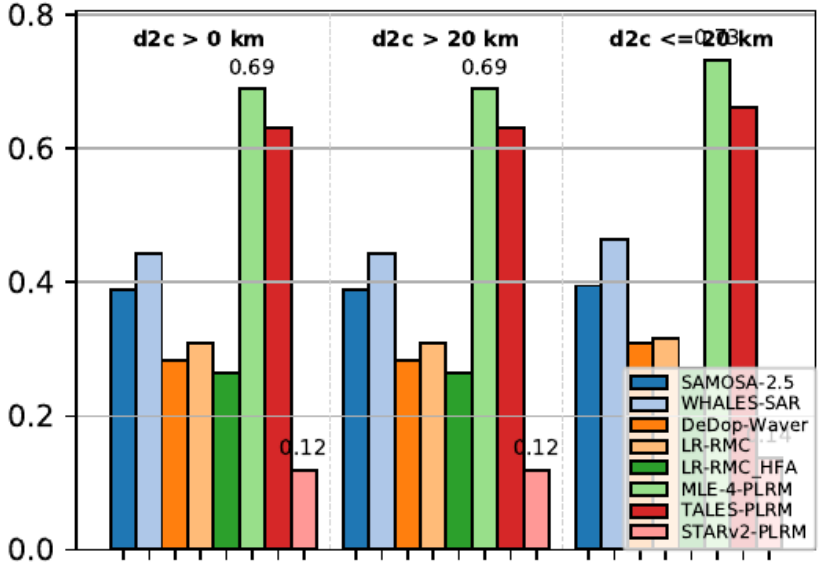
Full SWH range



Low sea state: 0m < SWH < 2 m



Average sea state: 2 < SWH < 5 m

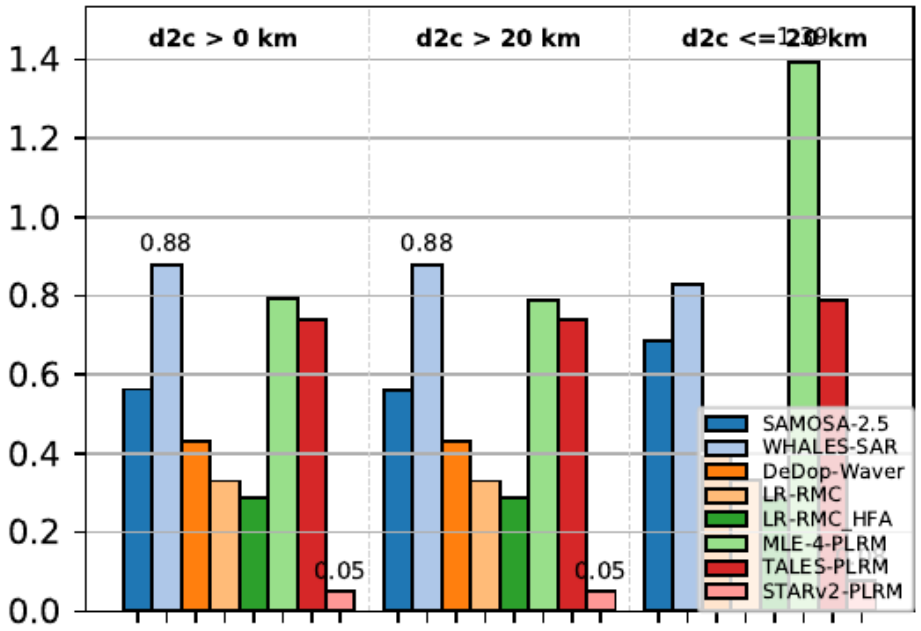


STARv2 is **all sea states**
→ minor dependency in open-ocean vs. coast in low and average sea state

