Observations of sea state variability across the south-west barrier reef-lagoon system of New-Caledonia from high-resolution Sentinel-3 measurements

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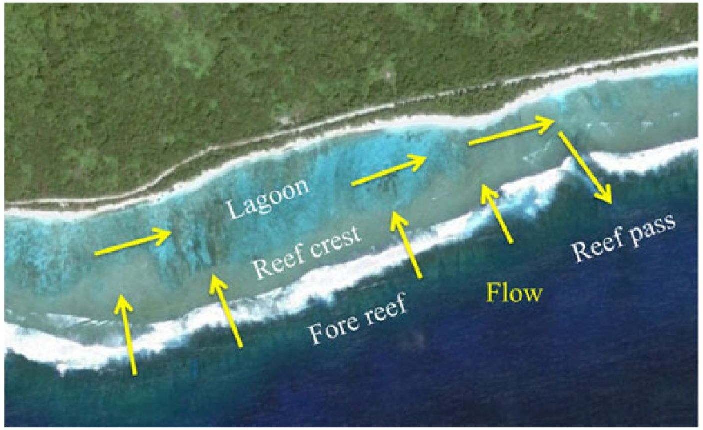
Context

- Ocean waves are key drivers of barrier reef-lagoon systems dynamics, and interactions between incident waves, tidal flow and reef morphology induce strong spatial gradients in the lagoon circulation (e.g. Monismith, 2014).

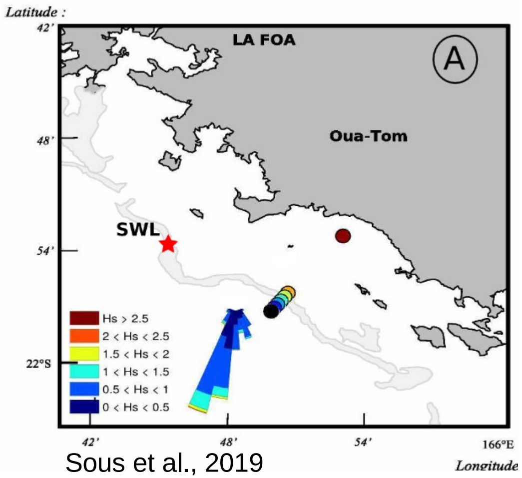
- Very few observing systems are able to monitor wave transformation from the deep water across the entire barrier reef-lagoon system. Such information is essential to investigate lagoon dynamics and validate high resolution numerical models (e.g. Sous et al., 2019).

- Delay/Doppler altimetry, with higher along-track resolution and reduced noise level compared to conventional altimetry, presents significant assets for coastal altimetry (Vignudelli et al., 2019).

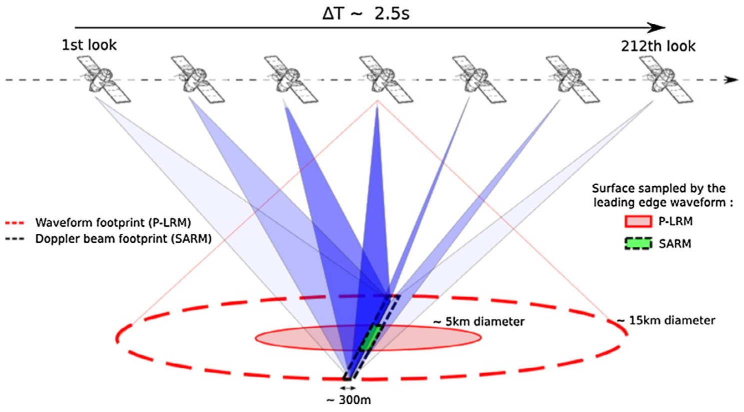
- We propose here a preliminary assessment of Sentinel-3A capabilities to measure significant wave heights at the south-west lagoon of New-Caledonia, using 20 Hz measurements combined with an adaptive denoising method based on Empirical Mode Decomposition (Quilfen and Chapron, 2020).



Monismsith, 2014



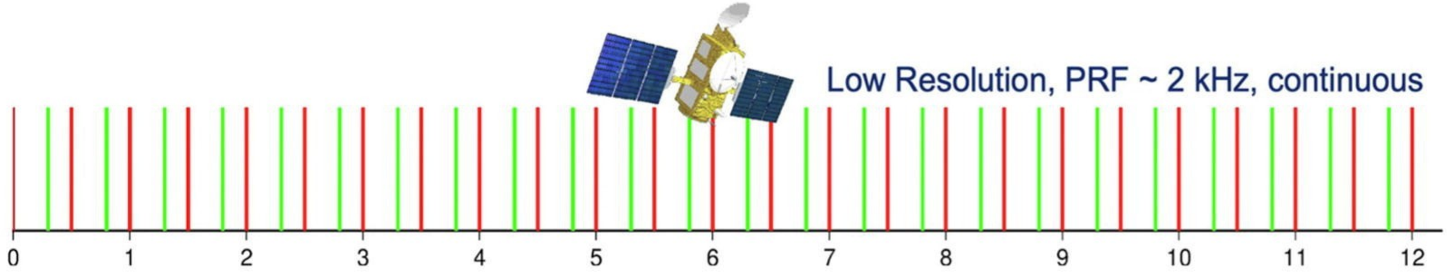
Sous et al., 2019

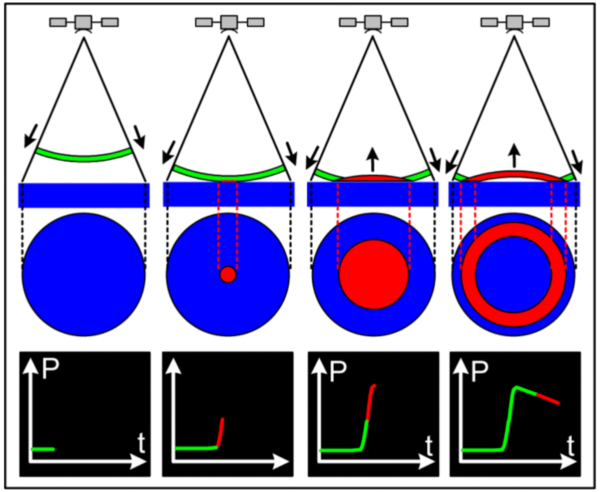


Aublanc et al., 2018

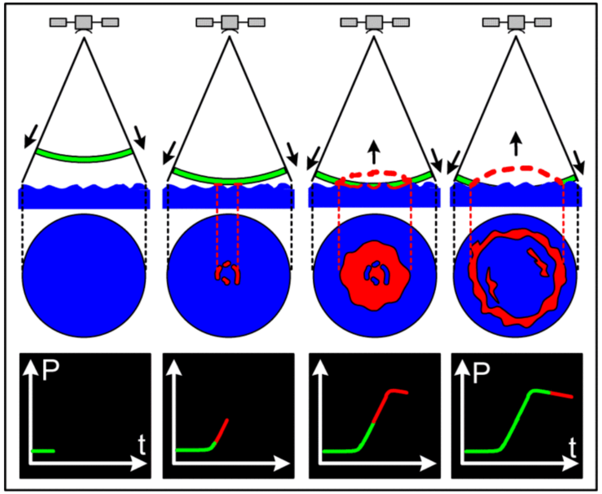
LRM altimetry principle

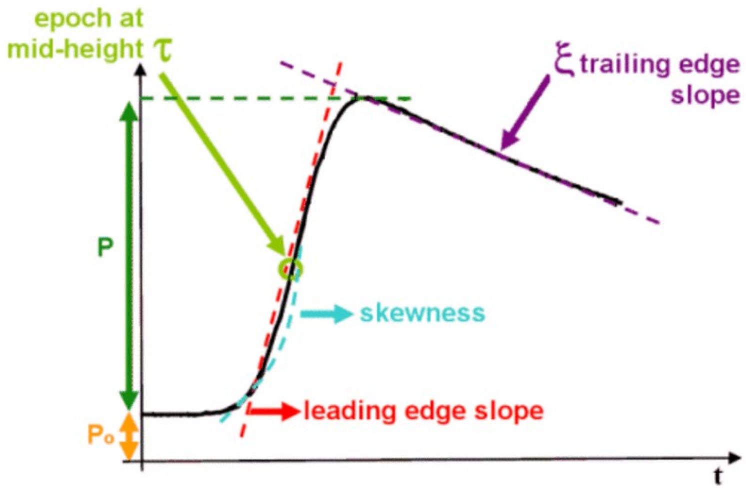
Conventional (aka Low Rate Mode) radar altimeters continuously emits pulses at ~2kHz PRF towards nadir, and record the pulses bounced back by the reflecting facets within the altimeter footprint. These echoes are registered in time and assembled as radar power signals (waveforms), from which geophysical parameters (SSH, Hs, wind) can be retrieved. In LRM altimetry the effective footprint depends on the satellite altitude, pulse width and Hs (Chelton et al. 1989)





