



High-Resolution Sea Surface Height Anomaly from Nadir Altimeters: Processing Improvements and Spectral Consistency with SWOT

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15 **Abstract.** The Surface Water and Ocean Topography (SWOT) wide-swath satellite altimetry mission represents a major
advance over conventional nadir-pointing altimetry in resolving small-scale ocean dynamics. Here, we demonstrate the
potential of conventional altimeters such as Jason-2, Saral/AltiKa, Sentinel-3A in observing small-scale ocean dynamics by
using High-Resolution Sea Surface Height Anomaly (SSHA_HR) products instead of classical Low-Resolution products. We
analyse SSHA_HR wavenumber spectra around New Caledonia in the southwestern tropical Pacific - an important study site
20 in the context of SWOT. This region is characterized by complex ocean dynamics, featuring high mesoscale activity and
internal tides. The comparison of SWOT Sea Surface Height Anomaly spectrum with Saral/AltiKa and Sentinel-3A SSHA_HR
spectra shows a good consistency between both nadir altimetric measurements for small scales down to 20 km wavelength.
SSHA_HR power spectra exhibit mesoscale spectral slopes extending down to 60 km wavelength, highlighting the dominant
Surface Quasi-Geostrophic dynamics in the surface layers, particularly present in austral winter while Quasi-Geostrophic
25 dynamics prevail in austral summer. A second k-2 spectral slope emerges at smaller scales down to 30 km wavelength in
accordance with the Garret and Munk spectrum. The spectral signatures of internal tides are visible over a broad range of
wavelengths up to 150 km in summer when submesoscale activity is less energetic. This study highlights the value of these
high-resolution along-track data for documenting fine scale dynamics over a long time period and their integration into
operational systems in conjunction with SWOT data or once the SWOT mission has been completed.

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1 Introduction

For more than 30 years, satellite altimetry has provided a continuous sampling of the ocean topography at global scale, allowing statistical and dynamical investigations of sea level variability. The different dynamical regimes that exist over the global ocean have been characterized using along-track Sea Surface Height (SSH) wavenumber Power Spectral Density (PSD) computation (Xu and Fu, 2011). These wavenumber spectra are also key tools to quantify the regional and seasonal variations in error levels in different altimetric technologies (Dufau et al., 2016; Vergara et al., 2019), and their impact on the observability of ocean dynamics. Studies using along-track SSH wavenumber PSD are mainly based on Low Resolution (LR) 1 Hz SSH measurements (SSH_LR, 6-7 km sampling) that allow to document the global distribution of SSH_LR spectral slopes, classically estimated in the 70-250 km “mesoscale” wavelength range.

TOPEX/Poseidon and the following Jason missions covering the time period from 1992 to the present day are classically used for that purpose (Stammer, 1997; Le Traon et al., 2008; Xu and Fu, 2011, 2012; Zhou et al., 2015; Biri et al., 2016). Recent papers also investigated other satellite missions such as SARAL/AltiKa (launched in 2013) using the Ka band instead of the Ku band used in the Jason missions, with a smaller footprint and a lower noise level (Dufau et al., 2016; Vergara et al., 2019). Inspired by the synthetic aperture radar (SAR) technique, a nadir radar altimeter concept called the “Delay/Doppler altimeter” or “SAR mode altimeter” provides better accuracy and resolution capabilities than conventional pulse-limited altimeters (i.e., low-resolution mode). This concept was initially tested in selected regions with the CryoSat-2 satellite (Boy et al., 2017), and then used globally on Sentinel-3 missions (Sentinel-3A launched in 2016 and Sentinel-3B launched in 2018). Sentinel-6b launched in November 2025 will extend the legacy of the Jason satellite series altimetry at least through 2030 and a second Sentinel-6c, should be launched five years later.

The pioneering Surface Water and Ocean Topography (SWOT) satellite mission is based on a wide swath SAR interferometry in Ka-band (KaRIN) (Desai, 2018); it was launched in December 2022 for a minimum duration of three years. SWOT offers the capability of making high-precision, high-resolution wide-swath measurements of SSH to detect small-scale oceanic signals unresolved by current altimeter constellations. It aims to characterize the spatial structure of the ocean mesoscale and submesoscale dynamics at resolutions down to 15 km in wavelength (Fu and Ubelmann, 2014; Morrow et al., 2019, Fu et al., 2024, Wang et al., 2025a). Recent results show that the mission has far exceeded expectations, as evidenced by clear observations of nonlinear internal waves (Archer et al., 2025). During the early validation phase of this mission and the SWOT Adopt-A-Crossover (AdAC) framework (d’Ovidio et al., 2019), particular emphasis was made on understanding the SWOT swath-averaged wavenumber spectra over the smaller scales from 200 to 15 km wavelength, and comparing the SWOT spectra to those derived from in-situ data and from conventional altimeter analyses over similar scales (Wang et al., 2025a, Wang et al., 2025b). When comparing spectra from different altimetric technologies at scales of 15-200 km, a strong gap was identified between the 40-70 km effective resolution of the low resolution 1 Hz (6-7 km sampling) along-track radar altimetry products commonly used in oceanography and the 15 km effective resolution for the SWOT basic ocean 2x2 km products. However, the finest spatial sampling in the along-track data for Jason missions and Sentinel3 missions is 20 Hz (350 m sampling), and



40 Hz (170 m sampling) for SARAL/AltiKa mission. These high-resolution (HR) along-track products are rarely used to
65 observe small scale dynamics because of the larger noise level of the SSH linked to the SSH PSD signal decrease with
increasing wavenumber (Scott and Wang, 2005; Xu and Fu, 2012). Using them to extract meaningful physical information at
small scales requires careful pre-processing, editing and filtering of the data, and applying spectral processing including de-
noising, to change the shape and slopes of the wavenumber spectra (Xu and Fu, 2012; Vergara et al., 2019).

The companion papers of Verron et al. (2018) and Bonnefond et al. (2018) used HR datasets to highlight the benefits of the
70 SARAL/AltiKa Ka-band over the Jason Ku-band from wavenumber spectra, but these globally-averaged wavenumber spectra
of SSH anomalies prevent any regional dynamical interpretation. Over the 15-200 km scales of interest for this study, SSH
variability results from many contributions ranging from geostrophically balanced mesoscale motions, unbalanced motions
linked to tides and internal tides, part of the internal gravity waves spectra, as well as unresolved altimetric errors and
corrections. Very few studies have compared regional wavenumber spectra from multiple altimetric technologies, and even
75 fewer using HR datasets. Such regional studies rely on short segments to calculate wavenumber spectra and require careful
pre-processing (e.g. Morrow et al., 2017; in the western Mediterranean Sea). Yet, it is worth the effort, as these HR along-
track altimetry products could be perfectly suited for use in conjunction with SWOT, in particular to evaluate SWOT data
during the validation phase.

