OSTST 2026

Presentation

A wave-effect mitigation SAR processing applied to Sentinel-6A

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Rationale

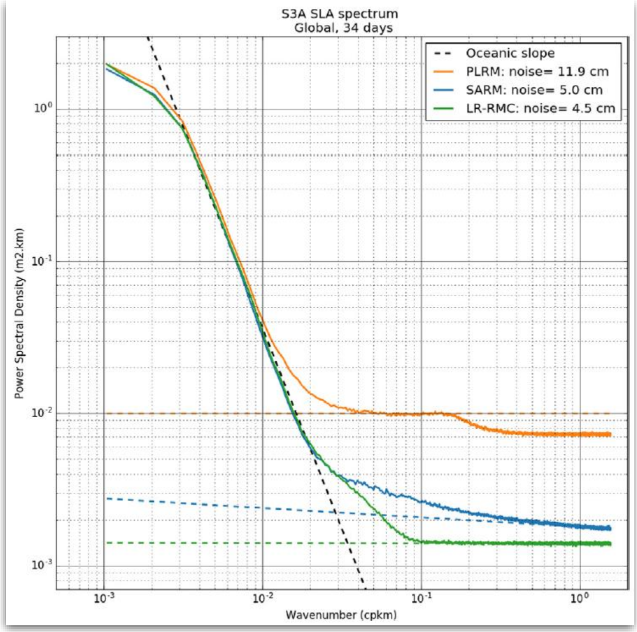
- **UF-SAR observations are sensitive to sea surface heterogeneities** (sigma0, waves, swell – e.g. Aouf and Phalippou 2015, Abdalla & Dinardo 2016, Raynal et al. 2016, Reale et al. 2020, Rieu et al. 2021, Moreau et al. 2021 – Talk by F. Ehlers just next) enabling detection of some small-scale ocean features such as swells (Altiparmaki 2022, Rodet 2026) but **currently limiting sub mesoscale topography retrieval**

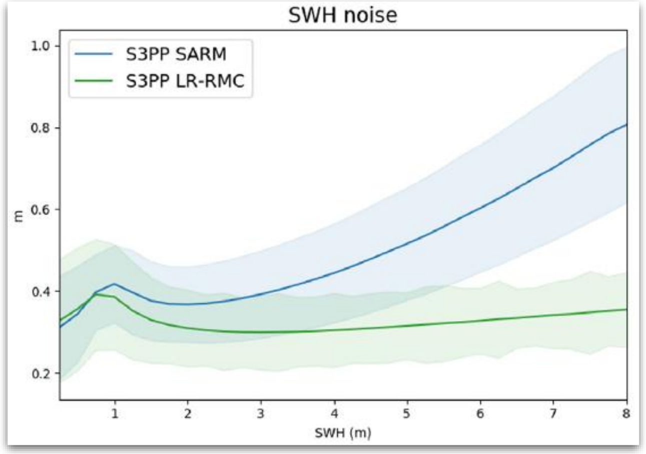
- Significant correlated errors at sub mesoscales on UF-SAR measurements (also observed on LR as the hump artefact): red noise signature on the sea level anomaly power spectral density dominating oceanic signal below ~70 km (e.g. Raynal et al. 2017, Vergara et al. 2019) mainly due to wave groups (De Carlo, 2024) but also e.g. internal waves

- The low-resolution with range migration correction (LR-RMC, Phalippou & Demeestere OSTST 2011, Boy et al. OSTST 2017) was designed to mitigate these effects

- The coarser footprint of LR-RMC w.r.t. UF-SAR smooths surface waves and attenuates correlated errors at sub mesoscales, yielding noise levels with negligible dependency on sea state (Moreau et al. 2021, Ehlers et al. 2025)

- However, as UF-SAR the LR-RMC exploits Doppler shifts and is **sensitive to sea surface dynamics** (Alpers et al. 1981, Alpers and Bruening 1986), which can be accounted for by applying recent **2D retracking models** that include the effect of surface motions (Buchhaupt et al. 2023)





Moreau et al. (2021)

Rationale

Assess the performance of the LR-RMC on Sentinel-6A data, namely when combined with 2D retracking, and highlight its potential applications

LR-RMC processing

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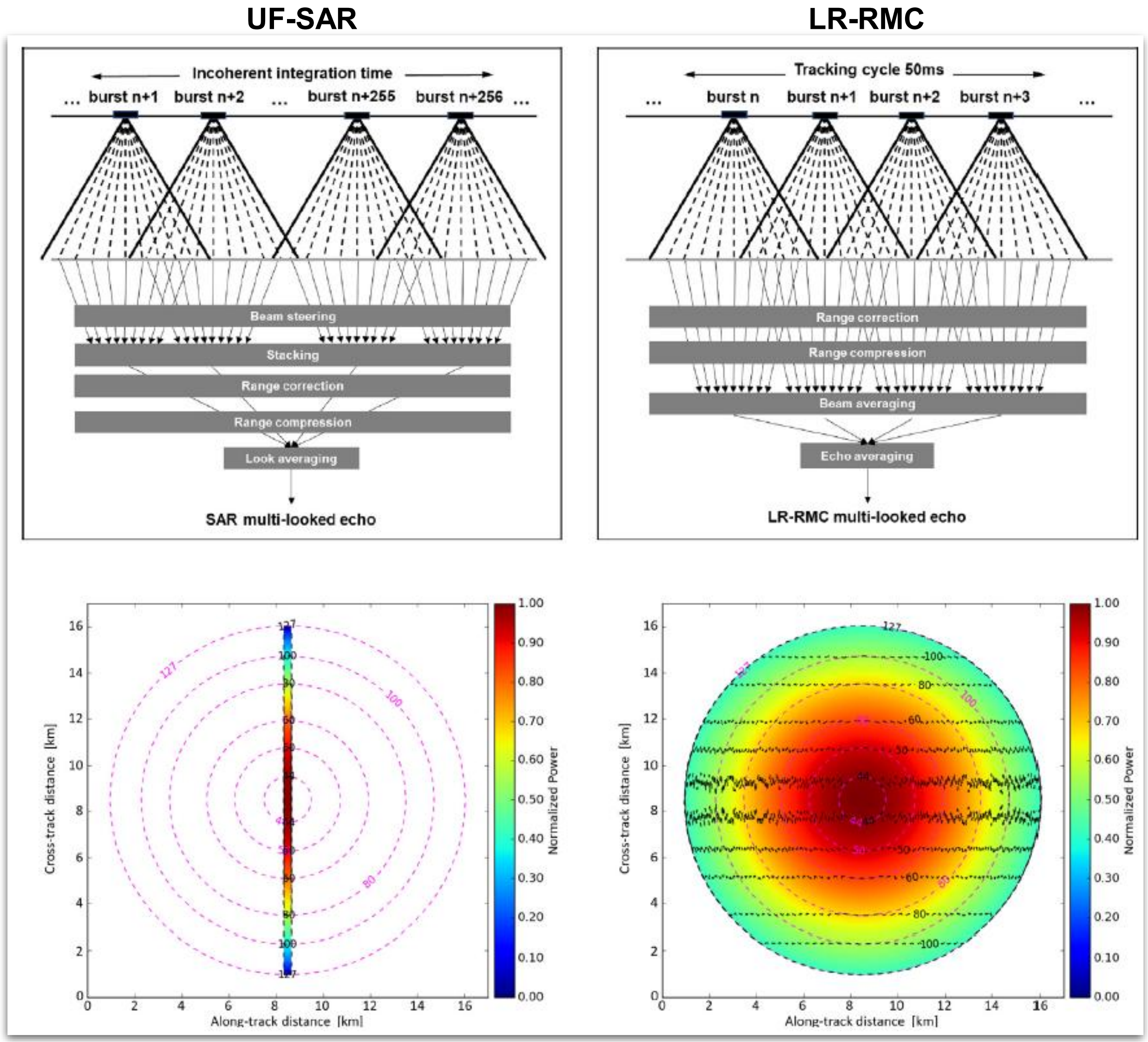

Moreau et al. (2021): Altimeter footprint geometry (bottom) with range bins of LRM (fushia dotted lines) and SAR/LR-RMC (black dotted lines) waveforms.

- Coherent combination of pulses within a burst to form a Delay Doppler map (DDM) with range walk correction;
- Doppler centroid shift, to centre the DDM at nadir, and range migration correction: Doppler, slant, tracker, mean sea surface (MSS) slope and curvature;
- Range-aligned beams of the DDM are summed incoherently;
- These are further averaged within a radar cycle (64 beams x 7 bursts for S6), resulting in a multi-beam echo at 20 Hz.