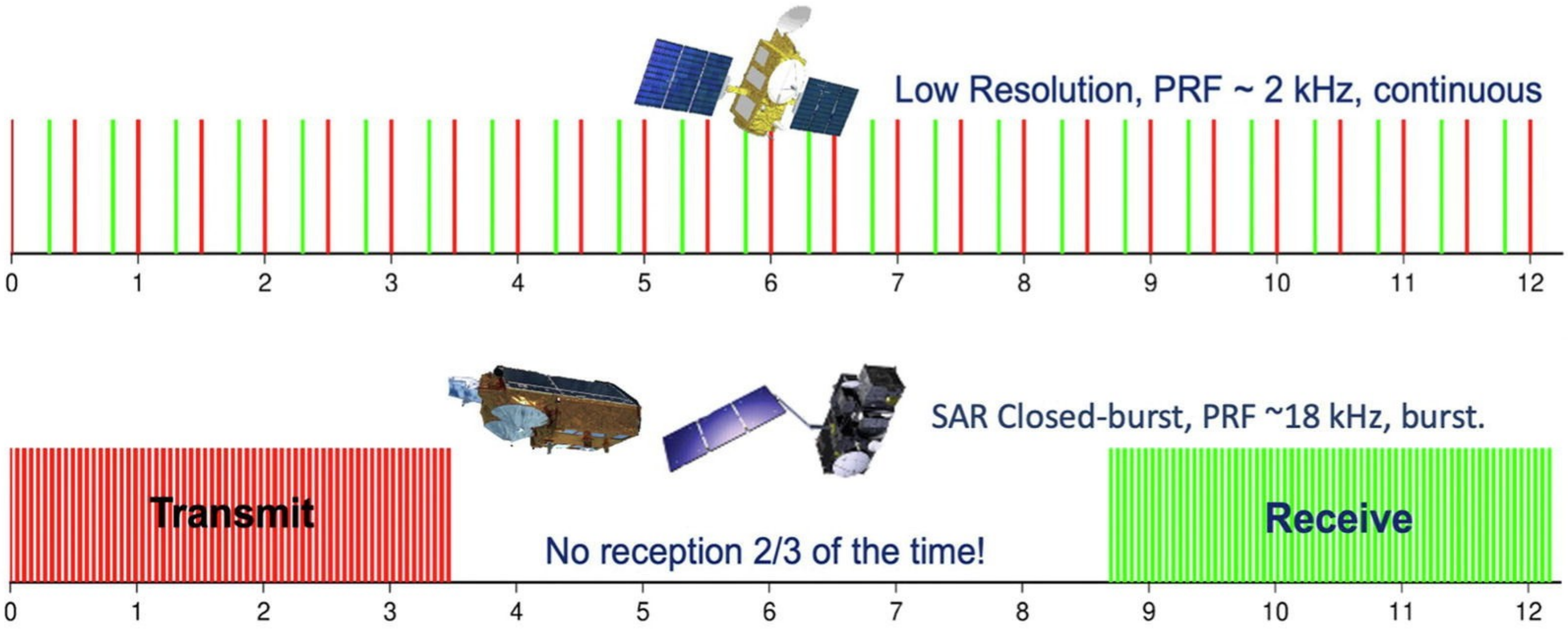
AVISO





SAR altimetry (closed burst) processing

In SAR (closed-burst) Mode, pulses are emitted in bursts of 64 pulses at high rate (18kHz) to ensure phase coherence between the successive intra-burst pulses to apply Doppler processing. The burst cycle duration is 12.5 ms and a 4-burst cycle is equal to the Low Rate Mode (LRM) cycle of 50 ms.

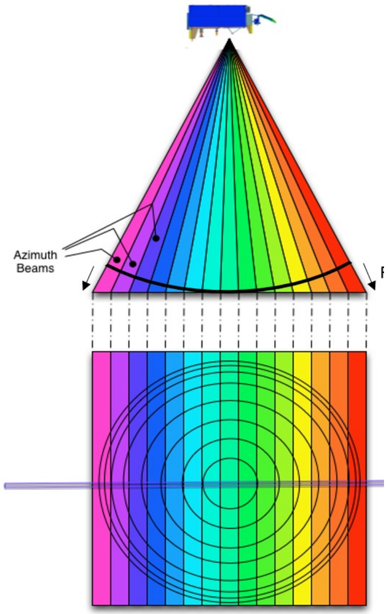


Donlon et al., 2021

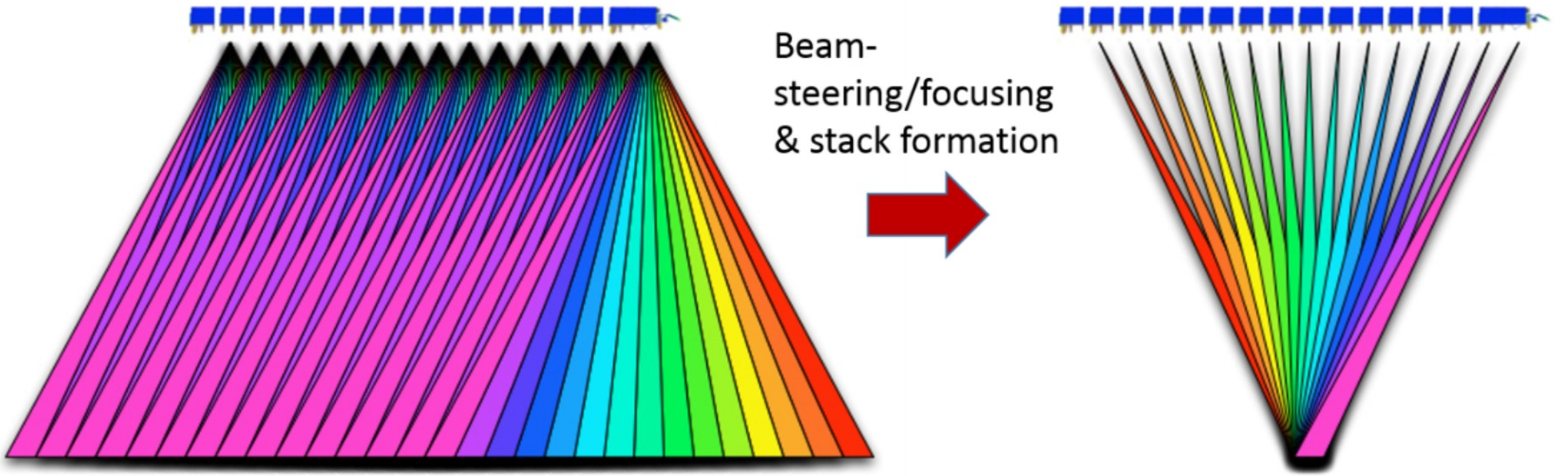
SAR altimetry (closed burst) processing

From the Doppler analysis of the intra-burst correlated pulses, a set of Doppler beams with different look angles and narrow footprints is synthesized.

Doppler beams of different look angles illuminating the same portion of the surface (i.e. from different bursts) are gathered (beam steering) to form a stack. The co-located Doppler beams in a stack are then aligned in range and averaged to produce a (multi-looking) SAR altimeter waveform



Doppler beams



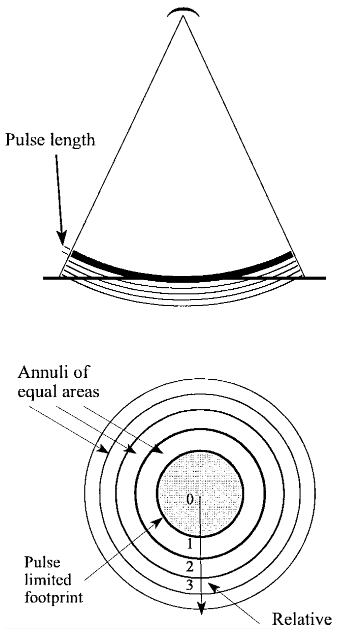
Credit : ESA SCOOP project

S3 SAR mode processing: PLRM / SAR / LR-RMC

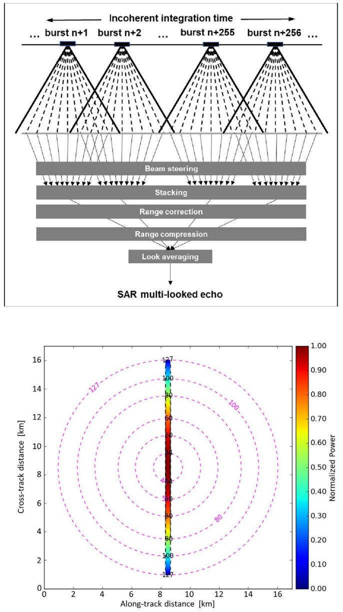
The radar echoes acquired in SAR mode can actually be processed in different manners :

- **PLRM**: incoherent averaging of all successive pulses in a radar cycle, no Doppler information used;
- **SAR**: coherent processing of intra-burst pulses (Doppler beams generation), beam steering, range migration correction and incoherent inter-burst (256) averaging (stacking) of co-located range-corrected Doppler beams;
- **LR-RMC**: coherent processing (Doppler beam formation) of intra-burst pulses (Doppler beams generation), range migration correction, and intra-burst averaging of Doppler beams. Larger footprint but reduced noise level wrt. SAR.