In this study, we focus on the region South of New Caledonia (SNC) in the South West Pacific (Fig. 1) that has been chosen
80 as a Calibration and Validation (CalVal) site for SWOT (SWOT AdAc Consortium, d'Ovidio et al. (2019)). A SWOT swath
has crossed the region every day (the Fast Sampling Phase) during the six months of CalVal phase in 2022-2023 (Fig. 1b).
SNC variability is characterized by large mesoscale eddies (Keppler et al., 2018) and energetic internal tides well documented
by model studies (Fig. 1b, Bendinger et al. 2023). The observability of internal tides depends on the seasonal modulation of
the meso/submesoscale activity (Fig. 1cd, Bendinger et al., 2025, 2026). SNC is therefore a challenging region for SWOT SSH
85 variability interpretation.

The first objective of this study is to address a technical challenge: it aims to reduce the noise of HR data and to improve their
spectral characteristics compared to the LR data, so they can resolve the finest scales of interest for SWOT. This is done with
careful processing and editing of HR along-track altimetric data for the three different missions Jason-2, SARAL/AltiKa and
Sentinel-3A. The second objective is to analyse SSHA wavenumber spectra to highlight the potential of HR data to shed light
90 on the balanced/unbalanced dynamics in the SNC region. The third objective is related to the validation phase of SWOT in the
SNC region with the motivation to use HR along-track altimetric products as an independent dataset to validate SWOT, and
in return SWOT data may assess the potential of HR data for fine scales dynamics. The latter offers a huge potential for
extending the time-series SSH observations of fine-scale dynamics, not only by going further back in time thanks to past nadir
missions, but also by ensuring continuity into the future, beyond the lifetime of SWOT.

95 The paper is organized as follows. Section 2 presents the altimetric data used for the different conventional satellite missions
with the computation of High Resolution Sea Surface Height Anomalies (SSHA_HR) datasets, and the methodology based on
a spectral approach. Section 3 illustrates the sensitivity of the spectral analysis to the different datasets and their processing.



Section 4 focuses on the dynamical aspects of the South New Caledonia region based on PSD analyses. Section 5 is dedicated to SWOT data and to the comparison of SWOT spectra and SSHA_HR spectra. Section 6 provides conclusions and a discussion.

2. Nadir altimetry and Methods

2.1 Altimetric datasets

Altimetric products are available at different levels: Level-0 (L0) is the raw telemetered data, level-1 (L1) is the Level-0 data corrected for instrumental errors, level-2 (L2) is the Level-1 data corrected for geophysical and environmental effects. HR variables are only available at L1 level for altitude, range, significant wave height and backscattering coefficient, whereas the environmental and geophysical corrections are only available at 1-Hz low resolution. Classically, along-track Sea Surface Height Anomalies (SSHAs) used for oceanographic applications are distributed at 1-Hz low resolution (SSHA_LR). The use of SSHA_HR requires a dedicated processing for HR environmental and geophysical corrections as detailed in section 2.2.

We use altimetric products available to the community from the AVISO+ FTP website. The environmental and geophysical corrections are taken from the 1-Hz L2P products delivered in Non Time Critical rather than the standard L2 products, since the L2P products have a homogenized format and content for all altimeter missions, and include some improved corrections. This provides a coherent altimeter database using the state-of-the-art recommendations from the altimetry community.

The Jason-2 and SARAL/AltiKa L2P products are generated by the CNES AVISO-SALP (Service d'Altimétrie et Localisation Précise), and distributed by AVISO+. Sentinel-3A L2P products are generated as part of the EUMETSAT Sentinel-3 Marine Altimetry L2P/L3 Service. More details on such L2P Sea Level Anomaly products and the details of the corrections are accessible for Jason-2 and SARAL/AltiKa on:

https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_L2P_all_missions_except_S3.pdf

and for Sentinel-3 on:

https://www.aviso.altimetry.fr/fileadmin/user_upload/hdbk_L2P_S3.pdf

The different altimeter characteristics are summarized in Table 1. For all missions, only the exact repeat orbit is considered for the spectral analysis and this limits the use of SARAL/AltiKa to the 2013-2016 period. Jason-2 (hereafter J2) is the longest mission covering 9 years, versus 4 years for SARAL/AltiKa (hereafter SRL) and 6 years for Sentinel-3A (hereafter S3A). Noted that Sentinel-3A and Sentinel-3B are identical so the longest time series of S3A is preferred. With a 10-day repeat cycle, more than 300 cycles are available along each J2 track, whereas SRL has 35 cycles during its 4 years, and S3A has 76 cycles over 6 years. These different altimetric missions differ in their spatial coverage, with SRL and S3A providing denser spatial coverage than J2 as illustrated on Fig. 1a.



Mission	Jason-2 (J2)	SARAL/AltiKa (SRL)	Sentinel-3A (S3A)
Radar characteristics	LRM / ku band	LRM / ka band	SAR
High Resolution (HR)	20 Hz	40 Hz	20 Hz
Along-track Sampling	~ 294 m	~ 175 m	~ 330 m
Repetitiveness	10 days	35 days	27 days
Period	2008 - 2016	2013 – 2016 (repetitive orbit)	2016 - 2021
Number of cycles	303	35	76

Table 1: Characteristics of the Jason-2, SARAL/AltiKa and Sentinel-3A altimeter missions