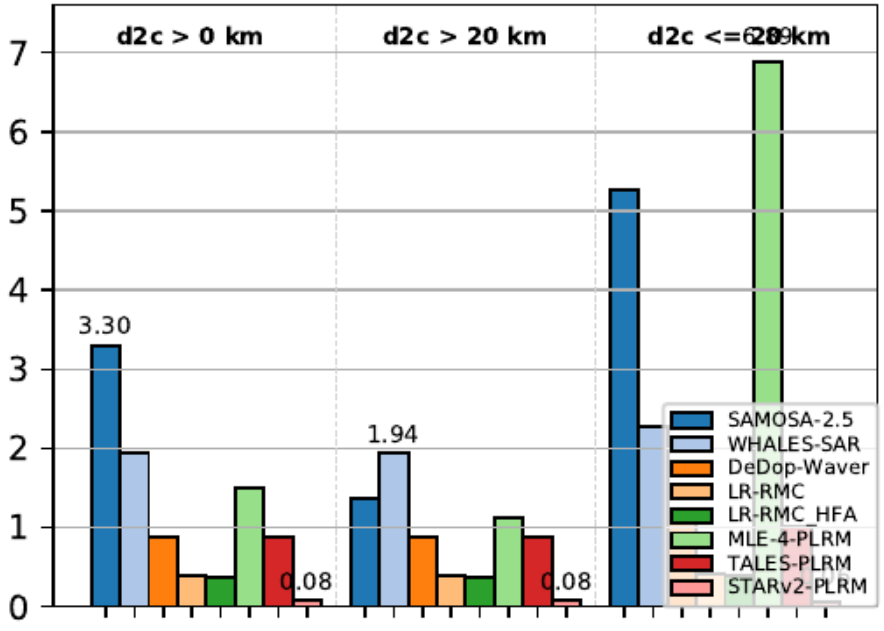
4.2 Results and Discussion – Noise Analysis (Sentinel-3A)