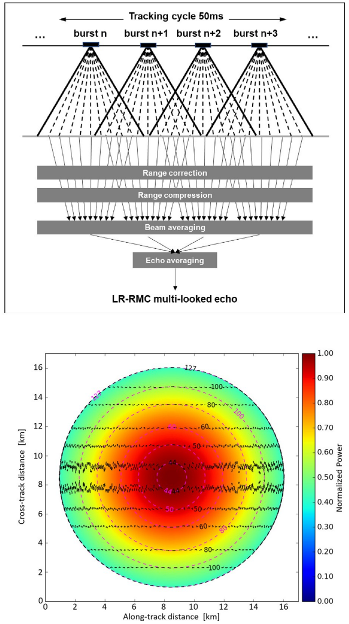
PLRM

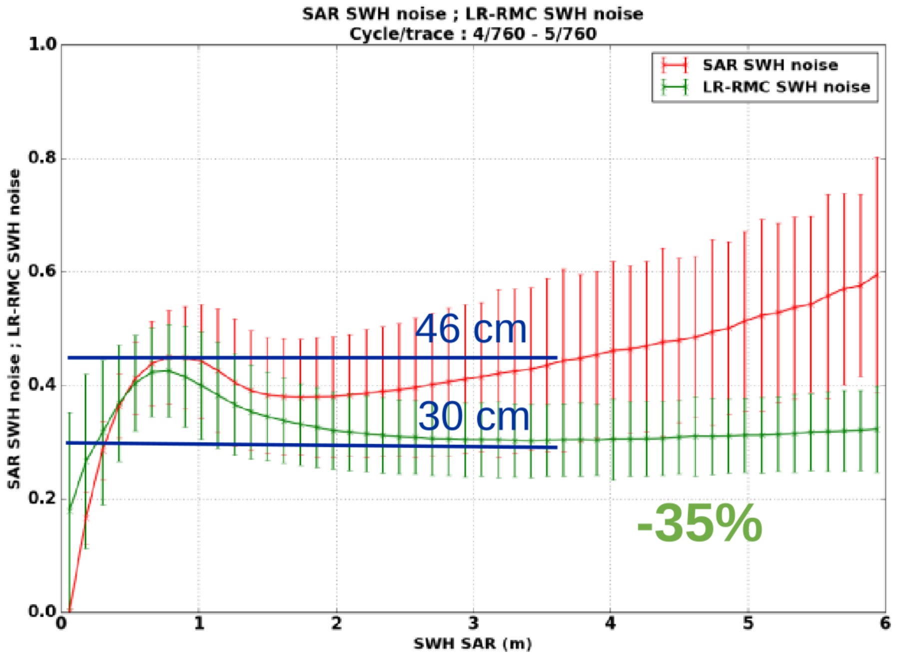


SAR



LR-RMC





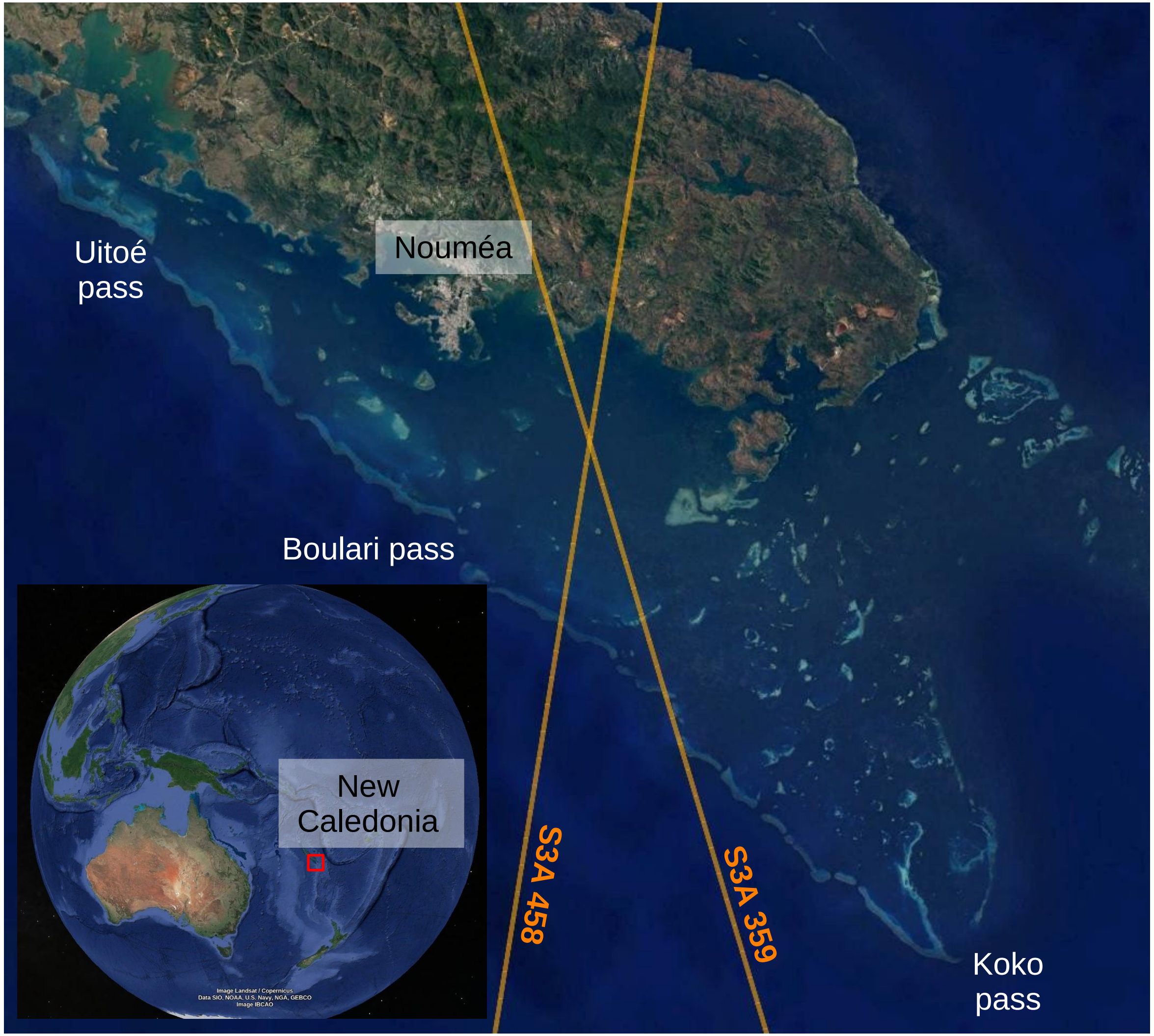
Moreau et al., 2021

Boy et al., 2017

Objectives

- Implement EMD-based denoising techniques to S3A LR-RMC 20Hz Hs records
- Investigate impact of reef barrier and islands on S3A data quality
- Characterize Hs gradients from deep water to lagoon using S3A data
- Compare filtered altimeter observations to in situ data and model results

Study area



The SW barrier reef-lagoon system of New-Caledonia :

Barrier reef : ~130-km long (from Uitoé pass to Koko pass), partially emerged at spring low tide, intersected by deep channels

Lagoon : 5-to-40-km wide, ~3000km^2 surface area, depth : 17.5m on average, up to 60m in the channels

Tides : mixed semi-diurnal, range between 0.6m (neap) and 1.6m (spring), currents between 0.05m.s^{-1} (lagoon) and 0.3m.s^{-1} (pass)

Winds : south-easterly trade winds from October to May, weak variable winds from June to September, ENSO-related inter-annual variability, occasional extreme winds from tropical cyclone

Waves : long-period swell from south-west to south-east direction, wind sea from east-south-east, extreme waves occasionally generated by tropical cyclones

Dataset

Sentinel-3A data
- 20Hz Hs along-track measurements
- SAR standard processing from GDR-F dataset (2016-2023)
- PLRM and LR-RMC processing from Sea State CCI dataset (2016-2021)

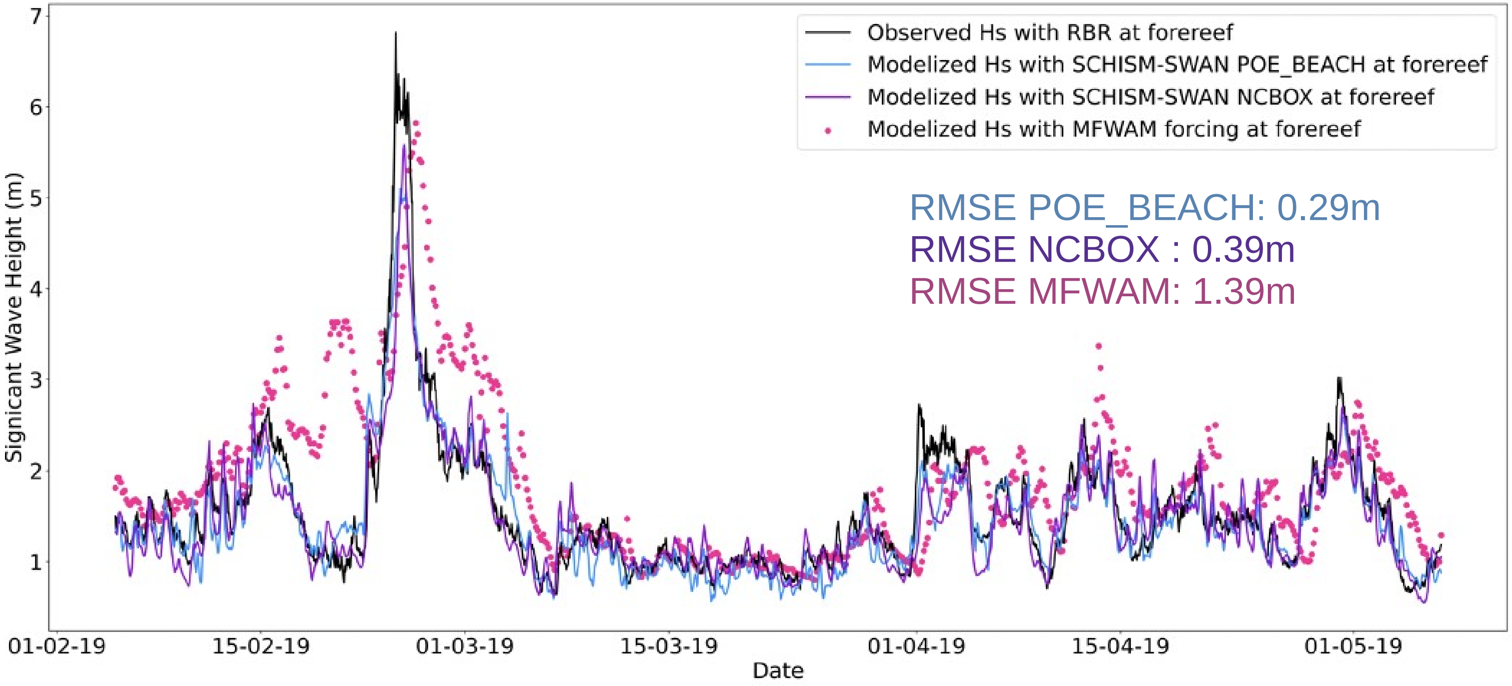
Low resolution wave model
- Ifremer global wave hindcast (T475)
- Spatial resolution: from 0.5° in global grid to 0.05° for New Caledonia (multi-grid strategy)
- Spectral: 24 directions/36 frequencies from 0.037 to 0.71 Hz
- Wind : ERA-5
- Currents: CMEMS-Globcurrent
- Ice: Ifremer SSMI-derived daily product (Girard-Ardhuin and Ezraty, 2012)
- Iceberg: Ifremer-Altiberg icebergs distribution database (Tournadre et al., 2015).