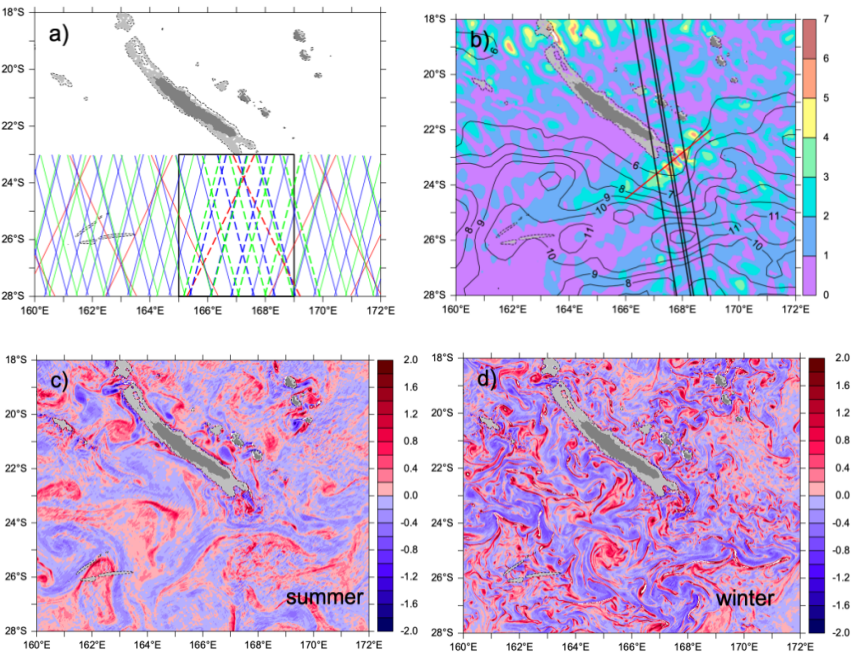


Figure 1: a) Altimetric tracks considered in this study within the New Caledonia domain for J2 (red), SRL (blue) and S3A (green). Dashed thick tracks refer to the tracks present in the subregion just south of New Caledonia bounded by the black box, where internal tides are particularly active. The shallow areas (lagoons) are shaded in light grey (depth < 20m) and the dashed line indicates the 100 m isobath. b,c,d) From regional simulations focusing on year 2014 of the New Caledonia area described in Bendinger et al. (2023, 2025): b) In contour, SSH mesoscale Eddy Kinetic Energy (in cm, > 5cm rms), in shading baroclinic M2 SSHA amplitude (in cm). The red line is along the direction of the internal tide energy flux. The SWOT swath T4 during the fast sampling phase is shown in black thick lines. Meso/submesoscale seasonal features illustrated by representative snapshots of the Rossby number in c) austral summer and in d) austral winter.



2.2 High resolution SSHA

Our objective is to compute SSHA_HR from the altimetric missions: Jason-2 (J2, 20 Hz), SARAL/AltiKa (SRL, 40 Hz) and Sentinel-3A (S3A, 20 Hz). Here, the corrections were linearly interpolated along-track from the 1Hz values to the 20 or 40 Hz positions. Standard corrections were applied including ionospheric, wet and dry tropospheric corrections, high frequency atmospheric correction, sea state bias, pole, solid and ocean barotropic tides corrections. Note that the ocean tide is one of the major geophysical signals observed by altimetry in the open ocean. The barotropic tide can be accurately modelled and extracted from altimetry measurements (Lyard et al., 2021). However, a residual tidal signal remains in the altimetry observations, which can be attributed to the internal tide signal (~1-10 cm magnitude) that arises from the interaction of the barotropic tide with bottom topography (Garrett and Kunze, 2007). A significant part of the internal tide signal is locked in phase with the ocean tide astronomical components and remains coherent over relatively long periods of time whereas an incoherent part (i.e. time varying) may exist that results from the interaction of the internal tides with its environment (mean circulation, meso/submesoscale activity, etc...). The coherent part of the internal tide can be deduced from altimetry observations and removed from the SSHA signal: today's altimetric products include the HRET internal tide correction (Zaron, 2019). However, residual errors in the barotropic or HRET internal tide corrections may exist, particularly in regional seas, and the incoherent part of the internal tide, unpredictable, remains in the altimetry observations, signing at wavelengths ranging from a few tens to around 250 km. Since we are interested in this study in the interplay of both meso/submesoscale and internal tide signatures, the HRET internal tide correction is not applied in the following analysis.

First, the corrected Sea Surface Height (SSH_HR) was computed, then the SSHA_HR after subtracting a gridded Mean Sea Surface (MSS) to only consider time variations of SSH_HR:

$$\text{SSH_HR} = \text{altitude-range- corrections}$$

$$\text{SSHA_HR} = \text{SSH_HR} - \text{MSS}$$

To compute SSHA_HR, we used the gridded CNES-CLS-2015 MSS (Pujol et al., 2018) recommended in the L2P products. The use of a gridded MSS is motivated by SWOT which covers new ground and has no choice but to reference SSHA onto a gridded MSS for points between the historical 1-D groundtracks. The use of a gridded MSS may introduce some errors at small scales compared to an along-track MSS derived from a long time series of data along a repetitive orbit (Pujol et al., 2018). On the other hand, it avoids interpolating the along-track data onto a fixed track. Note that because of the use of a gridded MSS that does not include S3A data, MSS errors may exist along uncharted S3A tracks for wavelengths from 30 to 80 km (Pujol et al., 2018).

We now describe the processing methods we used to discard outliers on SSHA_HR, illustrated on Fig. 2. The method is based on a classic editing procedure of the different variables (SSHA_HR_EDIT) completed by a filtering step to reduce the along-



track noise on SSHA_HR_EDIT (SSHA_HR_FLT). In the following, low Resolution SSHA (SSHA_LR) datasets (1 Hz) are
 190 also used for comparison.

2.2.1 SSHA_HR_EDIT

Firstly, a threshold editing is applied on the high resolution values from the GDR (altitude, range, significant wave height, the
 back-scattering coefficient) to eliminate outliers. The same threshold values as the L2P 1 Hz editing are used (details are on
 195 the handbooks mentioned above). Secondly, the 1 Hz L2P corrections are edited with the standard validation flag parameter
 provided in the L2P files before being interpolated at high resolution. Then SSH_HR and SSHA_HR are computed and edited.
 Despite these standard editing steps, a careful examination of the dataset shows that spurious data still exist whatever the
 mission (Fig. 2). Even if they are few, they can have a large impact on the spectral analysis (as shown in the next sections).
 This is the reason why we propose an additional editing procedure.