As a result:
LR-RMC uses the **same number of looks** as UF-SAR but its footprint and therefore its along-track **resolution is coarser**.

Processing setup

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CNES-CLS Sentinel Processing Prototype (SPP, Dinardo et al. 2023, **Poster by O. Gassot OSTST 2026**) to process S6A cycle 180 (27/09/2025 – 07/10/2025):

L1 (Beam sampling 1; 322 equivalent looks)	**L2 (Skewness 0.1)**			
		1D-3P	**2D-4P**	**2D-5P**
		A, ε, SWH	A, ε, SWH, σ_v	A, ε, SWH, σ_v, u_x
	LR-RMC	x	x	x
	UF-SAR			x

A = amplitude
ε = epoch
SWH = significant wave height
σ_v = standard deviation of the vertical wave motions
u_x = along-track geophysical Doppler
(**Talk by L. Rodet**, Wind & waves session)

SSHA vs LR

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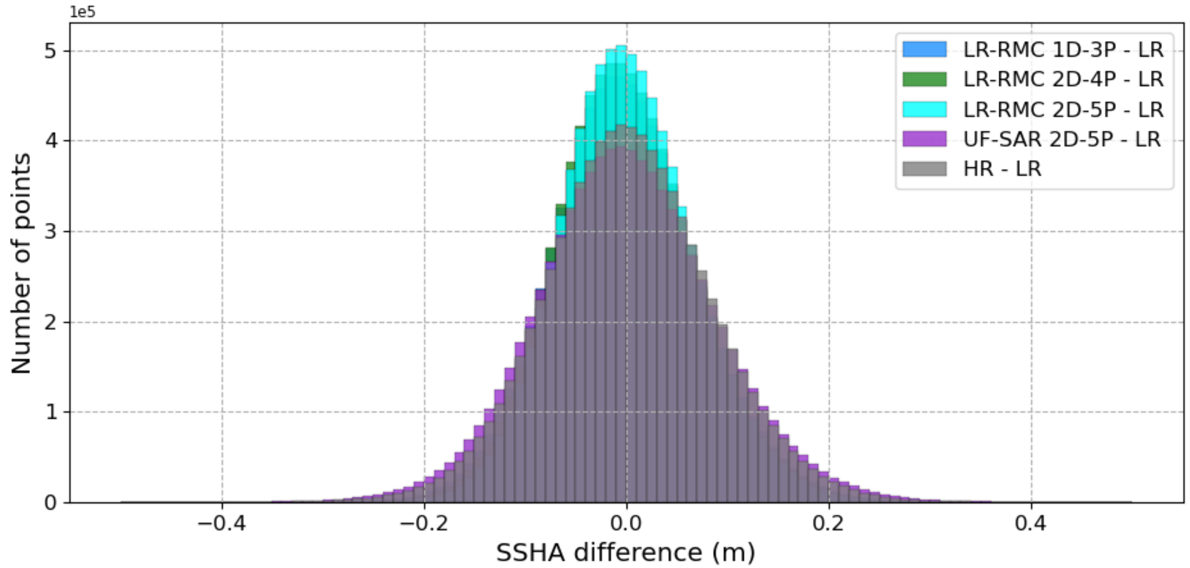
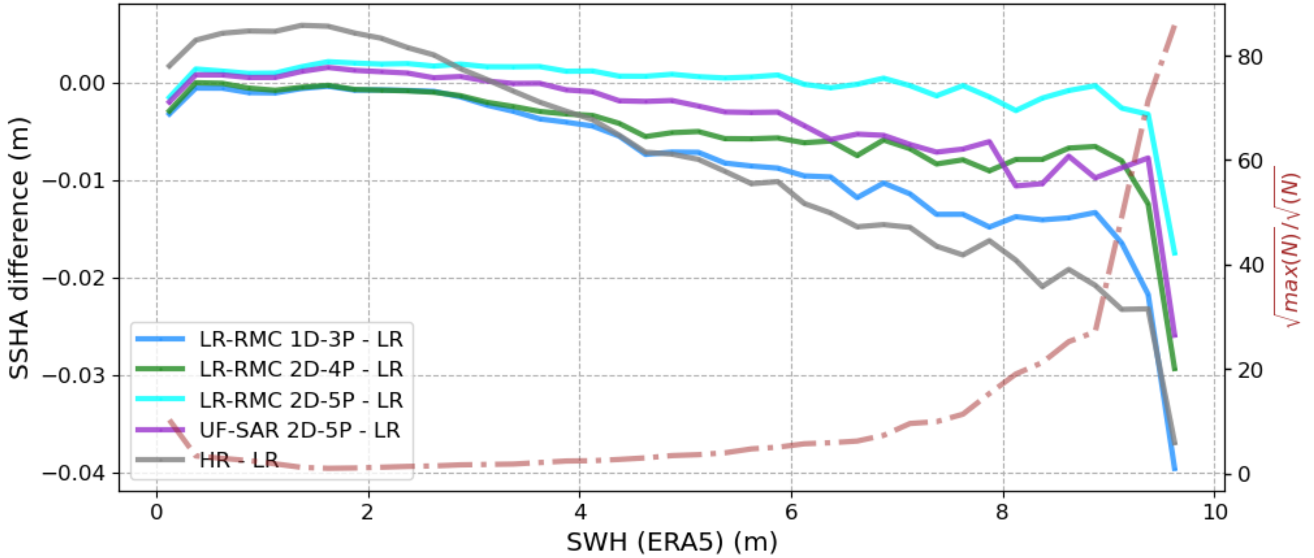
	nbr	min	mean	median	max	std
LR-RMC 1D-3P - LR	8.241e+06	-0.7772	-0.001854	nan	0.4821	0.07285
LR-RMC 2D-4P - LR	8.241e+06	-0.6595	-0.001442	nan	0.4681	0.07059
LR-RMC 2D-5P - LR	8.241e+06	-0.705	0.001648	nan	0.4933	0.06803
UF-SAR 2D-5P - LR	8.241e+06	-0.7171	0.0004727	nan	0.6752	0.08875
HR - LR	8.241e+06	-0.6331	0.002337	nan	0.6317	0.08349



	nbr	min	mean	median	max	std
LR-RMC 1D-3P - LR	39	-0.03962	-0.007932	-0.007145	-0.000345	0.007593
LR-RMC 2D-4P - LR	39	-0.02936	-0.005044	-0.005121	1.154e-05	0.005001
LR-RMC 2D-5P - LR	39	-0.01747	-9.703e-05	0.0006774	0.002173	0.003147
UF-SAR 2D-5P - LR	39	-0.02593	-0.003546	-0.001968	0.001581	0.005146
HR - LR	39	-0.03698	-0.007657	-0.007329	0.00591	0.01055



Residual 2 mm difference for HR (Buchhaupt et al. 2023);
Lowest difference found for UF-SAR 2D-5P (Rodet et al.);
Slightly lower std for the LR-RMC solutions.

Best agreement obtained for the LR-RMC 2D-5P;
Uncertainty on the data points (grey dot-dashed line) increases significantly beyond SWH = 8 m.