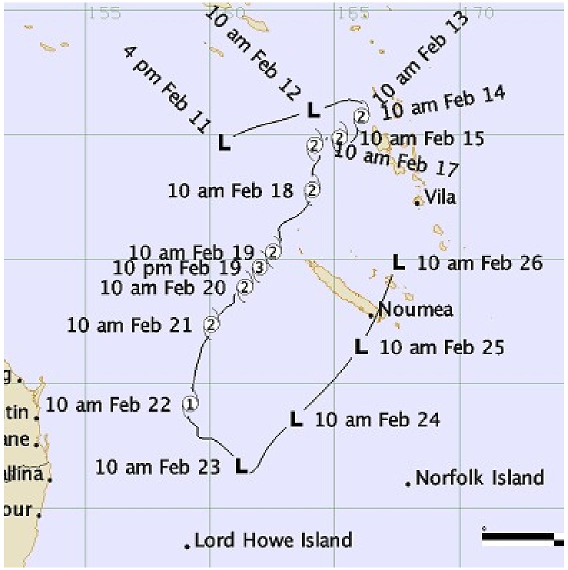
High resolution wave model
- SCHISM-SWAN 2D coupling (UMR Entropie/ M.Duphil)
- Unstructured grid (70-500m)
- Wind: AROME 2.5km
- Waves: MFWAM 25km
- Water level : Mercator Ocean
- Tide : OSU TPXO

In situ data
- Reeftemps data (pressure sensors)

Validation of the HR model

- Hs simulated with the SCHISM-SWAN coupled model over 01/02/2019-01//05/2019 were compared with in situ observations on the forereef (12-meter depth, same cut-off frequencies used for the integration of model and obs spectra).
- Peak Hs up to 6.5m on 25/02 short before tropical cyclone (Cat3) Oma landfall over NC
- Strong Hs tidal modulation well reproduced by the coupled SCHISM-SWAN model
- Underestimation of the peak Hs, likely related to unrealistic wind forcing

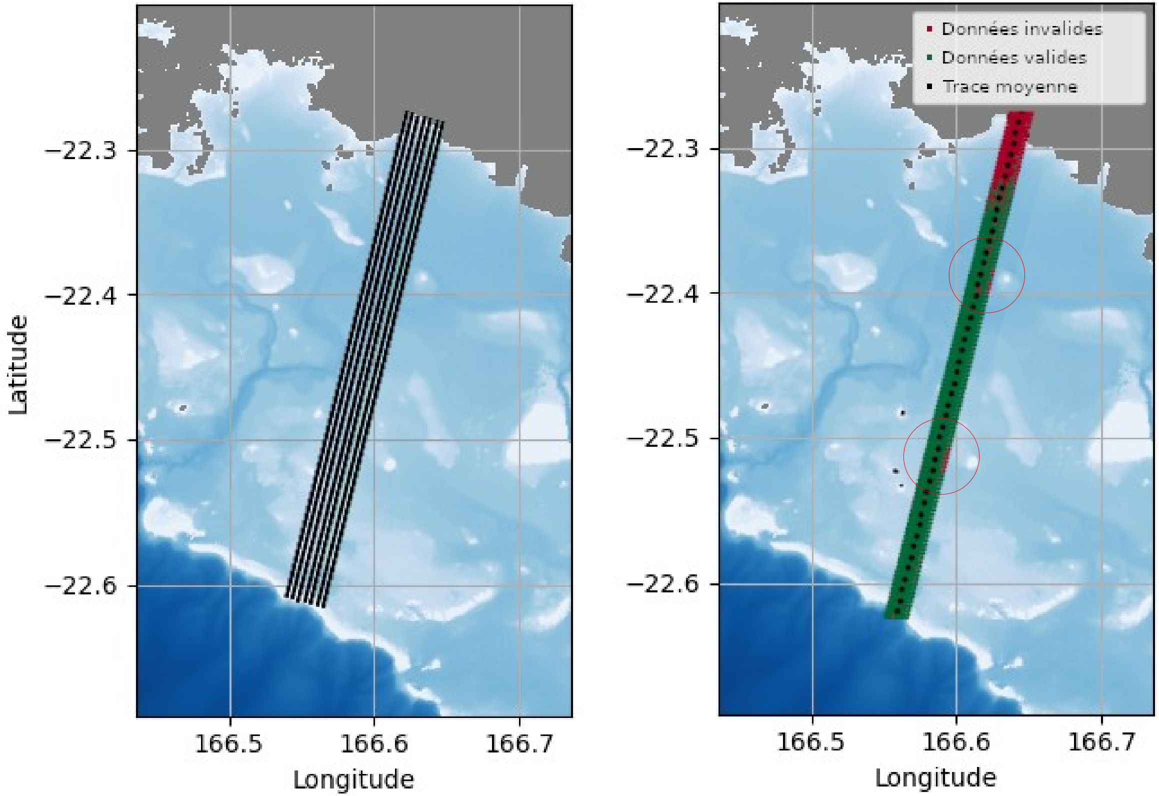


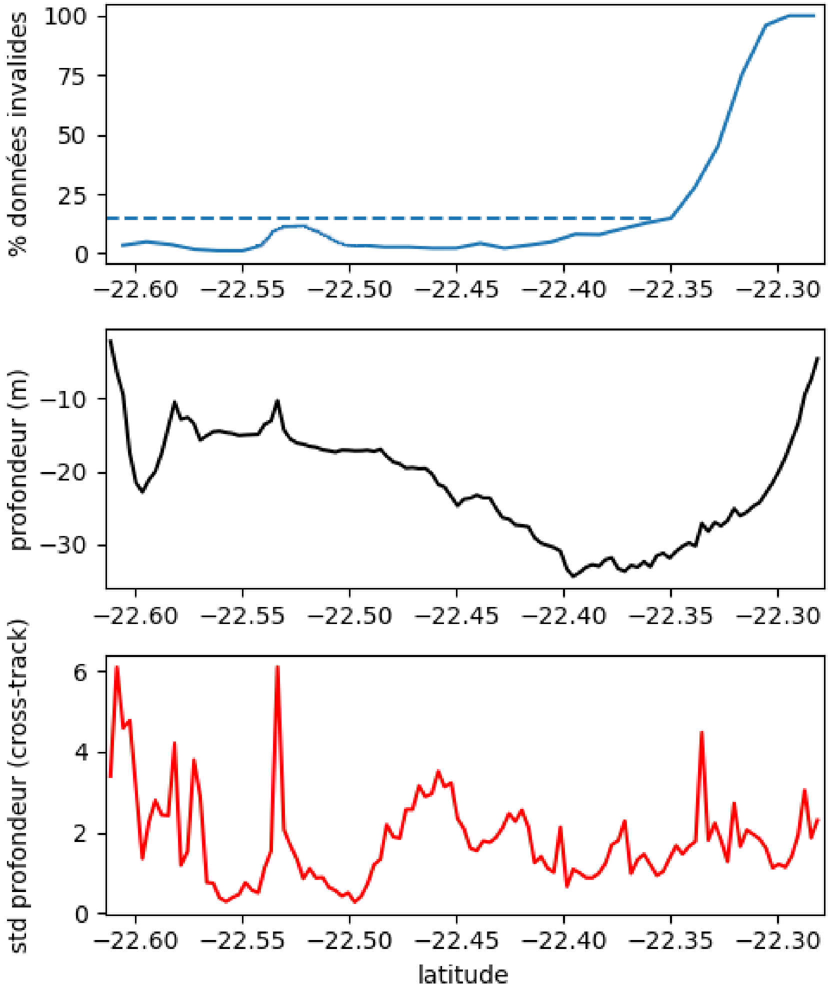


Oma TC track (http://www.bom.gov.au)

S3A quality flags across the reef-lagoon system

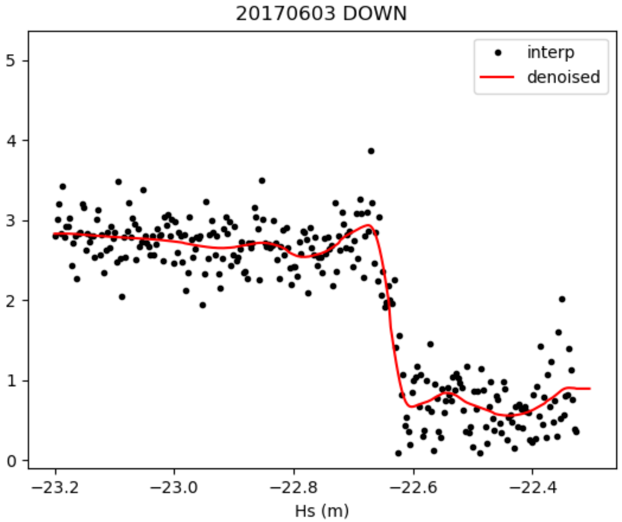
- S3A quality flags indicate limited data loss across the reef and in the lagoon up to 10km from the mainland
- localized invalid data can be attributed to the presence of small islands within the altimeter footprint