2.2.2. SSHA_HR_FLT

Using the SSHA_HR_EDIT computed for the different altimetric missions, we then apply a nonlinear iterative editing filter,
 as proposed by Dibarboure et al. (2014). This filtering technique is effective for mitigating the “hump artifact” visible on
 conventional altimetry products (J2, SRL, see next section) and for suppressing outliers (this is why it is also applied on S3A).
 205 The filter iteratively removes individual Sea Level Anomaly values that depart from a low-pass-filtered SSHA (cutoff: 50km)
 beyond 3-sigma of the local standard deviation. This nonlinear iterative filter can be summarized as follows:

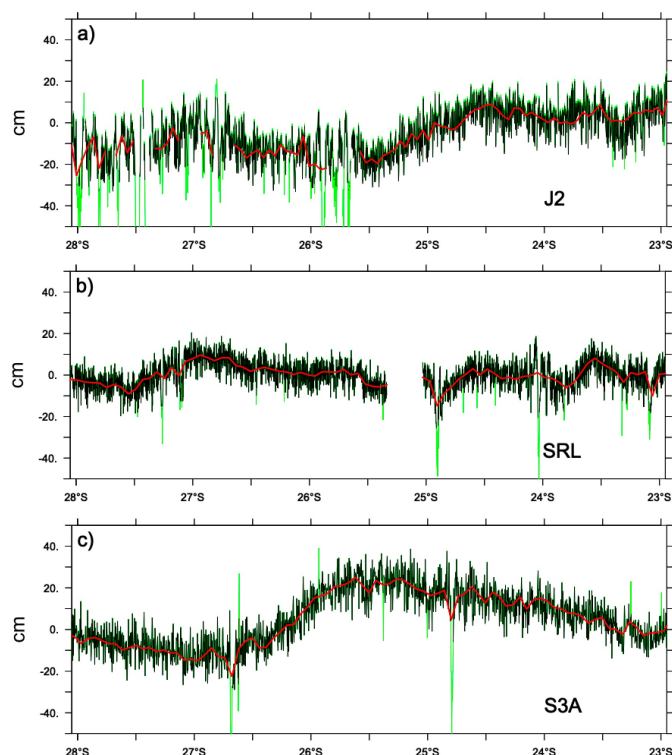
- 1) Apply a median filter (cutoff: 50km) on the SSHA_HR_EDIT along the track; the result is referred as ‘SSHA low-pass’
- 2) Compute $R = \text{SSHA} - \text{SSHA low-pass}$
- 3) If $|R| > 3 \cdot \sigma(R)$, remove the data point, where $\sigma(R)$ is the local standard deviation (computed over the 50km
 210 window)

Steps 1, 2 and 3 are repeated until no data is removed: the resulting along-track SSHA series is referred to as SSHA_HR_FLT.
 The impact of this filtering step on SSHA spectra is illustrated on Fig. 2 and discussed in the next sections.

Finally, Table 2 summarizes the three datasets used in this study for each altimetric mission.

Dataset	SSHA_LR	SSHA_HR_EDIT	SSHA_HR_FLT
Resolution	1 Hz	20 / 40 Hz	20 / 40 Hz
Editing	L2P editing	L2P editing	L2P editing and iterative median filter editing

Table 2: List and characteristics of datasets used in this study.



220 **Figure 2: Example of the different levels of processing for a) J2 (tr21-cyc54, b) SRL (tr202-cyc5) and c) S3A (tr473-cyc32) tracks south of New Caledonia: showing the SSHA_LR (red); SSHA_HR_EDIT (green) and SSHA_HR_FILT (black).**

2.3 Spectral methodology

2.3.1 Wavenumber spectrum computation

225 Spectral analysis is a powerful statistical technique to characterize and analyze sequenced data and highlight the periodic component of a signal. The PSD describes the distribution of the signal power into wavenumber components. Data needs to be equally spaced, and the data timeseries must be long enough to cover several cycles of the physical signals of interest. But altimetry series often present missing data and short segment lengths may have spectra polluted at small scales by energy at large scales. So, it is necessary to apply a pre-processing on the dataset to fill gaps and to limit the leakage between

230 wavenumbers.

The methodology used for the SSHA wavenumber spectrum computation is similar for the low and high-resolution data. The tracks are cut in relatively short segments of 500 km for SNC, so they are representative of the fine scales/high-frequency dynamics of the region. For every cycle, only segments with more than 75 % of valid data are selected if the distance between two consecutive missing points is lower than 20 km. Then for a given segment the missing points along the track are filled

235 with a linear interpolation applied on filtered data using a median filter. A 50 % Tukey windowing and a linear detrending are



then applied following Tchilibou et al. (2018), and the wavenumber spectrum is computed with a python function named *scipy.signal.welch* (Welch 1967).

A single spectrum is too noisy to be used individually, and it is necessary to average spectra together to reduce the uncertainty. The spectral uncertainty is estimated for a 95% significance level based on a chi-squared test. Depending on the altimeter mission (the number of cycles available and the number of segments used), the robustness of the spectrum varies a lot. The number of spectra varies from 1000 to 2200 depending on the mission; this is large enough to get robust spectra. But looking at spectra representative of a particular subregion or a particular season is more challenging because the smaller number of averaged spectra increases the spectral uncertainty (e.g. section 4). During the fast sampling phase, the SWOT swath was repeated daily over a short time period, but along-track data can be extracted every 2 km across the swath, providing 50 along-track data sets for every SWOT nadir track and improving the number of spectra to average (>4000).

2.3.2 Spectral characteristics definition

Following Dufau et al. (2016) and Dibarboure et al. (2014), three parameters are evaluated from the SSHA wavenumber spectrum: the error level, the mesoscale spectral slope and the mesoscale resolution capability. These parameters are then compared for the different datasets and for the two regions in section 3 and illustrated in Fig. 3.

Error estimate

The error level is analysed within the wavelength range where the physical signal in the spectra becomes dominated by errors. For J2 and SRL high resolution data, the observation of ocean scales smaller than 100 km is degraded by the existence of instrumental errors that have two distinct signatures in SSHA spectra. For wavelengths shorter than 2-3 km, we observe a flat spectrum, hereafter referred as the ‘plateau’, corresponding to the instrumental noise, and in the wavelength range from 5 km to a few tens of km, we observe a ‘hump’ that corresponds to correlated errors that originate from inhomogeneities in backscatter strength within the altimeter footprint, due for instance to waves, swell or rain cells, (Faugere et al., 2006; Dibarboure et al., 2014). The upper wavelength limit of the spectral hump (hereafter referred to as UWH) is defined as the wavelength corresponding to the minimal Power Spectral Density in the 10-100 km wavelength range (blue triangle in Fig. 3). Thus, we assume that when the spectral signal starts to increase with wavenumber it means that it is dominated by errors. Beyond the UWH, the error due to the backscatter events (the hump) is considered to be white. The error level in physical space (in cm rms) is then computed by integrating the signal below the spectrum for wavelengths < UWH and below the white level for wavelengths > UWH; this is equivalent to integrating the signal over the shaded area of Fig. 3.