2D model applies well to the LR-RMC data

SWH vs LR

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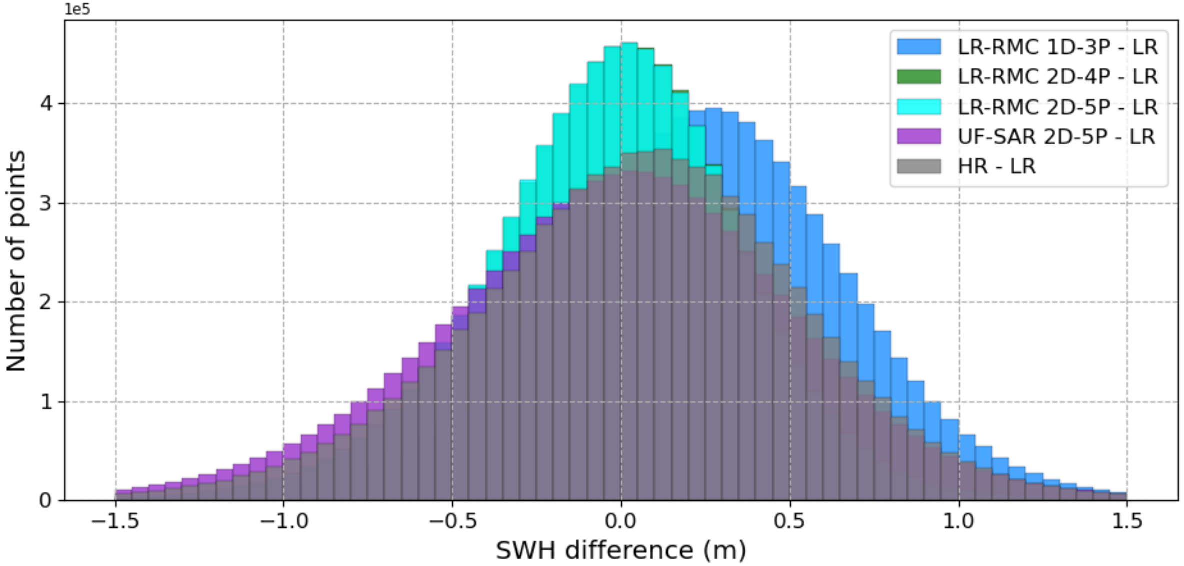
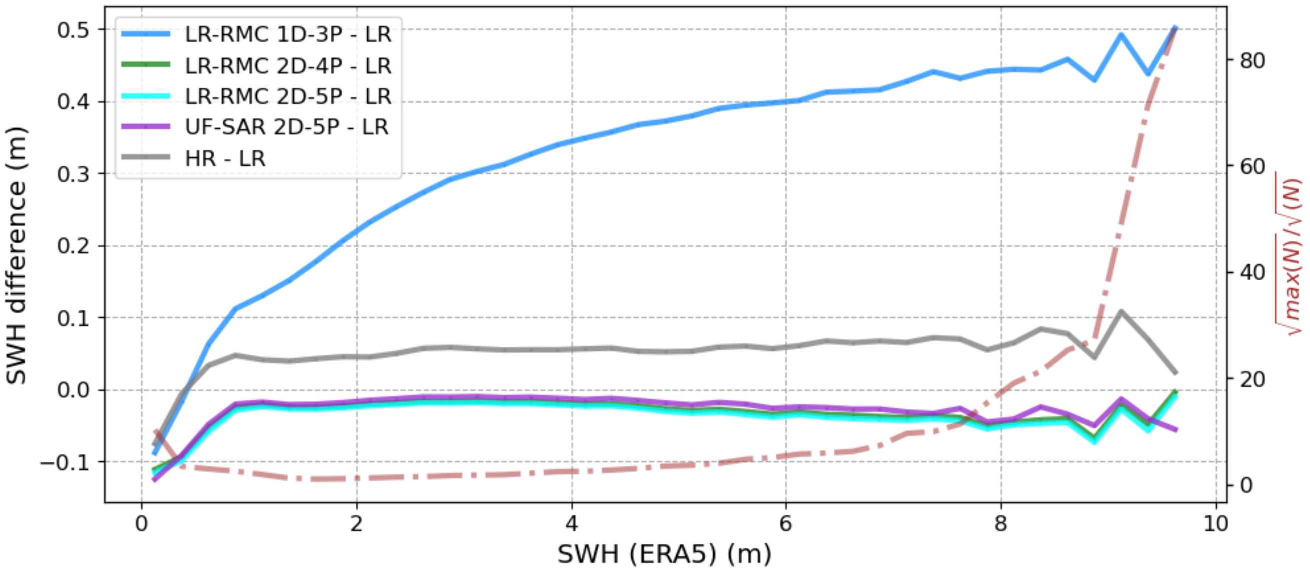
	nbr	min	mean	median	max	std
LR-RMC 1D-3P - LR	8.241e+06	-10.53	0.2368	nan	4.633	0.4469
LR-RMC 2D-4P - LR	8.241e+06	-9.739	-0.02357	nan	4.252	0.3923
LR-RMC 2D-5P - LR	8.241e+06	-9.734	-0.02625	nan	4.246	0.3928
UF-SAR 2D-5P - LR	8.241e+06	-10.73	-0.01825	nan	4.569	0.5364
HR - LR	8.241e+06	-10.68	0.0474	nan	4.169	0.5041



	nbr	min	mean	median	max	std
LR-RMC 1D-3P - LR	39	-0.08822	0.3244	0.372	0.5011	0.139
LR-RMC 2D-4P - LR	39	-0.1116	-0.03389	-0.02795	-0.004377	0.02035
LR-RMC 2D-5P - LR	39	-0.1158	-0.03779	-0.03191	-0.01077	0.02102
UF-SAR 2D-5P - LR	39	-0.1249	-0.02871	-0.02155	-0.01033	0.02229
HR - LR	39	-0.07578	0.05185	0.05587	0.1078	0.02699



24 cm difference for LR-RMC 1D-3P as expected;
With σ_v the differences decrease to about 2-3 cm;
Slightly higher for HR – correction based on look up tables, probably some fine tuning could be done?

The three 2D solutions give similar results: only 2-4 cm variation with sea state.

2D model applies well to the LR-RMC data

SSHA spectra

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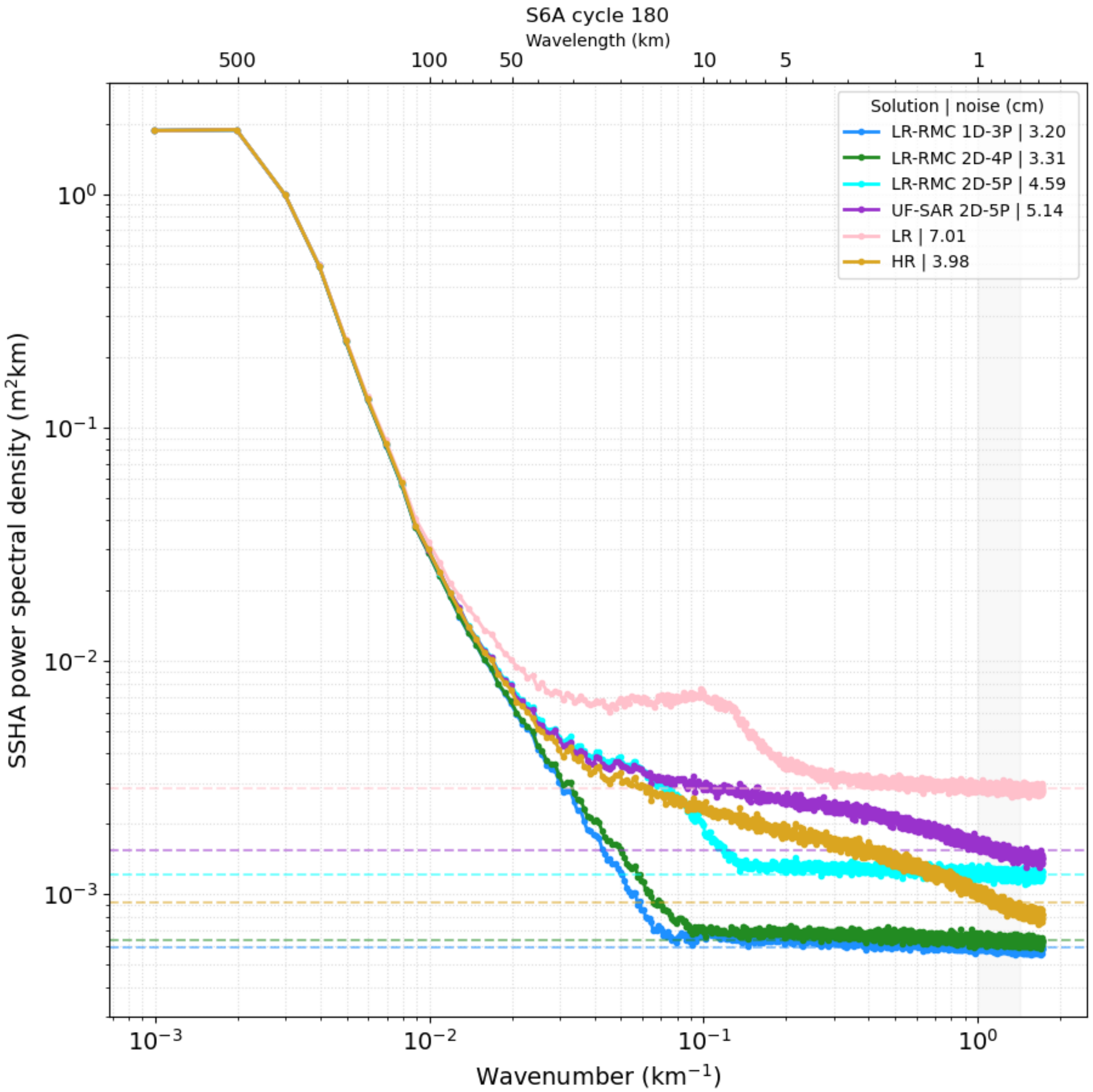

LR-RMC 1D spectrum:

- flat at scales below 10 km – consistent with white noise and the lowest obtained
- Slope break around 50 km – correlated to swell conditions and sigma0 inhomogeneities
- similar to that of S3 (Moreau et al. 2021)

LR-RMC 2D spectrum:

- With the 5P an LRM-like bump appears… which disappears when u_x is dropped from the fit (4P)
- Fitting for u_x picks up higher frequencies in SSHA

LR-RMC 2D-5P gives the lowest global SSHA difference w.r.t. LR – but the picture changes with the spectra!