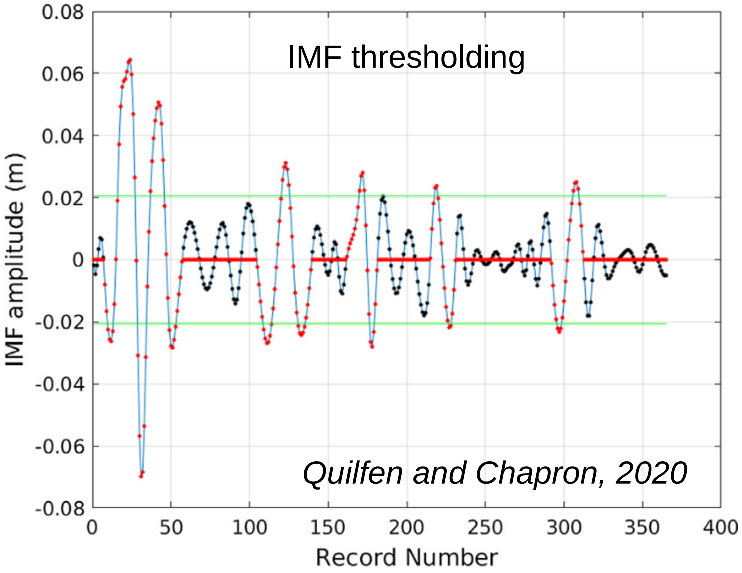


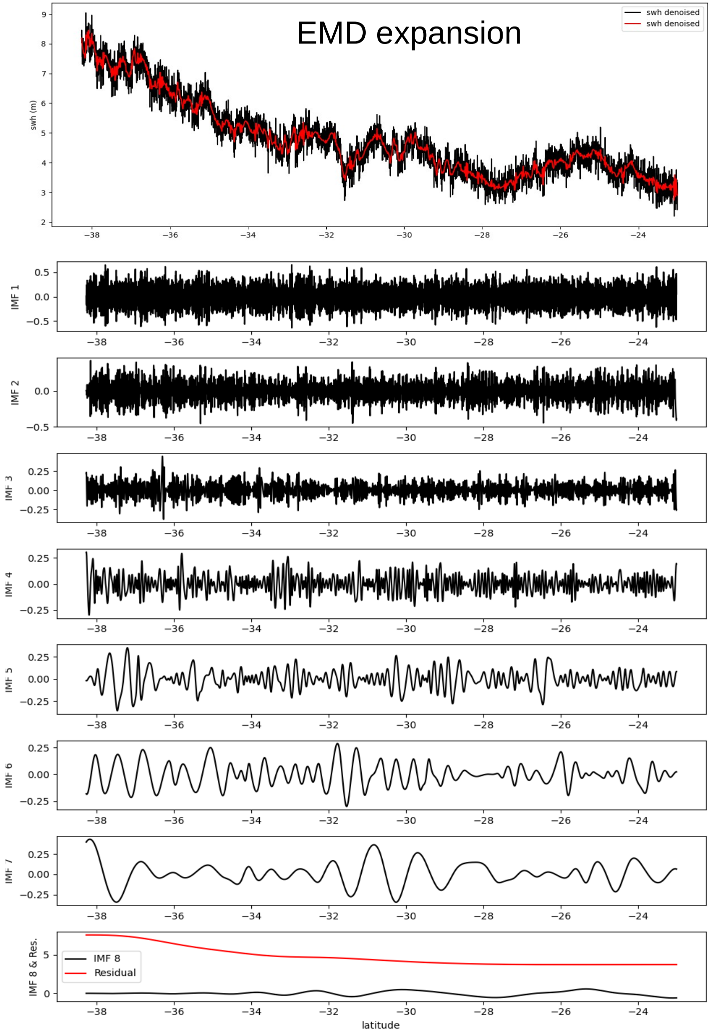


EMD-based denoising (direct thresholding)

- Empirical mode decomposition of the 20Hz signal (sifting process)
- Estimate of noise level (E_1) from first IMF $E_1 = (median|n_1(t)|/0.6745)^2$
- Computation of noise thresholds (T_n) of IMF_n from E_1 $E_n = \frac{E_1}{0.719} 2.01^{-n}$
- Denoising of IMF_n using noise threshold T_n $T_n = A\sqrt{E_n * 2\log N}$
- Reconstruction of the signal $y(t) = \sum_{i=M_1}^{M_2} \widetilde{h}^{(i)}(t) + \sum_{i=M_2+1}^{L} h^{(i)}(t) + d(t)$



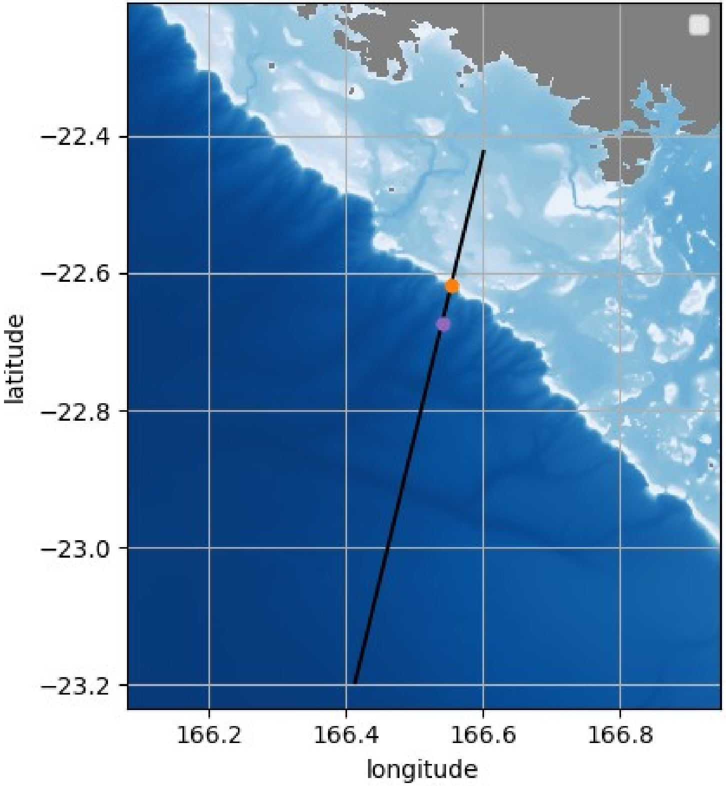


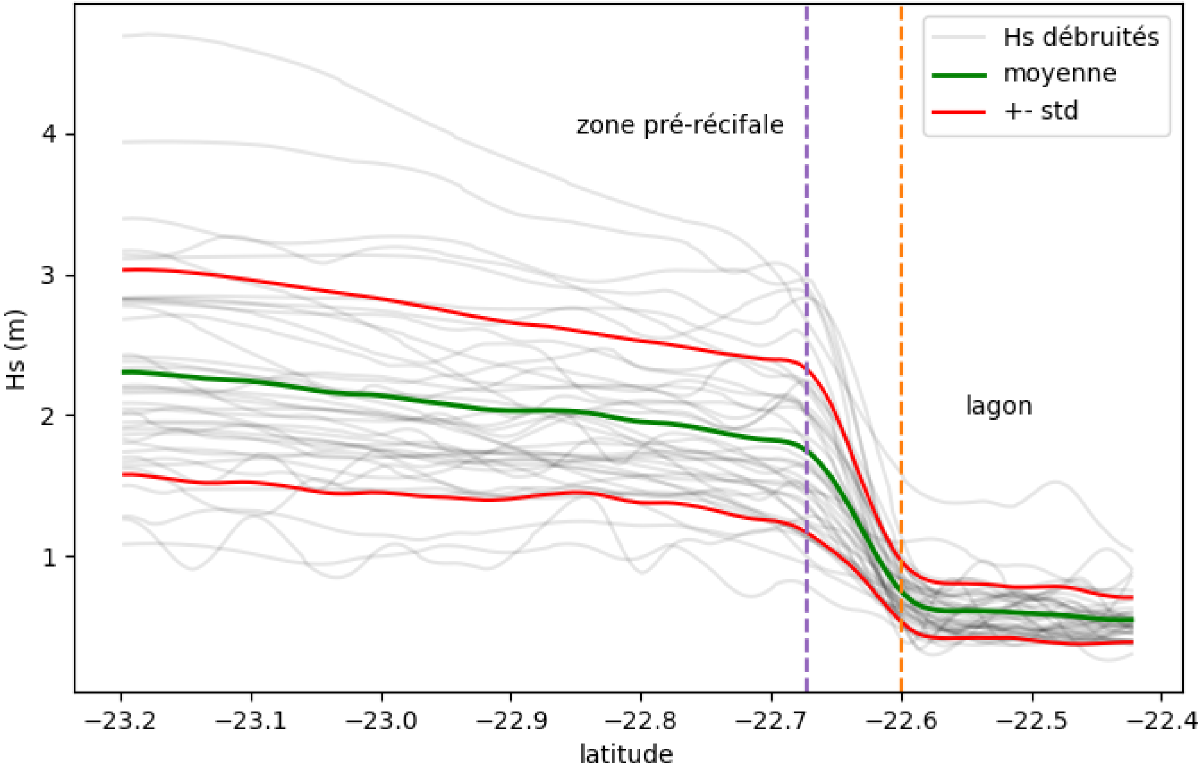


Wave transformation from deep water to lagoon

Analysis of 49 tracks (458) over the period 2016-2020 (with incident Hs conditions ranging from 1 to 5m)
Average Hs profile present three distinct regions :

1) Slowly decreasing Hs (20%) from deep water to ~8km from the reef ;
2) Strong Hs decrease (50%) from ~8km from the reef to the reef top (unrealistic spatial scale → footprint issue ?);
3) Moderate Hs variability within the lagoon ;

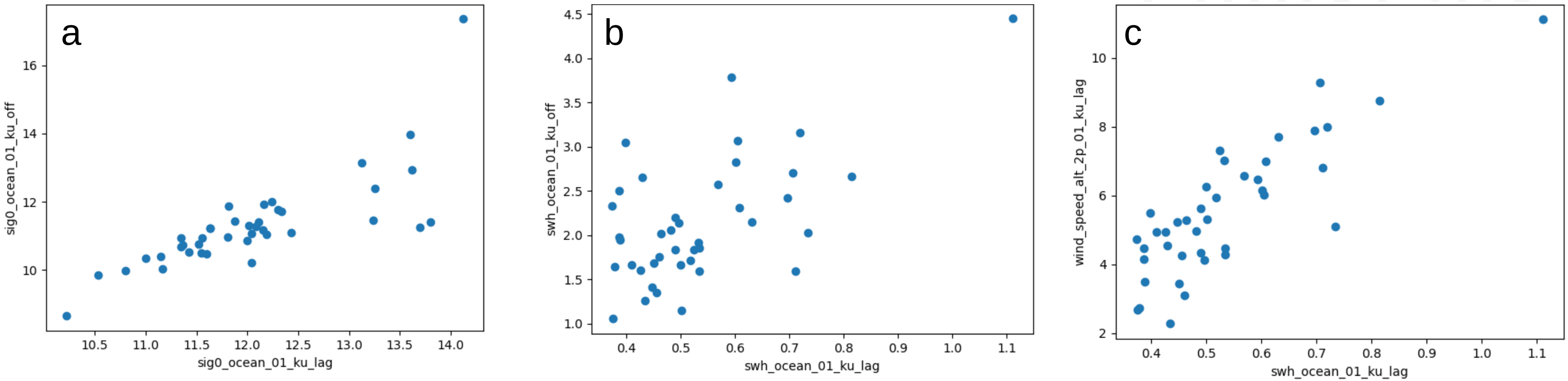




Correlations between offshore and lagoon parameters

Analysis of 49 tracks (track 458) over the period 2016-2020 (with incident Hs conditions ranging from 1 to 5m)

Hs, σ_0 and wind parameters are averaged over representative segments of offshore and lagoon regions.



a) σ_0 measured offshore and over the lagoon present strong correlation, indicating strong spatial coherency on either side of the reef barrier ;

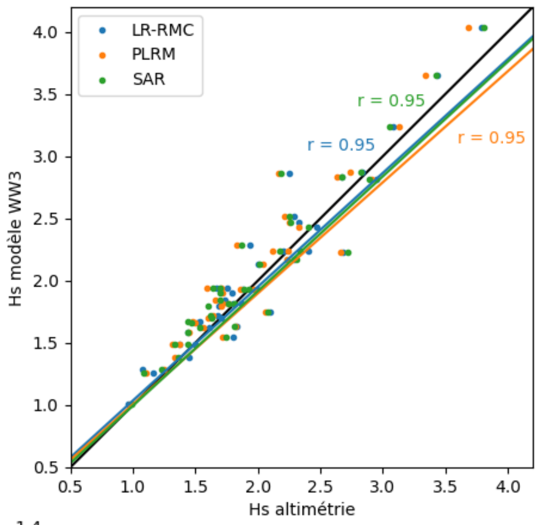
b) Hs measured offshore and over the lagoon present lower correlation, indicating the limited contribution of incident wave conditions on the lagoon sea state ;

c) Hs measured in the lagoon presents strong correlation with wind speed (2-parameter model from Collard, 2005) in the lagoon, indicating the dominance of local wind sea conditions in the lagoon.