For the 1 Hz data, the error level for J2 and SRL is classically defined as an instrumental white and uncorrelated noise corresponding to the spectral plateau in the 15-30 km wavelength range (following Xu and Fu, 2012; Dufau et al., 2016; Vergara et al., 2019), when in fact it results from both instrumental white noise and correlated error.



For S3A, the hump artefact does not exist in the SAR mode due to the narrow along-track footprint, however, the SAR
270 processed data does exhibit a slight red-noise slope in the 0.7-30 km band impacted by the swell period and its direction as
shown for Cryosat 2 data (Raynal et al, 2018). It is classically estimated from a linear function fit in the 0.7 - 3 km wavelength
range for the 20 Hz data (Boy et al., 2017) and in the 15 – 30 km wavelength range for the 1 Hz data as in Vergara et al. (2019).
Vergara et al. (2023) prefer to apply a white noise fit to define the 1Hz S3A error level because they get more robust unbiased
spectra. In the following, we rely on the recommendation of Vergara et al. (2023) and the 20Hz S3A error level is defined as
275 a white noise fit over the 0.7-3 km wavelength range.

To compare the error level estimations between each mission with different LR and HR sampling frequencies, an equivalent
1 Hz noise level is estimated from the 20 Hz (J2, S3A) and 40 Hz (SRL) noise levels, by dividing the noise levels in rms by
 $\sqrt{20}$ and $\sqrt{40}$, respectively.

Spectral slope in the mesoscale wavelength range

280 The mesoscale slopes are calculated by a least squares regression to the spectrum for a given wavelength band, once the spectra
are unbiased by removing the energy of the error level over the entire wavenumber range (Xu and Fu, 2012, Vergara et al.,
2023). The classical 70-250 km mesoscale wavelength range has been revisited to limit the contamination of mesoscale signals
by internal tides and mesoscale slopes are calculated over the 100-250 km wavelength range.

Observable wavelength (OWL)

285 The observable wavelength (OWL) is defined as the crossing point where the error level and the spectral slope intersect (green
triangle in Fig. 3). It sets the minimum size of dynamical structures that altimetry would statistically be able to observe with a
signal-to-noise ratio greater than 1. Note that with regard to mesoscale dynamics this spectral wavelength resolution can be
interpreted as the equivalent of twice the diameter of an eddy.

290 3. Spectral sensitivity from Nadir HR altimetry

In this section, we illustrate for each mission how the short wavelengths are impacted when comparing SSHA_HR against
SSHA_LR, depending on the different data processing: SSHA_HR_EDIT, SSHA_HR_FLT (e.g. section 2.2). We look at the
averaged spectra within the regional box (shown in Fig. 1a). We discuss first in a qualitative way the comparisons between
spectra before interpreting them in terms of dynamics in the next section.

295 The sensitivity to the data resolution and processing is illustrated for each mission. For each mission, spectra from the different
datasets are presented on Fig. 3abc, and their spectral characteristics are summarized in Table 3.

For mesoscale wavelengths longer than 100 km the spectra from the different datasets are similar with a continuous -3.6 slope
whatever the mission. This is consistent with the Vergara et al. (2023) analyses using longer 1500 km tracks.

For wavelengths below 70 km, the differences between SSHA_LR and SSHA_HR_EDIT data are particularly well marked
300 for J2. The filtering step (SSHA_HR_FLT) modifies the shape of the spectra for wavelengths up to 50-80 km. The differences
between SSHA_HR_EDIT and SSHA_HR_FLT are particularly significant for SRL where the level of variance of the hump
signature between SSHA_HR_EDIT and SSHA_HR_FLT is reduced by ~25%.



Whatever the mission, the highest error estimate is for SSHA_LR, and the lowest error estimate is for SSHA_HR_FLT. In the
 305 SSHA_LR products, the error level varies from 2.7 cm rms for J2 to 2 cm rms for SRL and 1.8 cm rms for S3A (Table 3).
 These estimations are in accordance with global error estimates of ~ 3 cm for Jason-class missions (e.g. Ablain et al., 2010,
 Dufau et al., 2016) and with the regional estimates of Vergara et al. (2019, 2023) for the three missions. The corresponding 1
 Hz error level for the SSHA_HR_FLT products varies from 1.7 cm rms for J2 to 1 cm rms for SRL and 1.2 cm rms for S3A.
 This error level reduction in SSHA_HR_FLT improves the regional observable wavelength by up to ~ 20 km compared to
 310 SSHA_LR for J2 and SRL. The observable resolution for SSHA_LR is about 80 km for J2 and 69-66 km for SRL and S3A,
 respectively. With the lower noise level for SSHA_HR_FLT, the resolution capability is reduced at 60 km for J2, 43 km for
 SRL and 57 km for S3A.

Finally, spectra for the different missions are superimposed for the SSHA_HR_FLT datasets (Fig. 3c). Whatever the mission
 technology, spectra are similar for wavelengths down to 60 km providing a robust characterization of the mesoscale range.
 315 Below 80 km, the spectra flatten. J2 differs from SRL. According to Dibarboure et al. (2014), the hump energy differs a lot
 between J2 and SRL products and can be explained by the smaller footprint of SRL that captures fewer backscattering events.
 J2 exhibits the highest error level with a UWH (cf. section 2) at 33 km wavelength against 12 km wavelength for SRL. The
 wavelength range of the transition between the hump and the instrumental noise plateau differs for J2 (3-10 km) and SRL (2-
 5 km): this difference can be linked to the size of the leading-edge footprint and the diameter of the entire footprint (Dibarboure
 320 et al., 2014). As a consequence, SRL has a better mesoscale resolution than J2 with a ~ 20 km benefit for SRL and has similar
 signatures than S3A down to 20 km.

To summarize, these results highlight that HR filtered products provide more accurate data up to scales as large as ~ 100 km
 compared with LR products with the consequences of increasing wavelength observability for the description of the locally
 governing dynamics. SSHA_HR_FLT datasets for S3A and SRL seem better suited than J2 to resolve small amplitude small-
 325 scale dynamics.