- Median noise

High sea state: SWH > 5 m



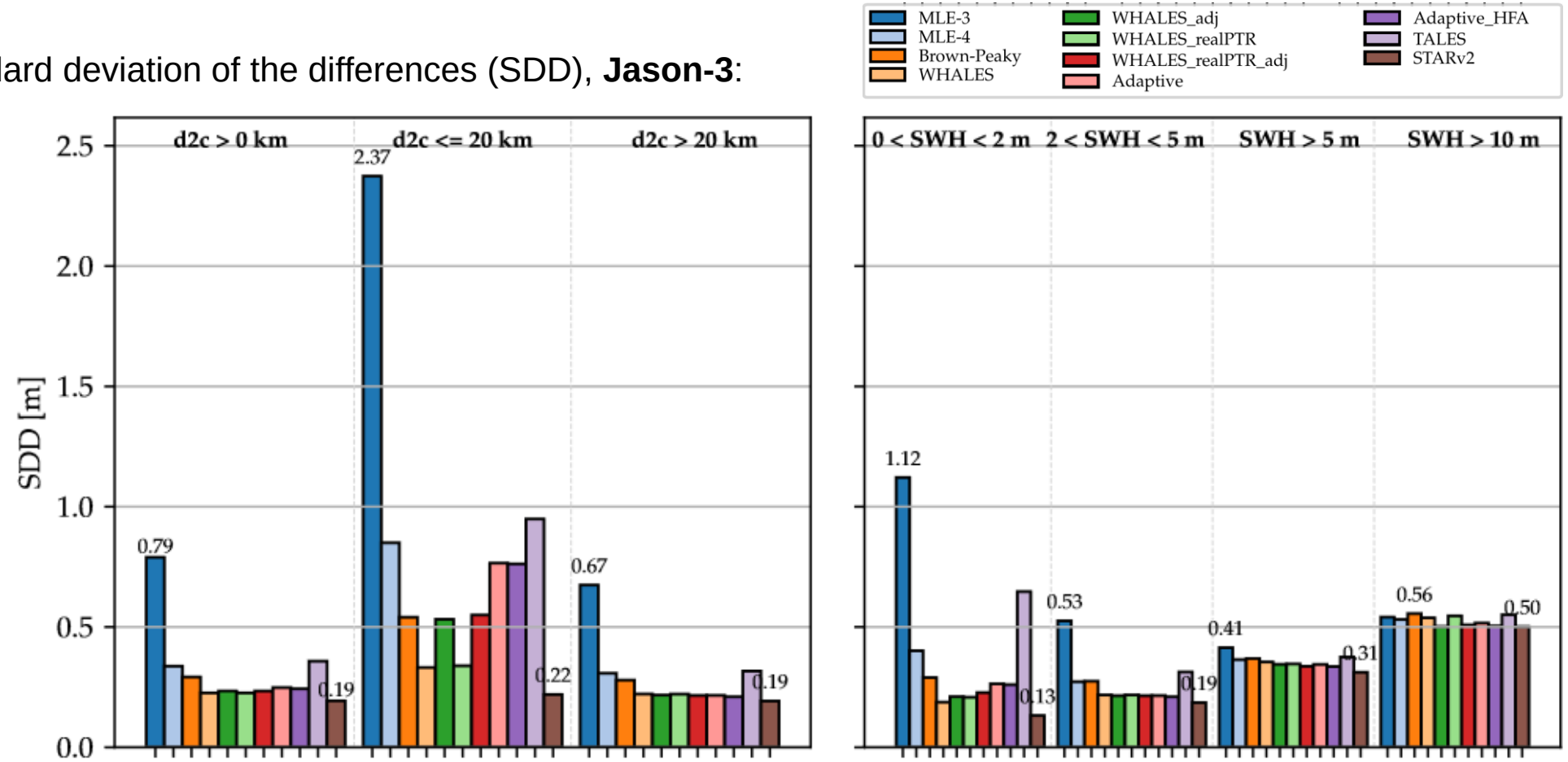
Very high sea state: SWH > 10 m



STARv2 is best in **high, very high** sea states
High noise level: **coast** + high/very high SWH