Comparison of S3A with coarse model and in situ data

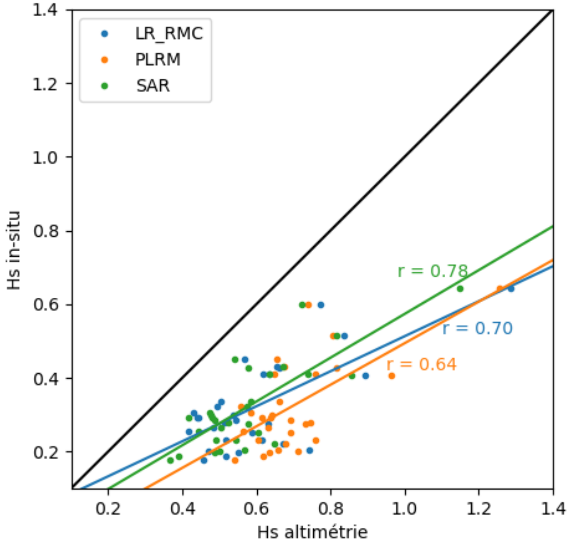
Offshore
S3A vs WW3

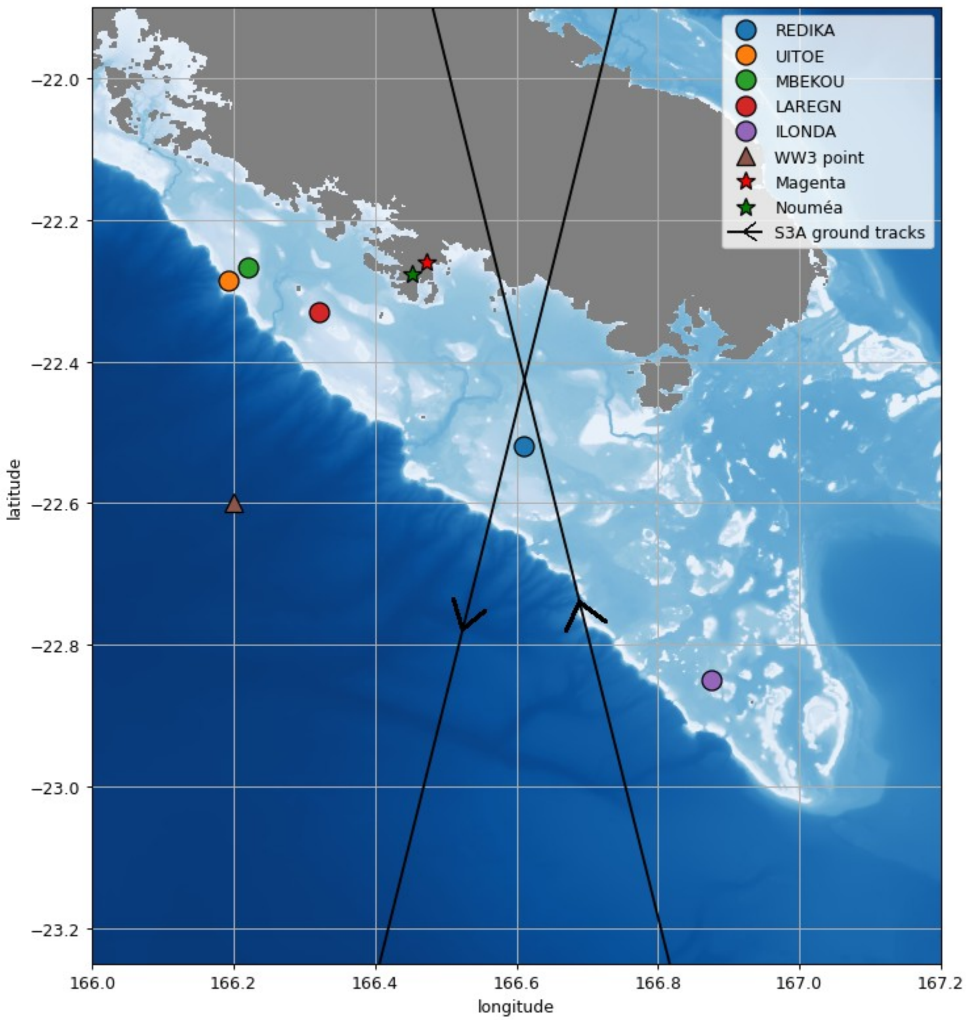
Strong correlations between WW3 and S3A. No significant differences between S3A processing methods



Lagoon
S3A vs In situ
(LAREIGN station)

Strong overestimation of S3A Hs with respect to in situ data, due to separation distance between pressure sensor and S3A ground tracks (insufficient data were available at MEDIKA), and high-frequency cut-off for in situ data processing.