SWH spectra

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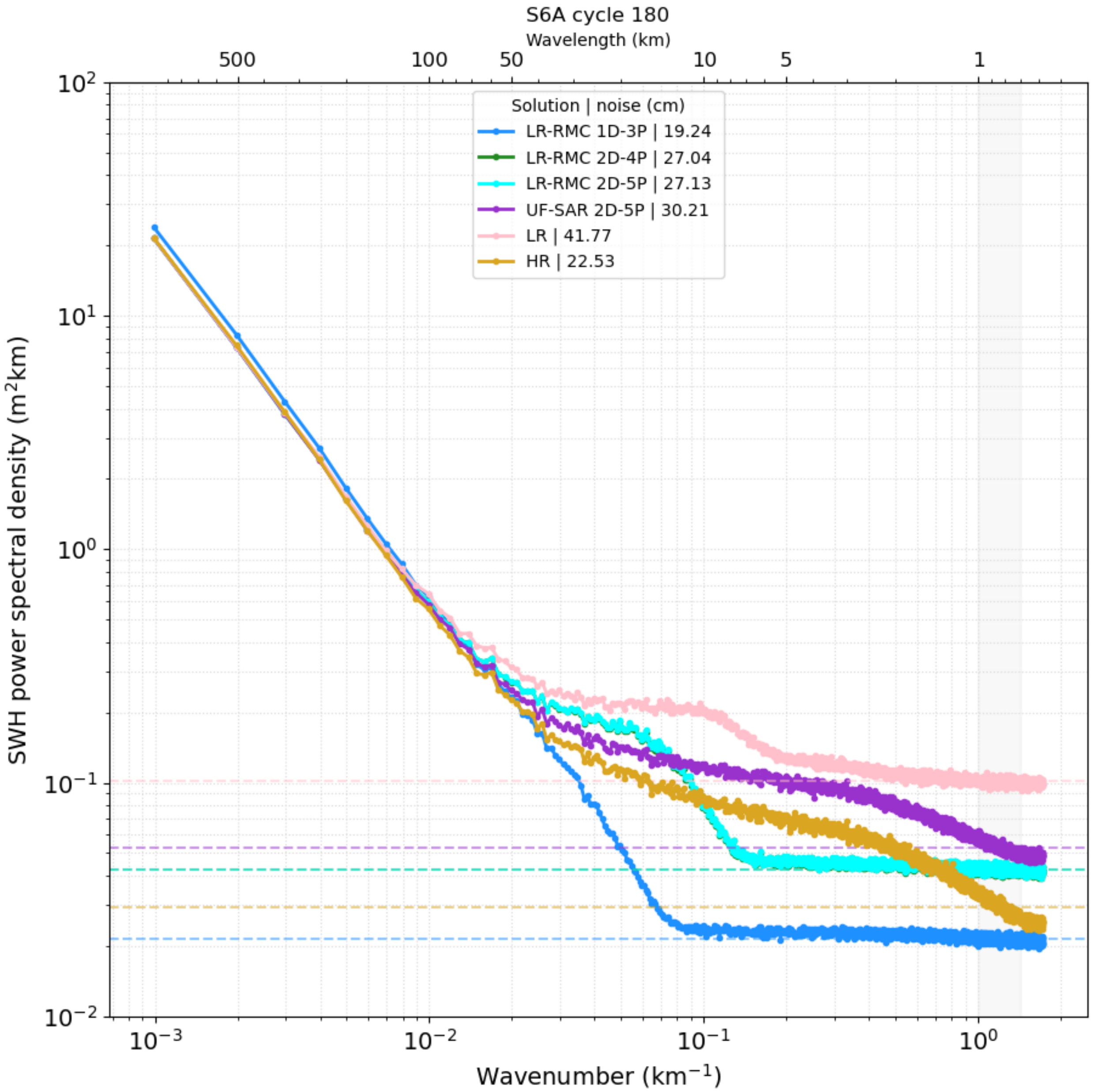

- As for the SSHA, the LR-RMC 1D-3P SWH spectrum shows the lowest power at meso-scales – lowest impact of sea surface heterogeneities (effectively smoothed out by the coarser LR-RMC resolution)

- The LR-RMC 2D spectra are alike: including or not u_x has no impact, but including σ_v does – it creates a bump, i.e. picks up wave height modulations in the footprint

SSHA and SWH noise

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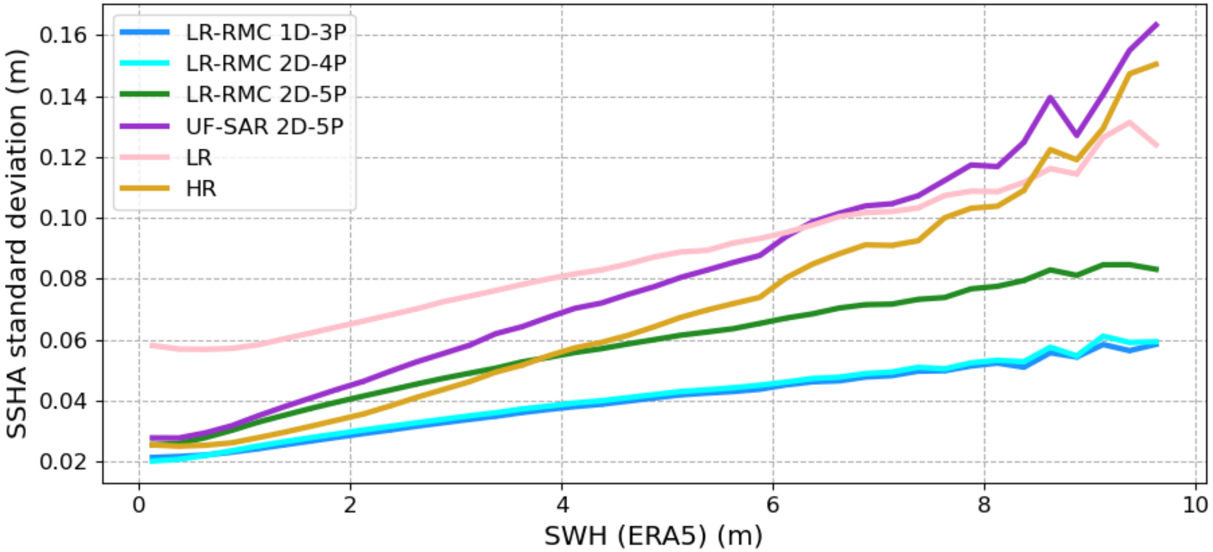
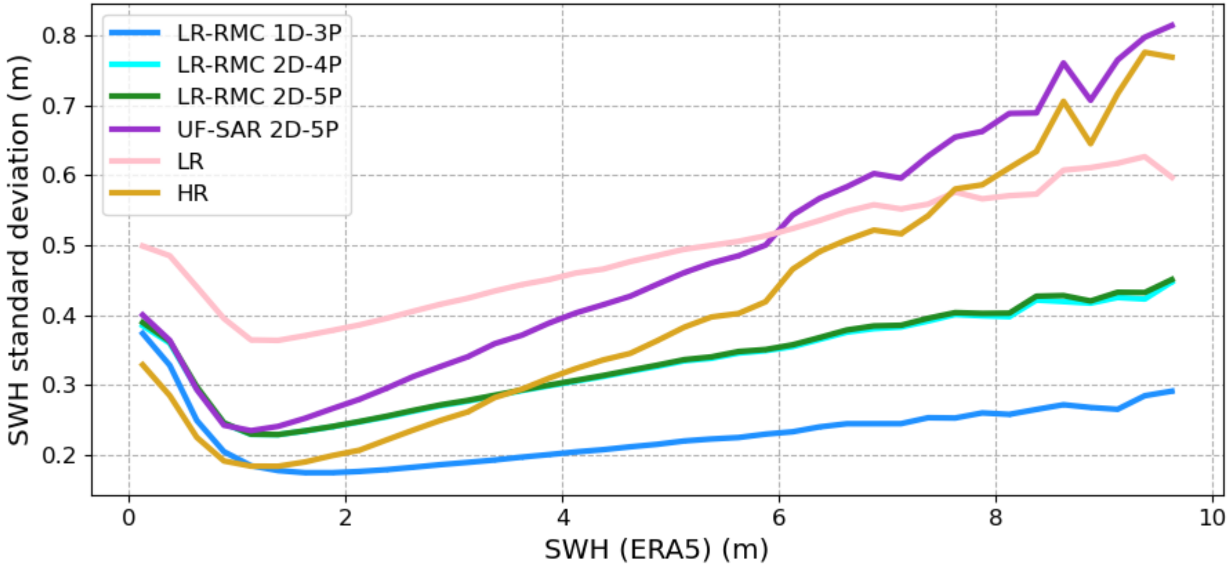
	nbr	min	mean	median	max	std
LR-RMC 1D-3P	39	0.02135	0.03997	0.04089	0.05848	0.01105
LR-RMC 2D-4P	39	0.02018	0.04102	0.04201	0.06117	0.01145
LR-RMC 2D-5P	39	0.02553	0.05821	0.06002	0.08465	0.01778
UF-SAR 2D-5P	39	0.02776	0.08124	0.07743	0.1633	0.0367
LR	39	0.05686	0.0874	0.08718	0.1313	0.0212
HR	39	0.02505	0.06983	0.06426	0.1505	0.03496