4.4 Results and Discussion – Comparison with ERA5-h Wave Model (J3)

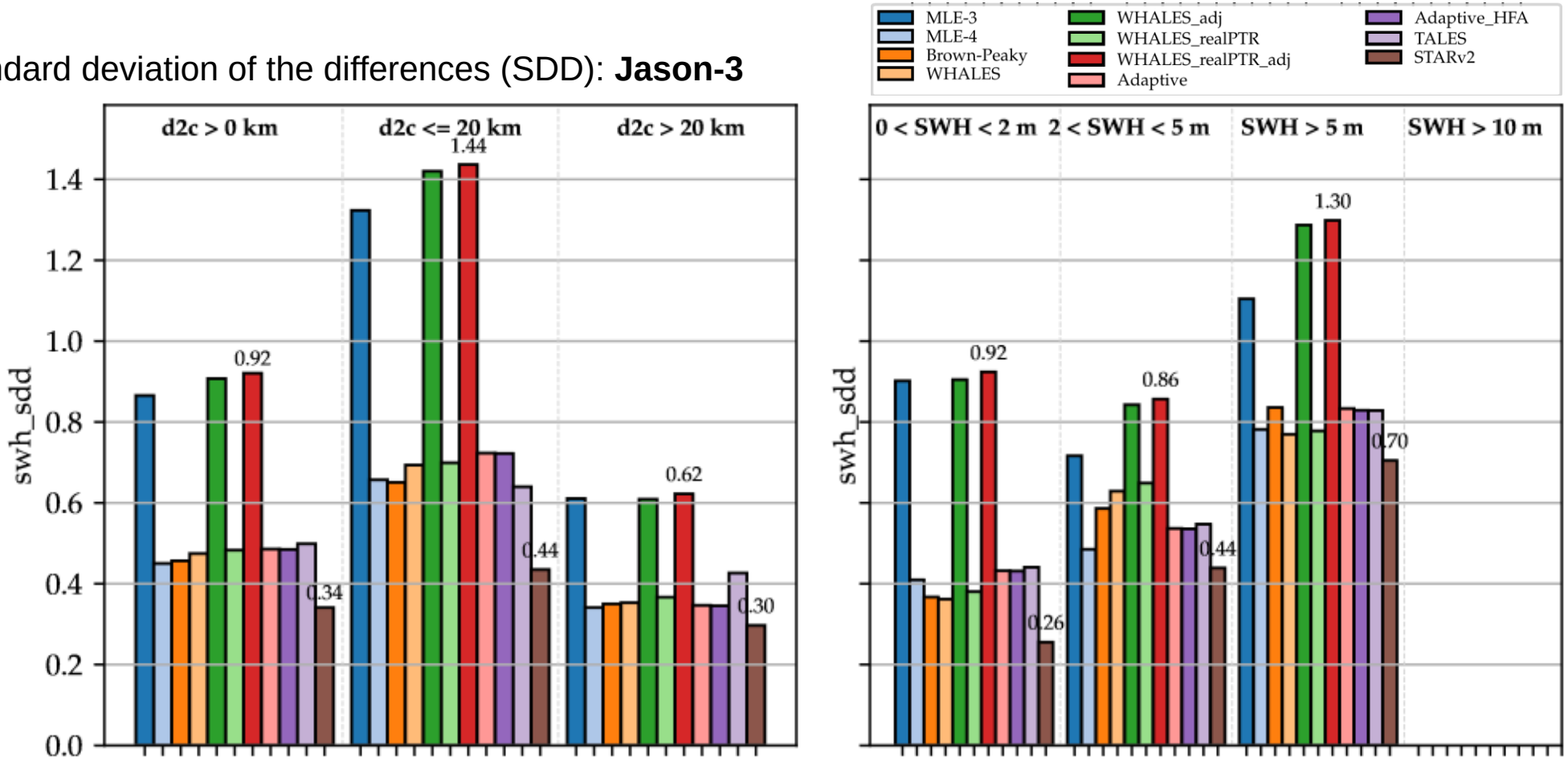
- Standard deviation of the differences (SDD), **Jason-3**:



Dist2coast: Increased SDD in coastal zone.
SWH: slightly increased SDD in high and very high sea states.