SNC	Error	slope 100-250	OWL
	LR/HR_EDIT/HR_FLT	LR/HR_EDIT/HR_FLT	LR/HR_EDIT/HR_FLT
J2	2.7/1.8/1.7 (7.9/20Hz) cm	-3.6/-3.6/-3.6 (+/- 0.08)	80/62/60 km
SRL	2.0/1.1/1.0 (4.3/20Hz) (6.1/40Hz) cm	-3.6/-3.6/-3.6 (+/-0.09)	69/44/43 km
S3A	1.8/1.3/1.2	-3.5/-3.7/-3.7 (+/- 0.13)	66/54/54

**Table 3: Spectral characteristics for the SNC region and the different satellite missions (J2, SRL and S3A) corresponding to the
 different datasets (LR, HR_EDIT, HR_FLT). In order to compare the error level or the instrumental noise of the 40 Hz SRL data
 (in cm rms) with 20 Hz J2 data, the error level of SRL is divided by $\sqrt{2}$. Similarly, in order to compare the error level of the 20 Hz
 330 data with the one of the 1Hz data, the error level at 20 Hz (indicated in parenthesis in the second column) is divided by $\sqrt{20}$.**

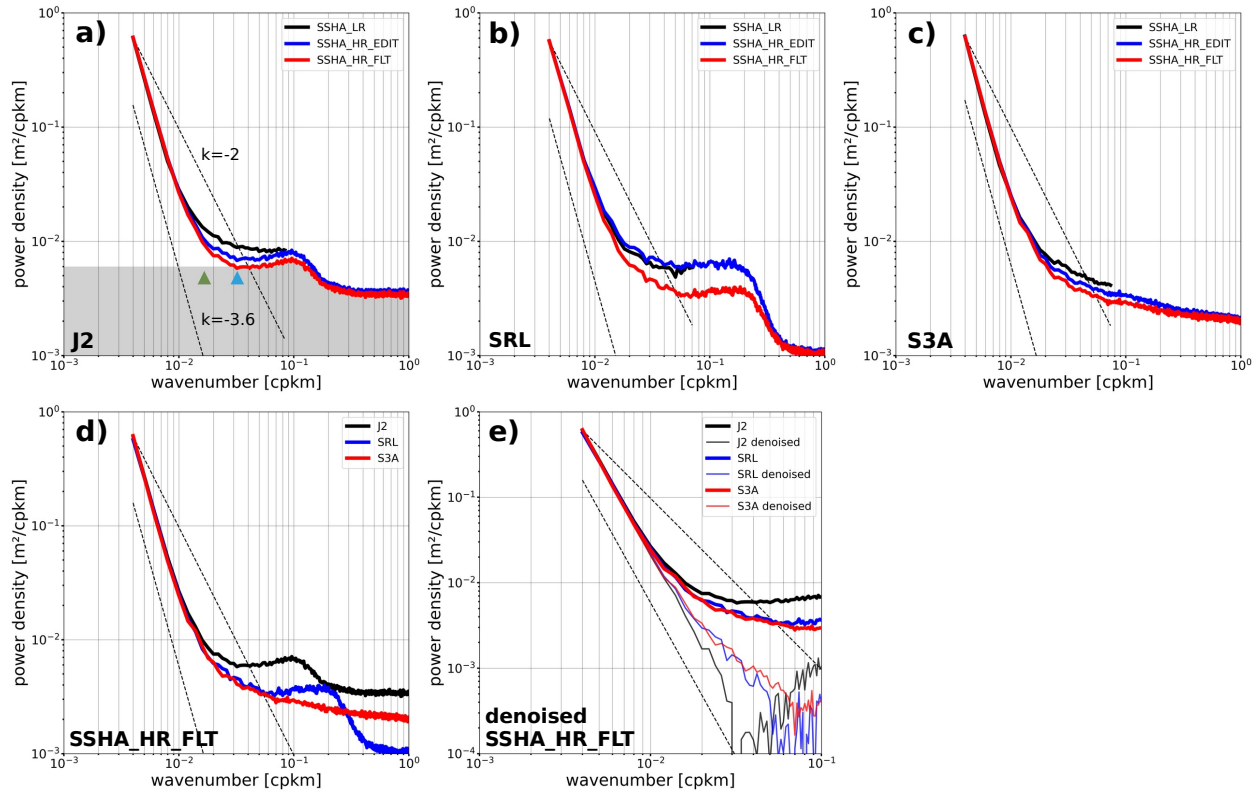


Figure 3: SSH wavenumber spectra for the SNC region shown in Fig. 1 for J2 (a), SRL (b) and S3A (c) function of the different datasets (SSHA_LR: Black; SSHA_HR_EDIT: Blue; SSHA_HR_FLT: red). Spectral characteristics as defined in section 2.3.2 are illustrated in a) for SSHA_HR_FLT with UWH (blue triangle at 31 km wavelength), OWL (green triangle at 60 km wavelength) and the error level corresponding to the integration over the grey domain. d) Comparison of SSH wavenumber spectra based on SSHA_HR_FLT datasets for the different missions: J2: black; SRL: blue; S3A: red. e) as in d) with the addition of unbiased spectra (thin lines). Note that the X and Y axes are different from the previous ones to concentrate on wavelengths higher than 10 km. The characteristic wavenumber slopes k^{-2} and $k^{-3.6}$ are represented by the dotted black lines.

4. Regional description: Seasonal mesoscale dynamics and internal tides signatures

The South New Caledonia region is characterized by a range of mesoscale (balanced motions) and internal tides (unbalanced motions) dynamics. The SNC region reveals a complex pattern of surface and subsurface currents (Cravatte et al., 2015) whose instabilities generate a strong Eddy Kinetic Energy (EKE) field (Qiu et al., 2009). SNC variability is dominated by large mesoscale eddies propagating westward from the central Pacific (Keppler et al., 2018). The intense mesoscale field is characterized by a variability in SSH up to 10 cm rms (Fig. 4a). In addition to mesoscale and submesoscale activity, the SNC



region exhibits energetic internal tides as shown by altimetry (Ray and Zaron, 2016) with amplitudes up to 6 cm in SSH (Fig. 1b). In order to understand the life cycle of internal tides in the region, Bendinger et al. (2023, 2025) analyzed a regional high resolution ($1/60^\circ$) simulation with tidal forcing. The area just south of New Caledonia corresponds to a barotropic to baroclinic conversion zone from which energy tidal flux propagates southwestward through the mesoscale field before dissipating after a few hundred kilometres (Bendinger et al., 2023). Internal tides are mainly coherent (fixed amplitude and phase) but the interactions between internal tides and mesoscale currents are a source of incoherent (ie. time-varying) tidal variability (Bendinger et al. 2024, 2025).