LR-RMC 1D-3P and 2D-4P have the best SSHA noise performance;
u_x increases the global noise level:
u_x changes the noise behaviour with sea-state: extra geophysical signal in the footprint

	nbr	min	mean	median	max	std
LR-RMC 1D-3P	39	0.1748	0.2306	0.2251	0.374	0.04377
LR-RMC 2D-4P	39	0.2292	0.3345	0.3384	0.4476	0.06437
LR-RMC 2D-5P	39	0.2294	0.3371	0.3404	0.451	0.06613
UF-SAR 2D-5P	39	0.235	0.478	0.4443	0.8144	0.173
LR	39	0.364	0.4918	0.4943	0.6267	0.07797
HR	39	0.1841	0.4075	0.3636	0.776	0.1772



Same comments apply to SWH, except that here σ_v plays a role and not ux.

LR-RMC 1D: excellent agreement with the speckle noise model of Ehlers et al. (2025)

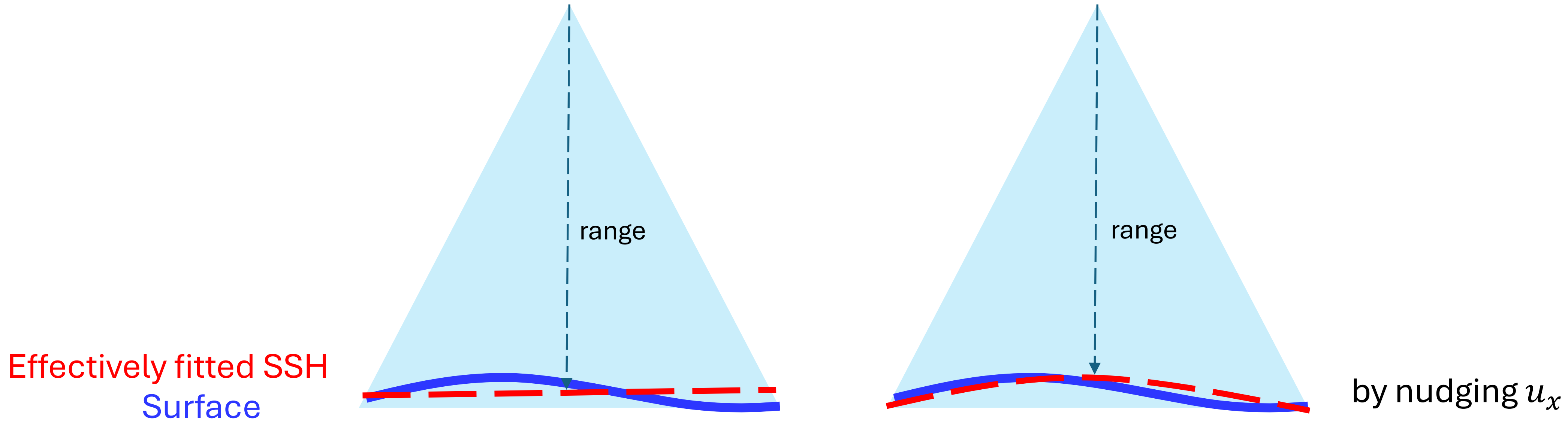
Why LR-RMC 2D 5P retracking admits higher frequencies…

In the LR-RMC geometry, the effect of the new parameters on the Doppler stack is indistinguishable from along-track variations in SSH and SWH:

parameter u_x ⇔ along-track SSH curvature

LR-RMC 1D & 2D **3 params**
LR-RMC 2D **4 params**

LR-RMC 2D **5 params**

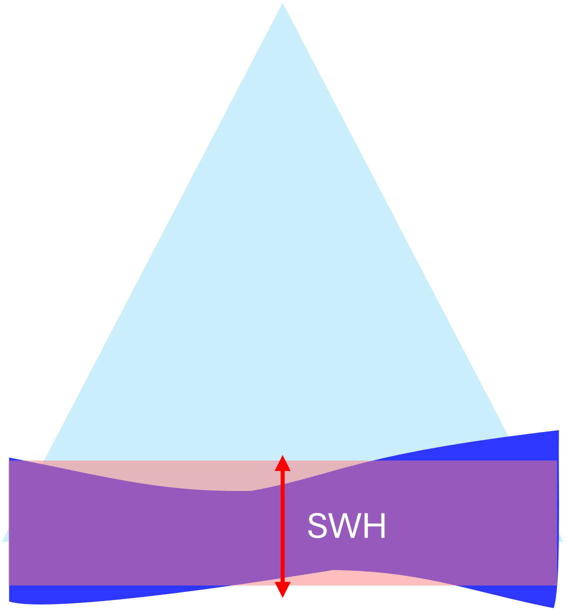


Why LR-RMC 2D 5P retracking admits higher frequencies…

In the LR-RMC geometry, the effect of the new parameters on the Doppler stack is indistinguishable from along-track variations in SSH and SWH:

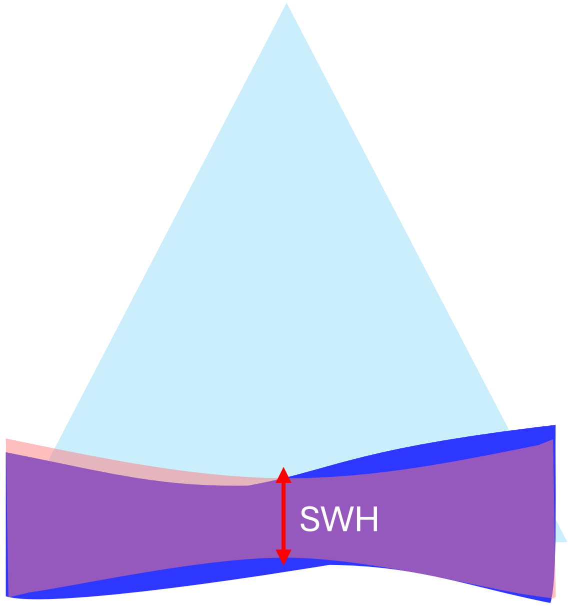
parameter u_x ⇔ along-track SSH curvature
parameter σ_v ⇔ along-track SWH modulations