4.4 Results and Discussion – Comparison with In-situ Buoy Data (J3)

- Standard deviation of the differences (SDD): **Jason-3**

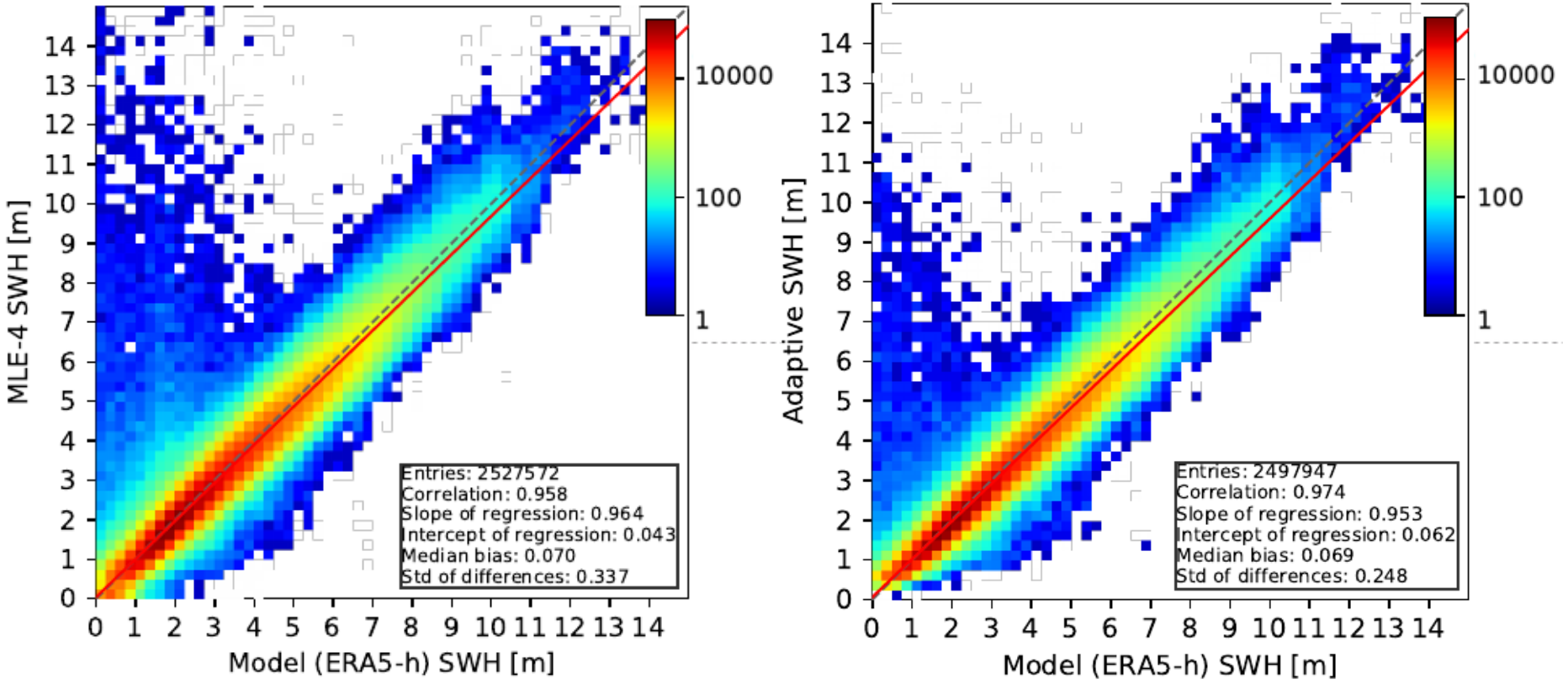


Dist2coast: Increased SDD in coastal zone.

SWH: Increasing SDD for average and high sea states.