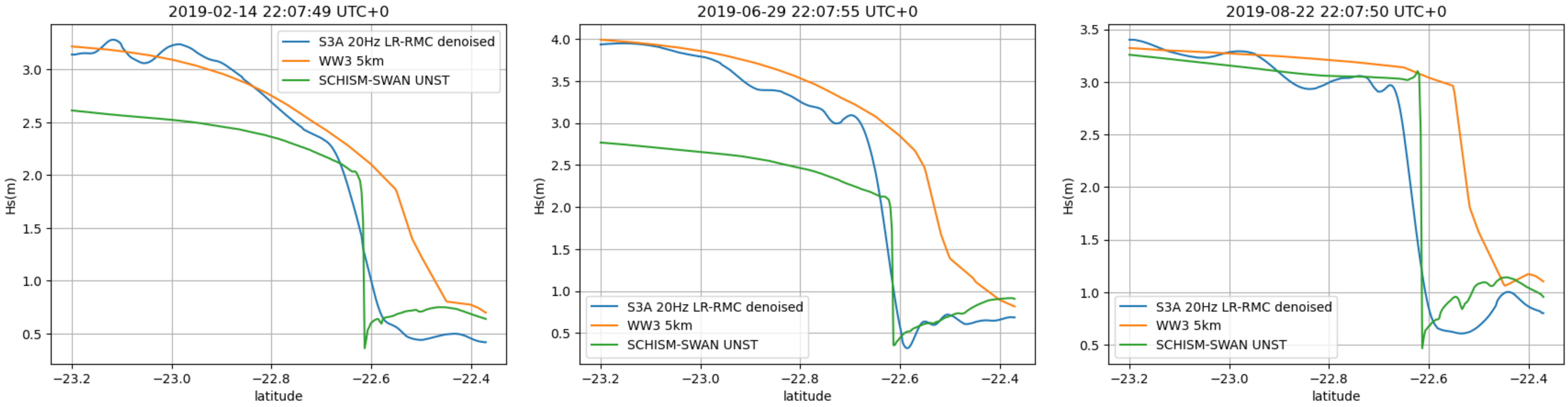




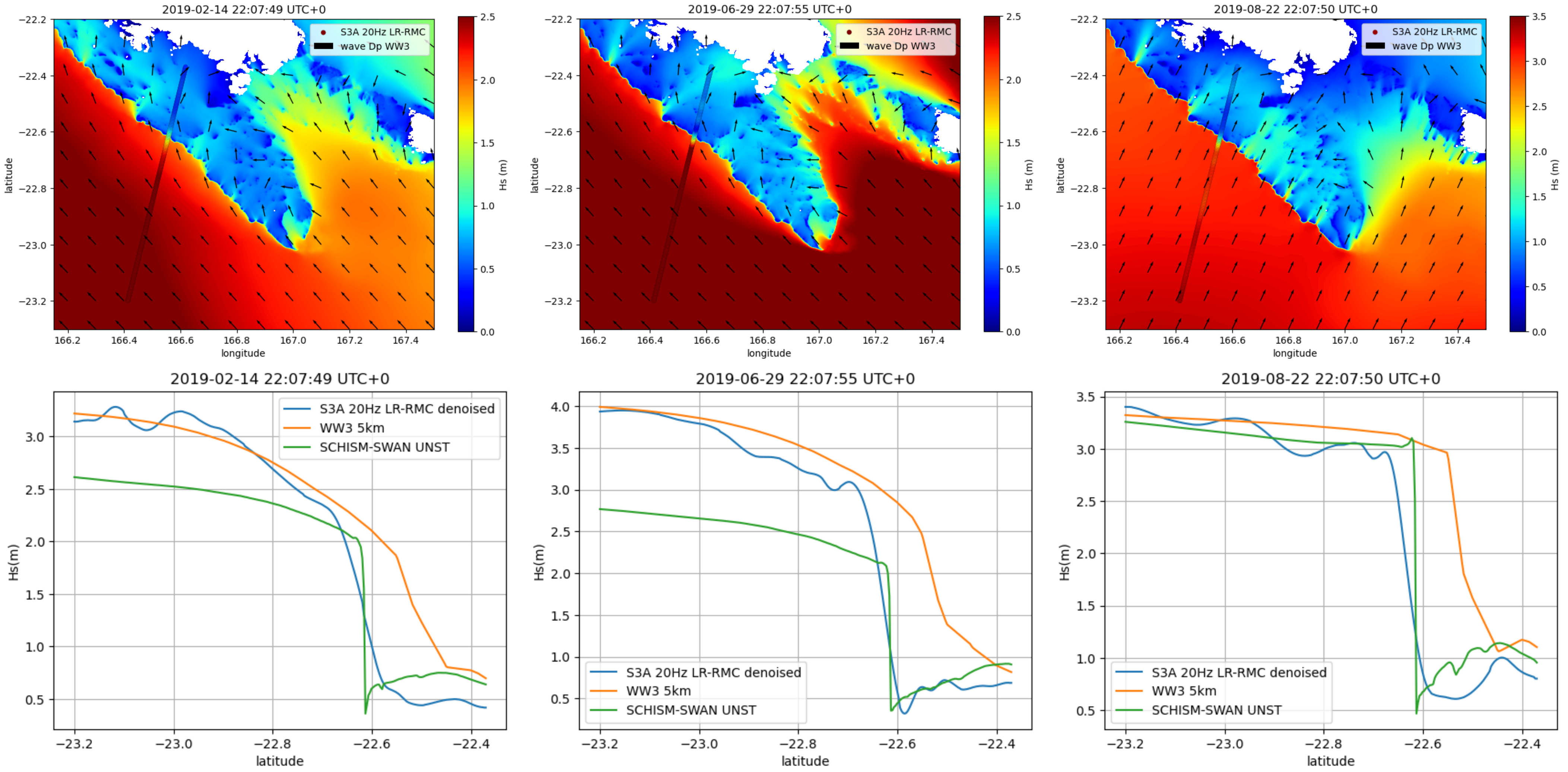
Comparison with high resolution model

3 events with energetic offshore wave conditions are selected to compare S3A observations with model results.

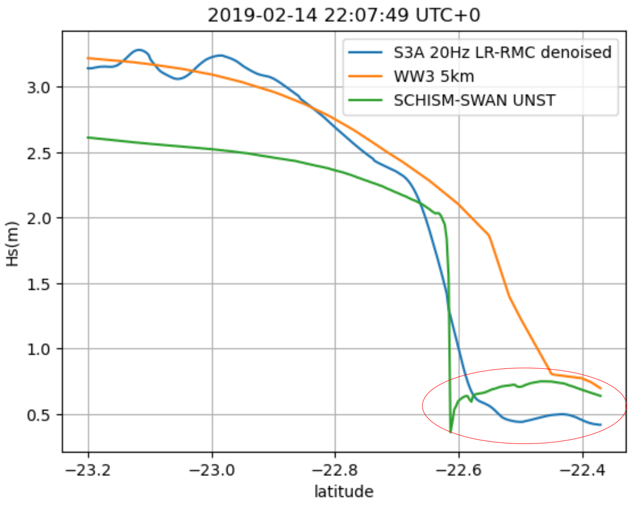
- Hs trends measured by S3A in the offshore region is very similar to WW3 LR (5km) model results for all events, but significantly lower when simulated by the coupled SCHISM-SWAN HR model for the 14/02/2019 and 29/06/2019 events ;
- The abrupt Hs decrease over the reef (depth-limited wave breaking) simulated by the HR model is clearly missed by the LR model, and partially observed by S3A, with some significant smoothing due to LR-RMC processing ;
- Hs trends over the lagoon are not always consistent between HR model and S3A, likely due to limited range resolution of S3A and model inaccuracies (wind forcing) ;

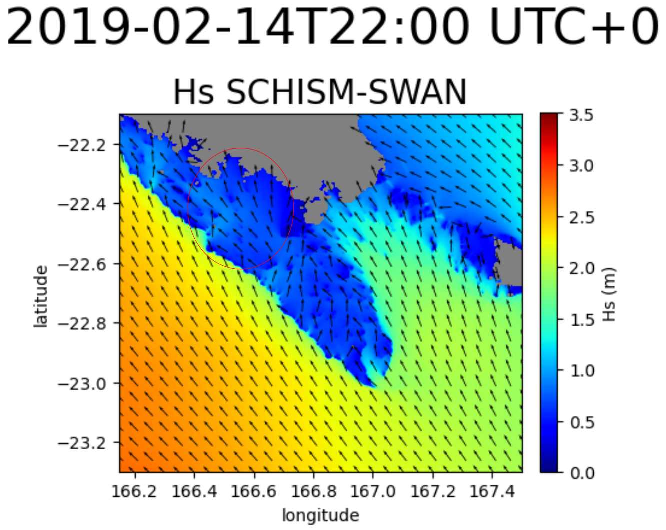


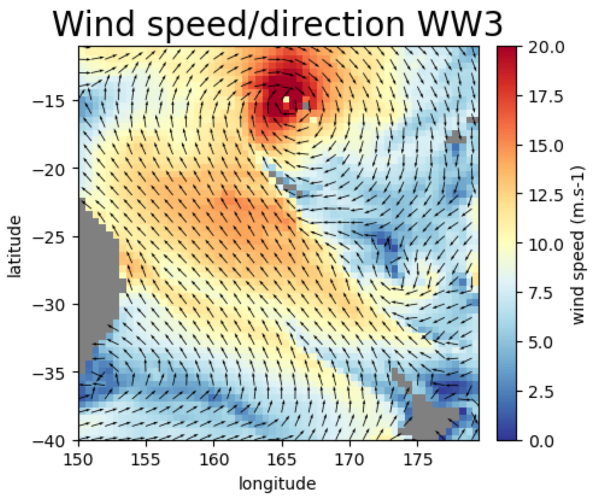
Comparison with high resolution model

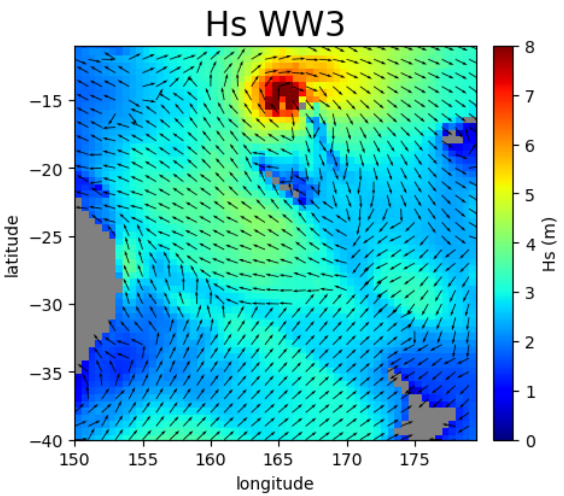


Impact of synoptic conditions on lagoon sea state









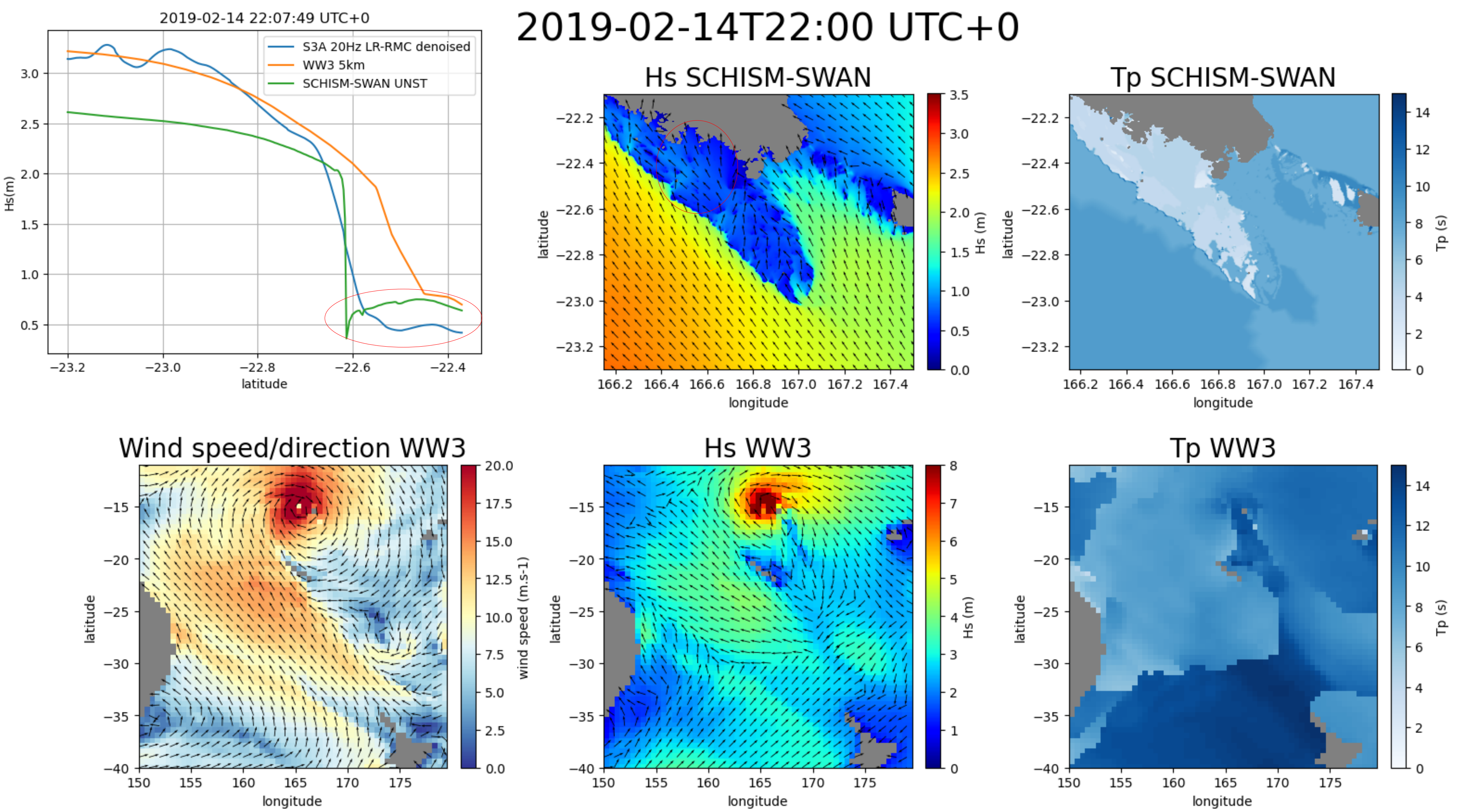
Tropical cyclone Oma developped north of NC on 11-15 February 2019 before moving southward.