LR-RMC 1D & 2D **3 params**



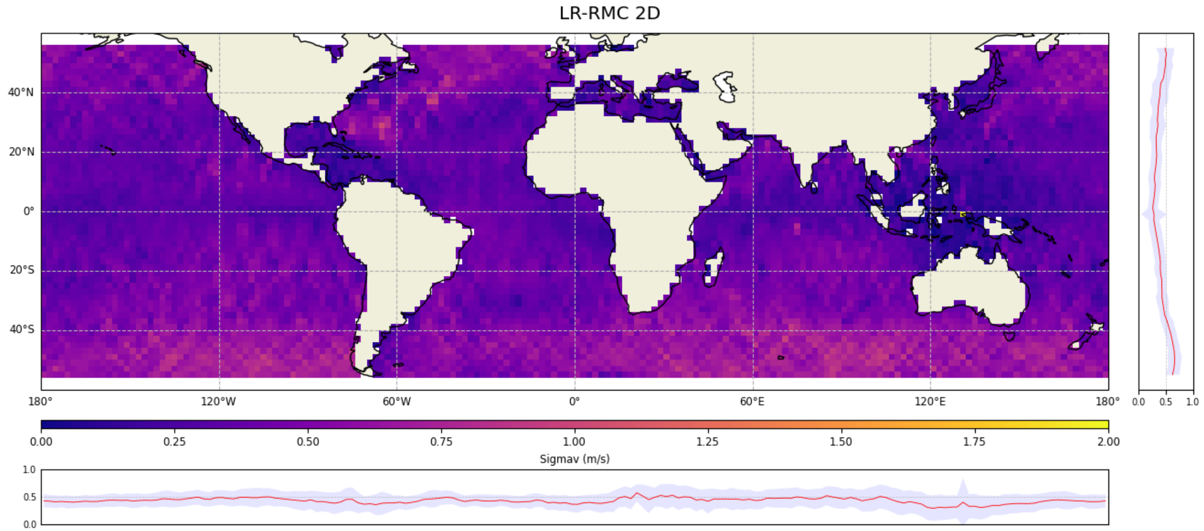
Effectively fitted SWH
Surface

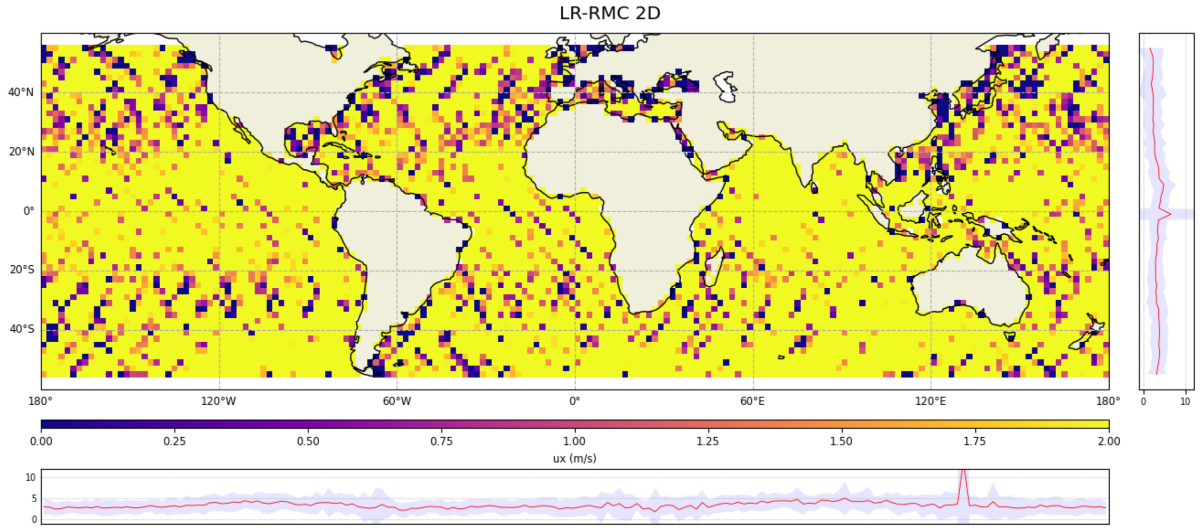
LR-RMC 2D **4 params**
LR-RMC 2D **5 params**

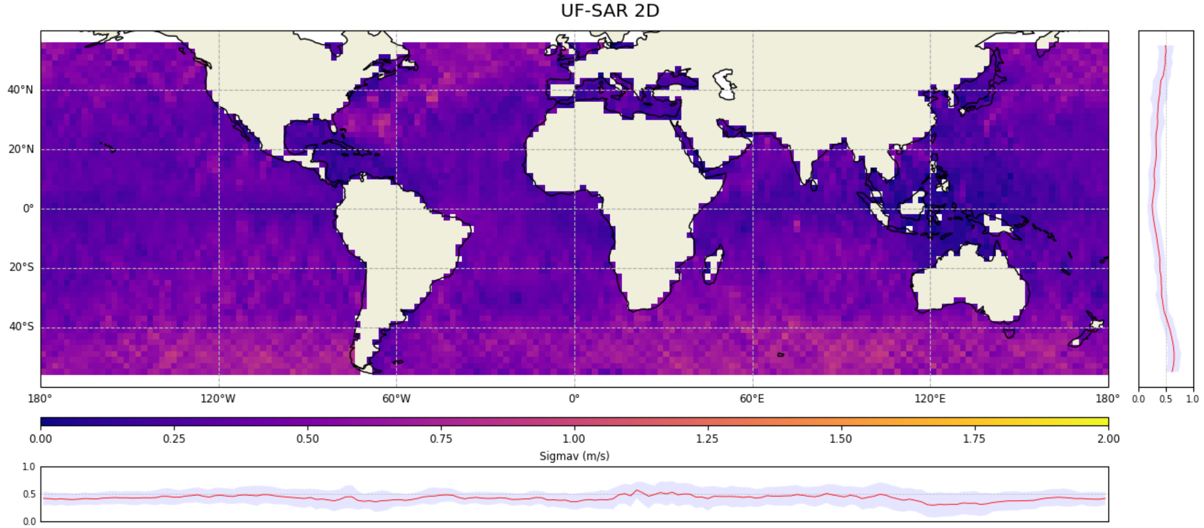


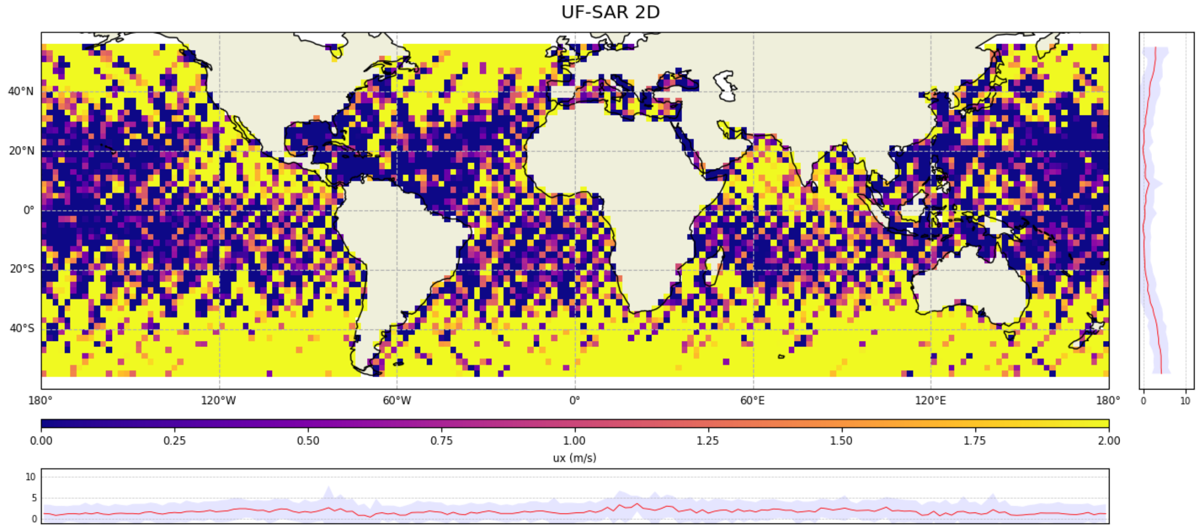
by nudging σ_v

σ_v and u_x 5P









LR-RMC capable of retrieving σ_v, hence presumably T02 too,
u_x probably affected by surface curvature effects.

What do we learn & what's next?

Conclusions

- **LR-RMC 2D retracking with all 5 parameters produces the most consistent SSH and SWH statistics w.r.t. conventional LR data,**

- **But it suffers from the similar problems due to admitting higher frequencies: the "spectral hump".**

What's next?

- A simple approach to restore the spectra of SSH and SWH to the LR-RMC 3-parameter shape, while keeping the smallest biases w.r.t. LR, is potentially a two-step approach:
  I. Perform UF-SAR 2D-5P retracking to get estimates of σ_v and ux
  II. Thereafter, run LR-RMC 1D-3P retracking, informed by along-track averages of σ_v and ux

As an added benefit, this approach will avoid increased noise due to the increased number of parameters.