4.4 Results and Discussion – Comparison with ERA5-h Wave Model (J3)

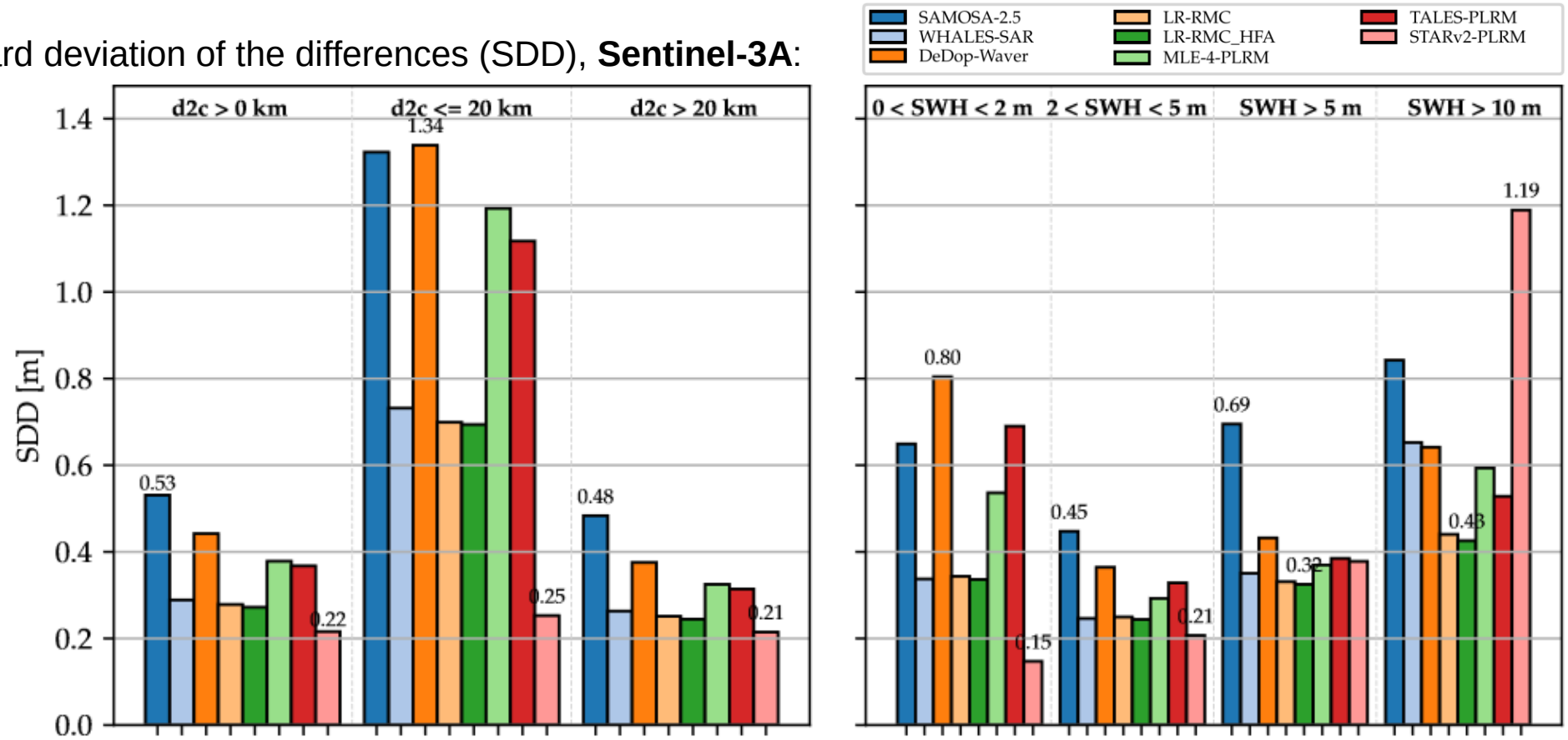
- 2D-histogram plot (comparison against ERA5-h): MLE-4 vs. Adaptive



Correlation was significantly improved in comparison to the standard SAMOSA-based retracker