Once the full model dynamics were decomposed into subinertial ($\omega < f$, balanced motions) and superinertial ($\omega > f$, unbalanced motions) frequencies, SSH wavenumber spectral signature allowed quantification of the contributions from internal tide activity and/or turbulence activity. Bendinger et al. (2025) illustrate how SSH wavenumber spectra in tidal beam propagation direction differs from the ones in along-track direction because of strong anisotropy in the internal tide signature. Along the tidal beam propagation direction, superinertial processes dominate over subinertial motions at scales up to 180 km. Along the altimetry track direction, only a fraction of the internal tide energy is captured, causing the SSH wavenumber spectra to emphasize the more isotropic balanced flow regime. Bendinger et al. (2025) also showed that spectra exhibit seasonal modulation because the turbulent regime evolves from a dominance of mesoscale dynamics in summer to a dominance of submesoscale dynamics in winter (Fig. 1cd). As a result, the transition scale between balanced and unbalanced motions varies from 115 km in austral summer months to 41 km in austral winter months.

In the following, we document these different aspects from altimetric HR products by looking at their spectral signatures that vary geographically and seasonally in the limit of residual altimetric errors and observable wavelength. In order to better define the transition between balanced and unbalanced motions the noise spectral level (e.g. section 2.3.2) has been subtracted from the PSD estimates over the entire wavenumber range, which provides an unbiased estimate of the regionally average spectrum as in Xu and Fu (2012) and Vergara et al. (2019; 2023). This is roughly in line with the argument that the steep spectrum is associated with nonlinear turbulent dynamics and the flat spectrum is associated with more linear wave dynamics. Such unbiased spectra are presented on Fig. 3d for SSHA_HR_FLT and they are discussed below.

For all satellite missions, mesoscale slope extends down to 80 km wavelength. For smaller wavelengths, S3A and SRL spectra differ from J2 with a second k^{-2} spectral slope down to 40 km wavelength. If we can infer a dynamical interpretation of the spectral slopes from SRL and S3A extending to these shorter wavelengths, the higher error level of J2 prevents such an analysis. In the following, we focus on SRL and S3A missions. Both missions provide similar results so we will present results for S3A only, since it covers a longer time period with a shorter repetitive cycle. The physical interpretation of altimetry spectra is supported by SSH wavenumber spectra based on model SSH extracted along S3A altimetric tracks.

4.1 Turbulent dynamics



To investigate turbulent dynamics, mean and seasonal spectra are averaged over the full domain in order to minimize the signature of internal tides in the altimetric spectra (Fig. 4a). For the model the internal tide signature has been filtered out and the modelled SSH spectra are only representative of subinertial dynamics (Fig. 4b).

With a mean altimetric SSHA spectral slope around $k^{-11/3}$ (Fig. 4a, Table 3), the mesoscale dynamics in SNC is consistent with the analysis of structure functions applied to high resolution in-situ data by Sérazin et al. (2020, their Fig. 6). They show that the surface layers of the SNC are dominated by SQG dynamics, consistently with a spectral wavenumber analysis from S3A along-track altimetry (Vergara et al., 2023). The mean model SSH spectrum (Fig. 4b) has a steeper slope more in accordance with QG dynamics (k^{-4}). The seasonal contrast of the subinertial dynamics is well visible in the SSH modelled spectra where the austral winter spectrum exhibits more energy at smaller scales with a break in slope at 150 km wavelength than in austral summer which has a more continuous slope (Fig. 4b). The flatter mesoscale slopes in winter than in summer result from the fact that the cool season is more favorable to baroclinic instabilities leading to more energy for the shortest meso/submesoscale wavelengths (Bendering et al., 2025). Even if altimetry mixes both subinertial and superinertial motions, the altimetric spectra also exhibit such seasonal variations with steeper mesoscale slopes (-4.1) in summer than in winter (-3.3) down to 60 km wavelength (Fig. 4a). As suggested by model analysis, these differences in altimetric spectra can be attributed to changes in the turbulent regime. At shorter wavelengths, the spectra flatten due to the contamination by internal gravity waves.

4.2. Internal tides

To identify the spectral signatures of internal tides, we focus on model and altimetry spectra over the few tracks crossing the area of strong internal tide amplitudes south of New Caledonia (the thick tracks on Fig.1b) that we compare to spectra over the full regional domain where internal tides are less dominant (Fig. 4cd). The austral summer season is chosen to illustrate more efficiently internal tides because of the predominance of superinertial motions over subinertial motions at this period of the year. Indeed, in austral summer, the enhanced surface stratification amplifies SSH internal tides signature (Lahayé et al., 2020), and submesoscale features are weaker (Bendering et al., 2025); the altimetric noise floor is also weaker (Vergara et al., 2019). Note that altimetric tracks are not aligned along the tidal beam therefore they cannot capture the strongest internal tidal signal well and we don't expect a clear tidal signature as already discussed in Bendering et al. (2025). Spectra calculated from model data along the S3A groundtracks clearly show more SSH variance up to 150 km wavelength for the local region compared to the full region that should be attributed to internal tide signatures (Fig. 4d). Altimetric spectra show behavior similar to the model spectra but the highest SSH variance in the local region extends to 110 km in wavelength (Fig. 4c). Two peaks are visible at 70 and 40 km wavelengths. Their significance could be questionable but it is notable that both altimetric and model spectra exhibit peaks at similar wavelengths. Such peaks don't exist when looking at spectra from a similar simulation without tidal forcing (not shown). This reinforces our dynamical interpretation that these peaks can be attributed to internal tides, even though the tracks cut diagonally across the internal tide beam.

To summarize, altimetric spectra behave similarly as model spectra. Model analysis is helpful to interpret the signatures of the meso-submesoscale dynamics and of internal tides in SSH wavenumber spectra.



S3A SSHA_HR_FLT data appear to be particularly efficient to highlight seasonal modulations in the submesoscale field and strong internal tide signature in the local region just South of New Caledonia, especially in summer.