Open Question

It seems that the differences between LR and SAR are almost fully understood. Can LR stay the reference for all purposes?

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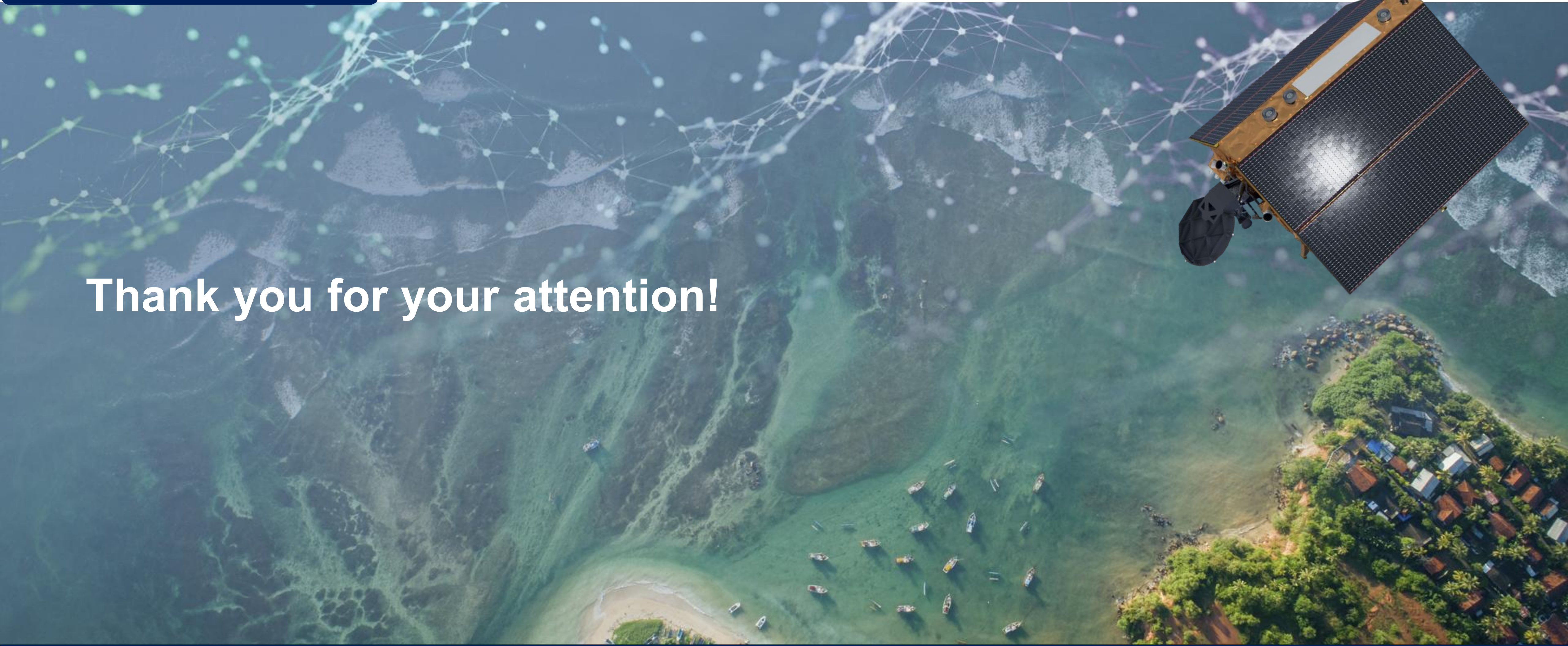

Thank you for your attention!

COLLECTE LOCALISATION SATELLITES

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SSHA vs LR

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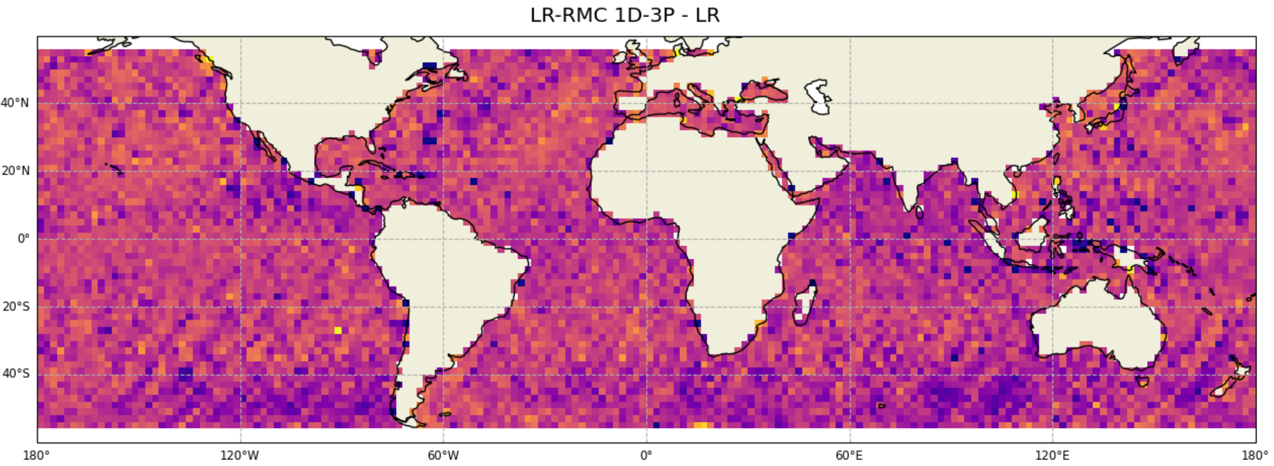