4.5 Results and Discussion – Comparison with ERA5-h Wave Model (S3A)

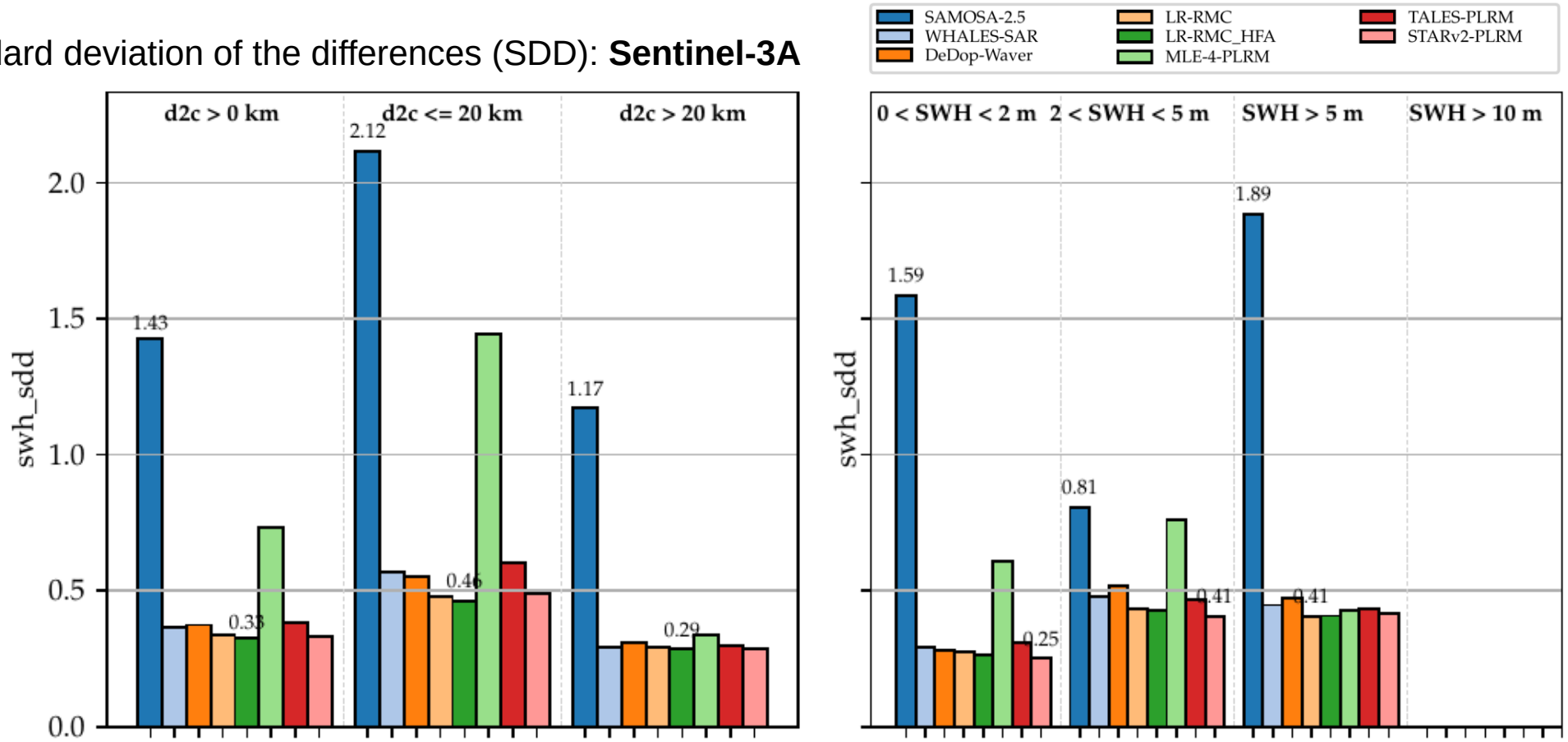
- Standard deviation of the differences (SDD), **Sentinel-3A**:



Dist2coast: Increased SDD for coastal zone.
SWH: Increasing SDD for high sea states.

4.5 Results and Discussion – Comparison with In-situ Buoy Data (S3A)

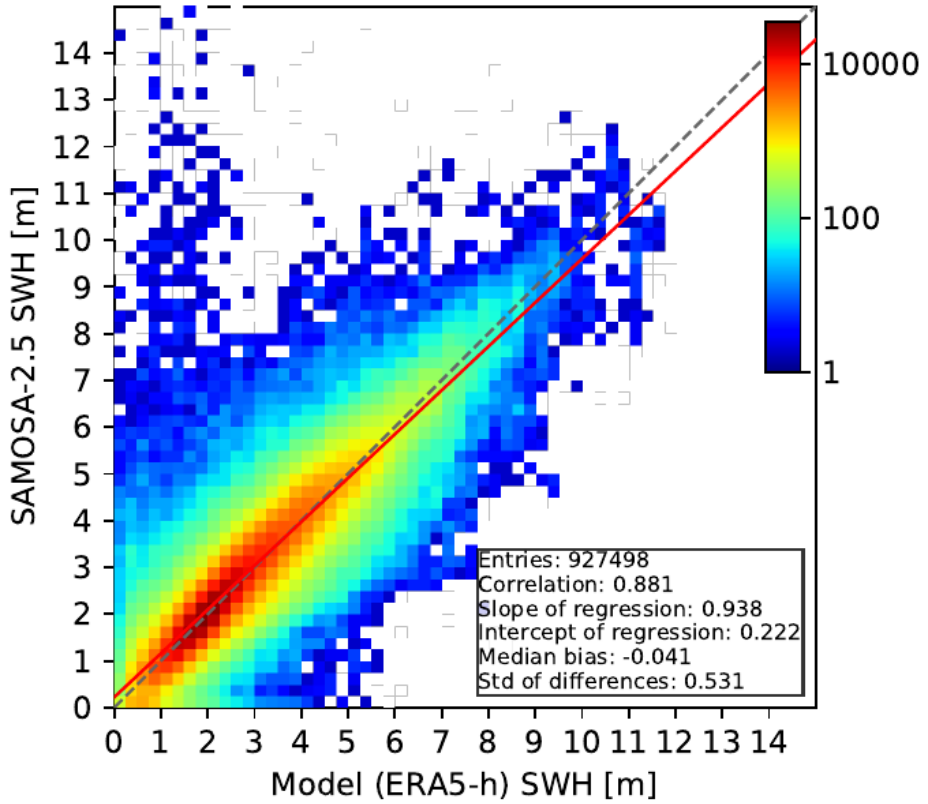
- Standard deviation of the differences (SDD): **Sentinel-3A**