Strong SE winds prevailed south of NC, generating a short period SE wind sea, superimposed with SW swells coming from southern ocean

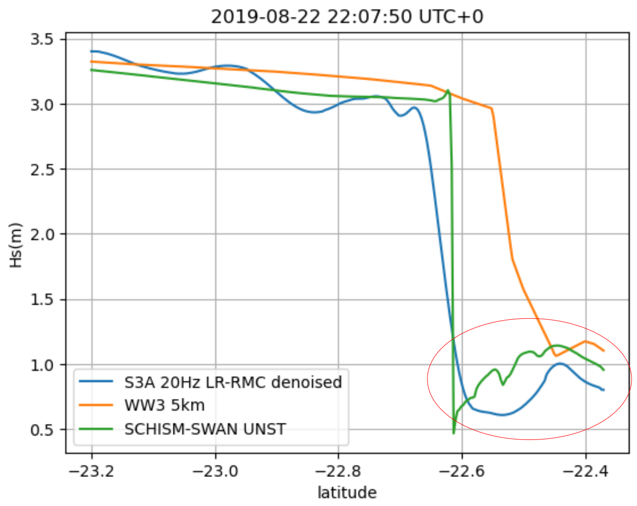
Lagoon sea state is clearly dominated by the locally generated wind sea, with little influence from reef-parallel incident waves

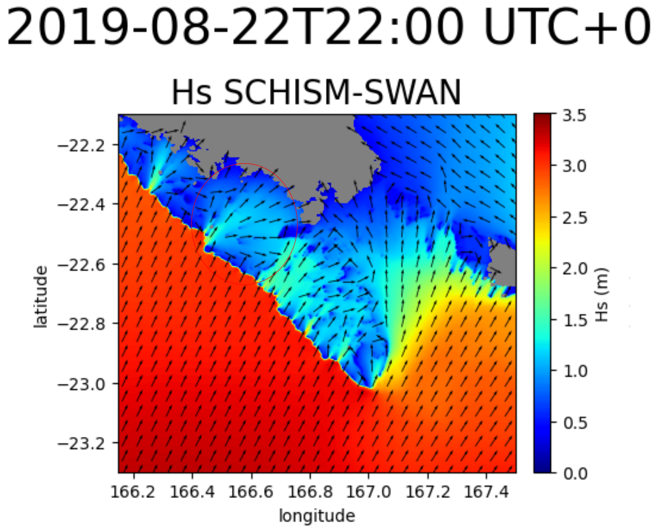
S3A and HR model both indicate little spatial Hs variability over the lagoon during this event, but HR model gives significantly larger values

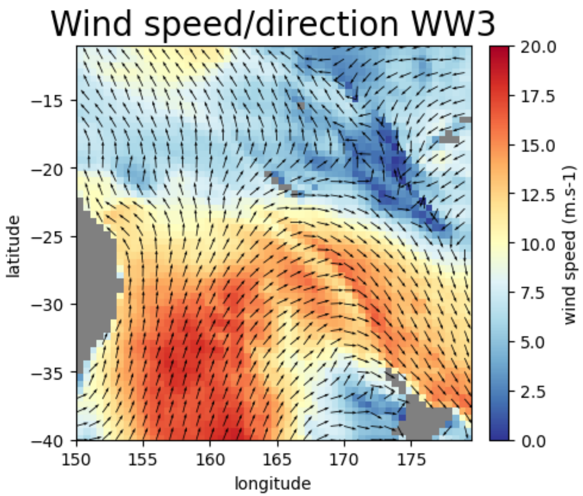
Impact of synoptic conditions on lagoon sea state

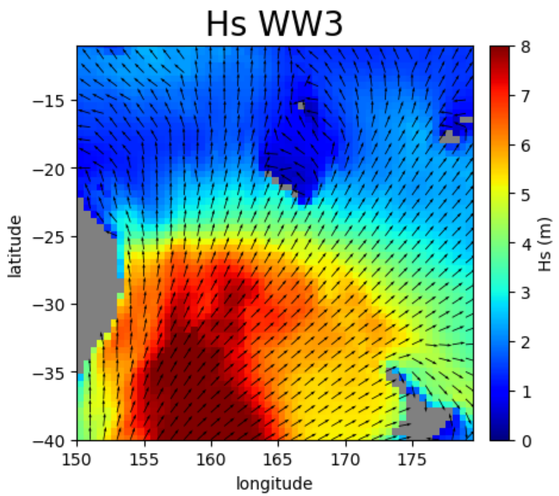


Impact of synoptic conditions on lagoon sea state









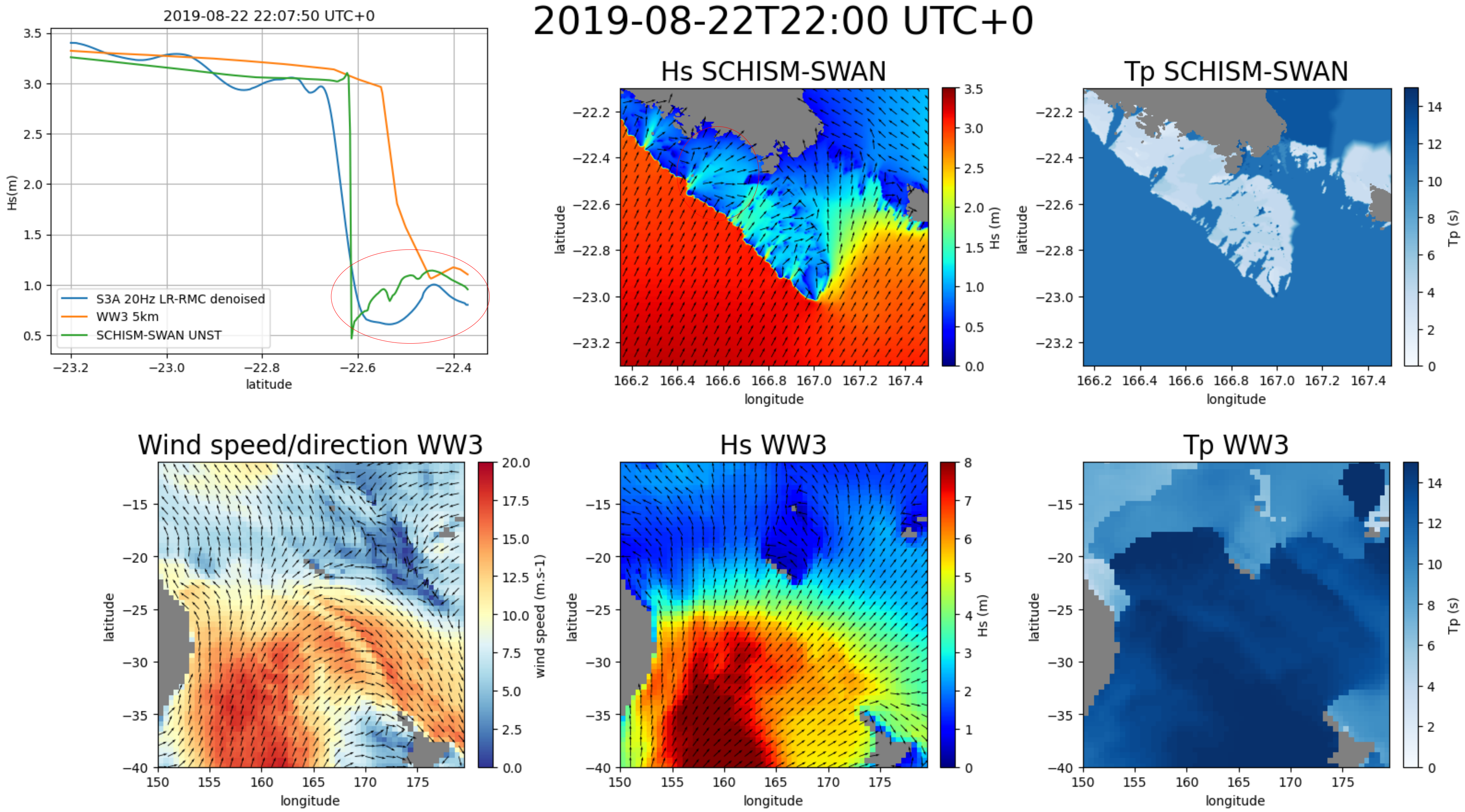
On August 21 2019, a southern ocean extratropical storm moved northward in the Tasman Sea and generated large waves that propagated in the NE direction.

On August 22, 22:00 long period swell waves up to 3.5m reached the south coast of NC, while the local winds remained weak (<7.5m.s^{-1})

The incident swell oriented perpendicular to the reef barrier propagated across the lagoon through the reef pass

S3A and HR model both indicate a significant Hs increase from the reef to the middle of the lagoon, consistent with the wave incursion through the pass.

Impact of synoptic conditions on lagoon sea state



Conclusions and perspectives

- Preliminary comparisons between S3A measurements and high-resolution model simulations were carried out to investigate wave transformation in the barrier-reef lagoon system of south New-Caledonia
- Analysis of the S3A quality flags do not indicate significant loss of data quality when the satellite ground track intersects the barrier reef
- S3A measurements indicate strong along-track Hs variability from offshore to the lagoon, consistent with the HR model results
- The abrupt Hs decrease due to depth-limited wave breaking over the reef top is well captured by S3A but spatially smoothed as a result of the LR-RMC processing (extended ground track)
- S3A and simulated Hs offshore and in the lagoon present consistent trends but significant differences in magnitudes that require further investigations
- Future work will use a larger dataset of HR model results for comparisons with S3A, and the analysis of standard SAR observations plus dedicated coastal products

Thank you !

Photo credit : Pierre-Alain Pantz