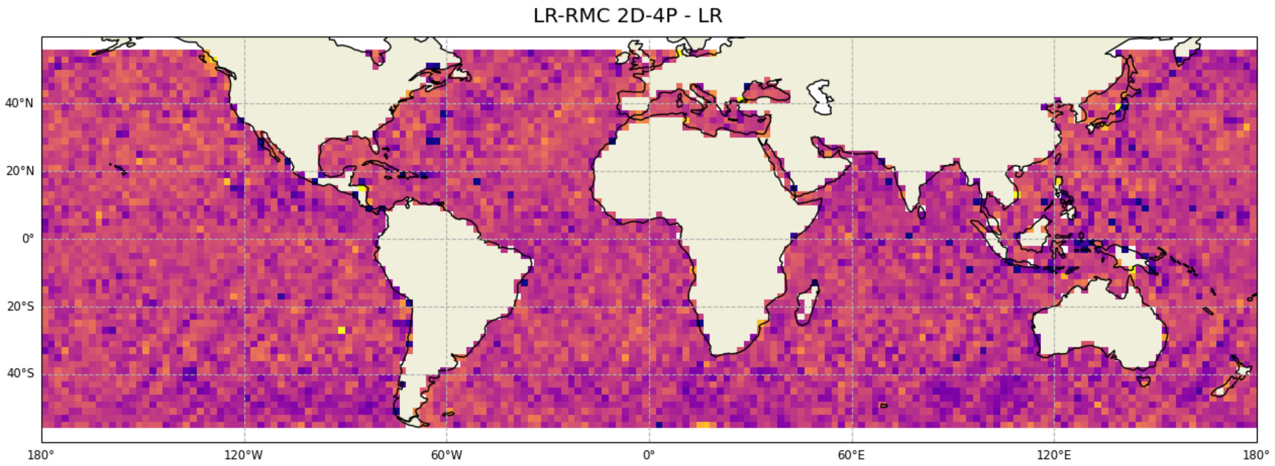

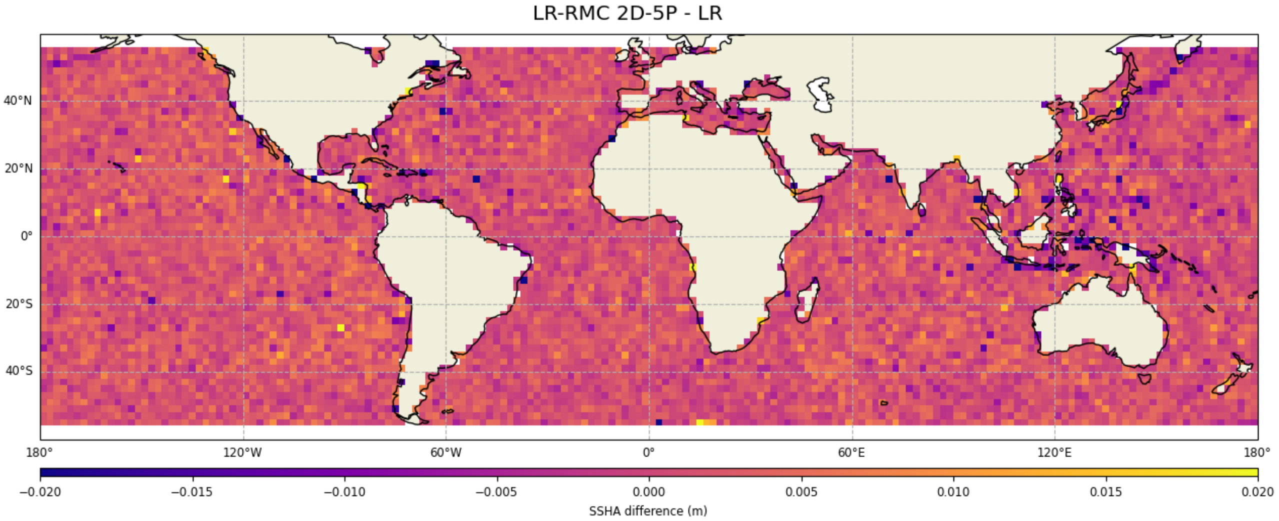

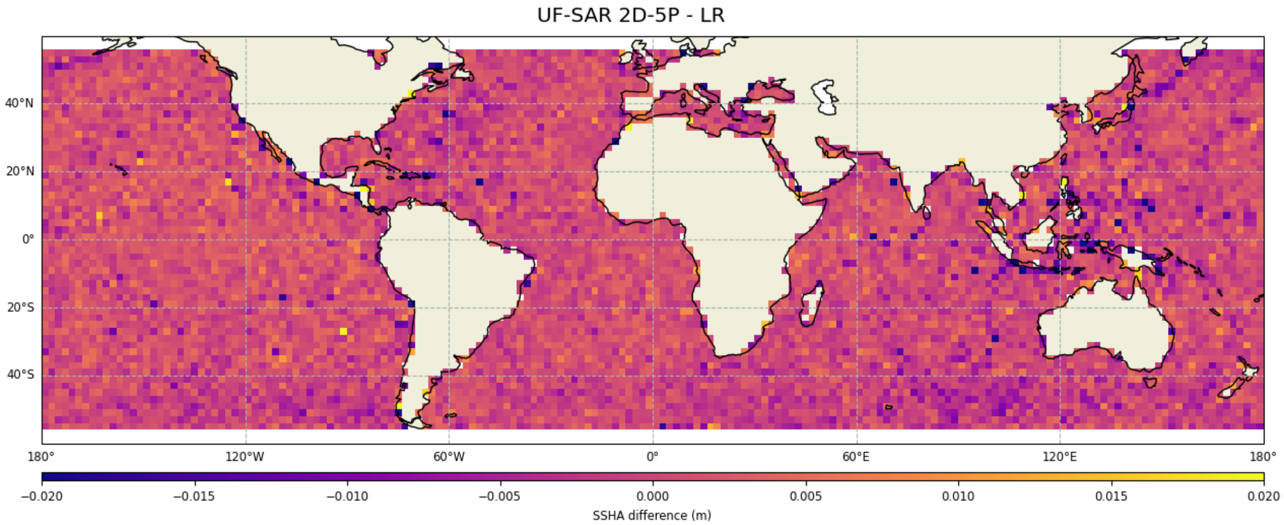

SWH vs LR

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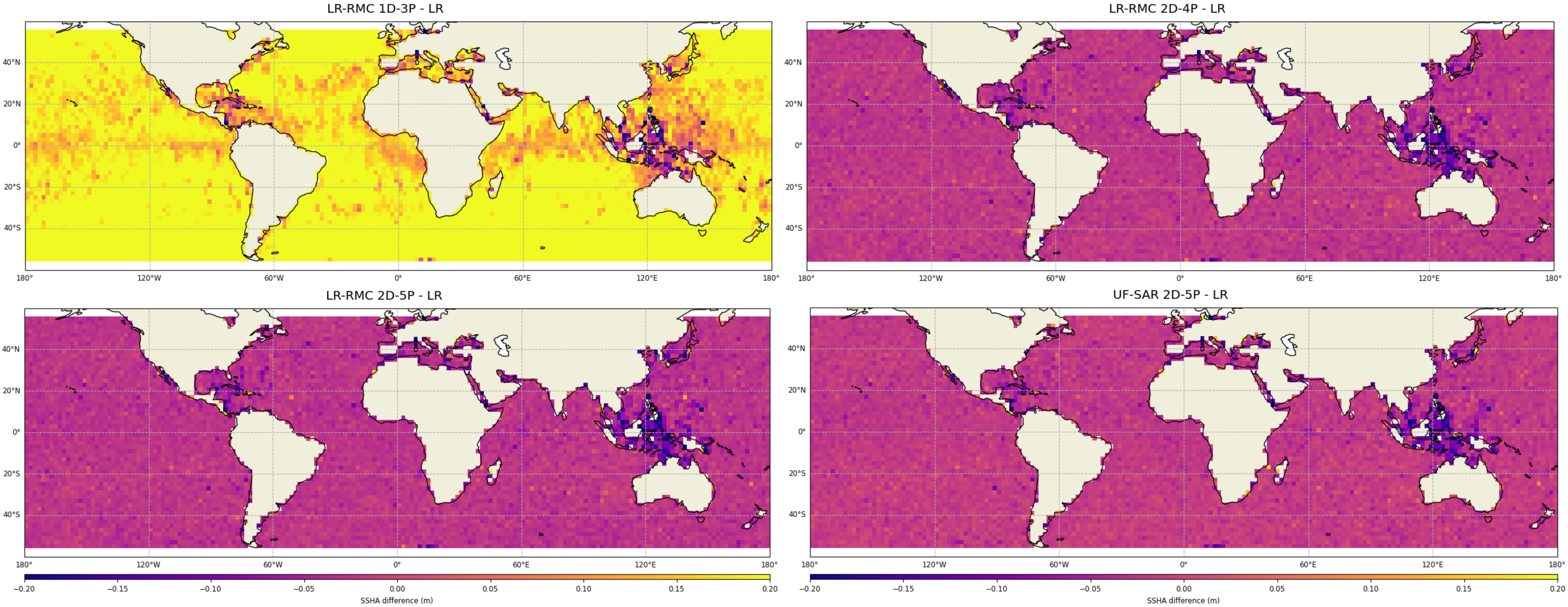

σ_v and u_x

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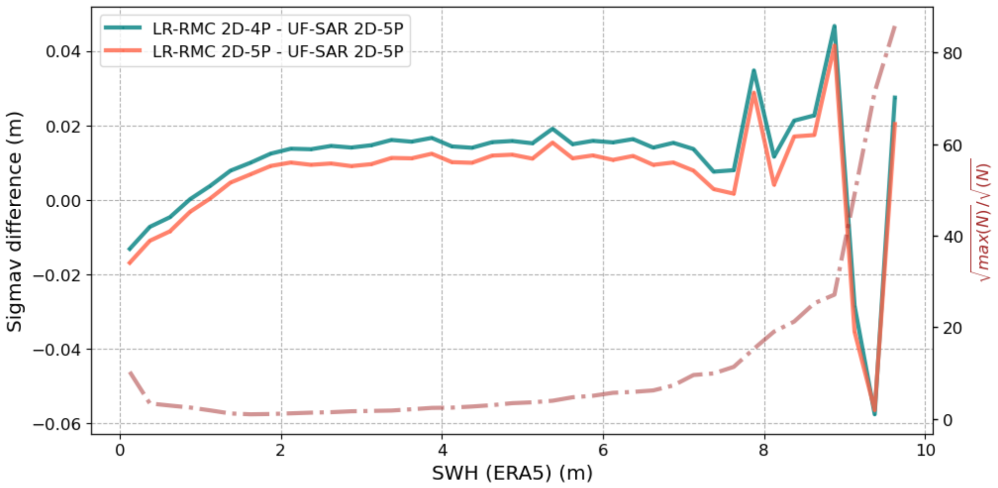
	nbr	min	mean	median	max	std
LR-RMC 2D-4P - UF-SAR 2D-5P	39	-0.05757	0.01079	0.01434	0.04666	0.0163
LR-RMC 2D-5P - UF-SAR 2D-5P	39	-0.05644	0.006383	0.009944	0.04144	0.01564



nbr:	39	min:	-0.9143	mean:	0.9394	median:	0.7164	max:	3.125	std:	1.107