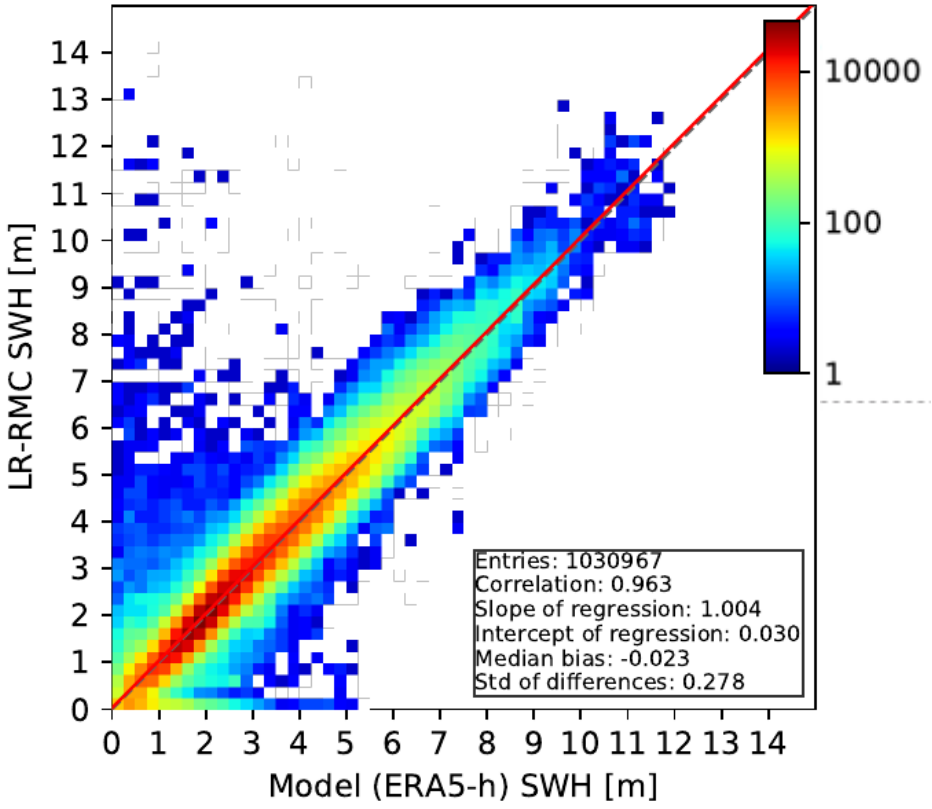


Dist2coast: Increased SDD for coastal zone.
SWH: Slightly increased SDD for average and high sea states.

4.4 Results and Discussion – Comparison with ERA5-h Wave Model (S3A)

- 2D-histogram plot (comparison against ERA5-h): SAMOSA-based vs. LR-RMC





Correlation was significantly improved in comparison to the standard SAMOSA-based retracker