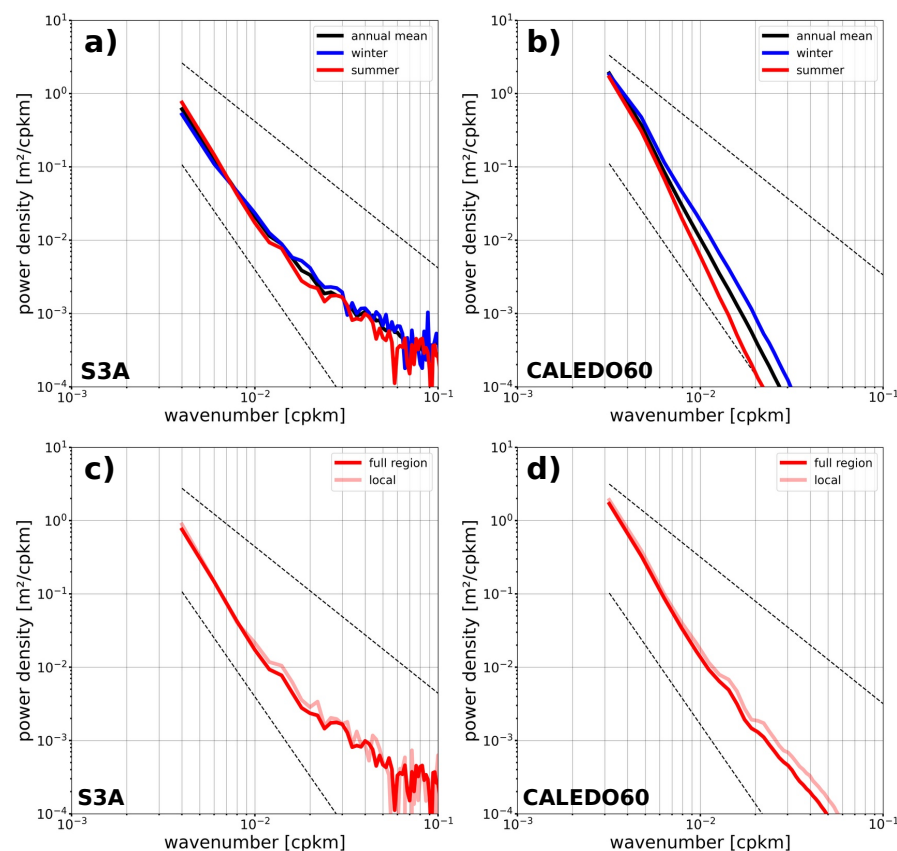


Figure 4 : SSH wavenumber spectra illustrating the seasonal modulation of the mesoscale/submesoscale fields for a) The S3A SSHA_HR_FLT dataset and b) the model simulations with the use of SSH filtered to keep only subinertial frequencies by removing superinertial frequencies and interpolated along S3A tracks. Spectra are averaged over the full domain (see Fig. 1). Austral winter spectra are in blue, austral summer spectra are in red and the mean averaged spectra are in black. SSH wavenumber spectra illustrating internal tide signature during the summer season (see Fig. 1) for c) the S3A SSHA_HR_FLT dataset and d) the model simulation. The spectra for the full region are in dark red. The spectra for the local region just South of New Caledonia are in light red. The characteristic wavenumber slopes k^{-2} and $k^{-3.6}$ are represented by the dotted black lines.

5. SWOT spectra

The KaRIn basic ocean product is on a fixed 2km by 2km grid, distributed over two 50 km wide swaths separated by a 20 km gap and is used here despite it exists a 250 m Unsmooth SWOT product that could be more in accordance with the HR nadir altimetric products, but the 2km SWOT product is the “optimal” product in terms of signal/noise to analyse meso and



submesoscale dynamics in the open ocean. KaRIn SWOT observations used in the current work correspond to SWOT Level-3.0 v2.0.1 (L3_LR_SSH). A full description of the product can be found in the AVISO website :

430 https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/handbook_duacs_SWOT_L3.pdf

Standard geophysical corrections are applied to KaRIn data. However, its unique configuration and new technology require new corrections (Dibarboure et al., 2022):

- a) **Data-driven calibration (calibrated SWOT product):** a particular error source for KaRIn estimates are the so-called systematic errors that arise from imperfect knowledge of several platform-specific parameters (attitude, interferometric phase delay knowledge, thermal dilation of the mast carrying the KaRIn instrument; Rodriguez et al., 2017). These errors are correlated in space and in time, and the amplitude before calibration might reach several tens of cm, dominating the mission error budget. However, their geometric nature makes them relatively easy to correct, reducing their impact below the cm mark.
- b) **Random noise reduction (filtered):** new instrumental errors are also present in the KaRIn observations that are random in nature and cannot be analytically modelled from observations. The impact of this error term on the observation budget is at cm level, which is relatively low. However, the major impact of this error term arises when computing higher order diagnostics from the sea level measurements (e.g. geostrophic velocity, vorticity). Given that the main goal of SWOT is to observe the ocean variability at meso to submesoscale, a simple single filter-based solution could not be adopted and a novel methodology that preserves most of the features that have a geophysical origin at meso to submesoscale, while removing almost entirely the residuals due to random noise was developed, based on a neural network architecture (Treboutte et al., 2023).

The motivation here is to confront spectra from the along-track HR altimetric datasets discussed above to new SWOT data specifically dedicated for small scale dynamics. Both calibrated and filtered SWOT products are discussed in the following. As mentioned in the introduction, the region just South of New Caledonia was flown over by a single SWOT swath (T4, Fig. 1b) during the fast sampling phase characterized by a 1-day repeat cycle during the first 6 months of the mission; the last 4 months (March 28-July 10 2023) devoted for scientific purposes are used here.

For a given cycle, a SWOT spectrum is an average over around fifty along-track spectra inside the swath. Therefore, the mean SWOT spectra discussed here and shown on Fig. 5 are an average of around 6000 spectra. Significant differences between the calibrated SWOT data and the filtered SWOT data for wavelengths smaller than 200 km lead us to use only the filtered SWOT data. The SWOT filtered spectrum compares very well with the S3A spectrum down to 40 km wavelength (Fig. 5). It confirms a $k^{-3.6}$ mesoscale slope for wavelength down to 140 km wavelength where the spectra flatten to a k^{-2} slope characteristic of superinertial motions (internal wave continuum) down to 40 km wavelength. For smaller wavelengths, the SWOT PSD decreases monotonically whereas the S3A spectrum flattens because S3A data become too noisy; in contrast, the denoised S3A spectrum compares well with the SWOT one confirming the effectiveness of the denoising performed on the S3A data until 20 km wavelength.



These preliminary results on SWOT SSH spectra confirm the high potential of SWOT data to observe small scales. These results also highlight the potential of conventional altimetry, especially S3A, to extend SSH observability to small scales when using HR datasets.

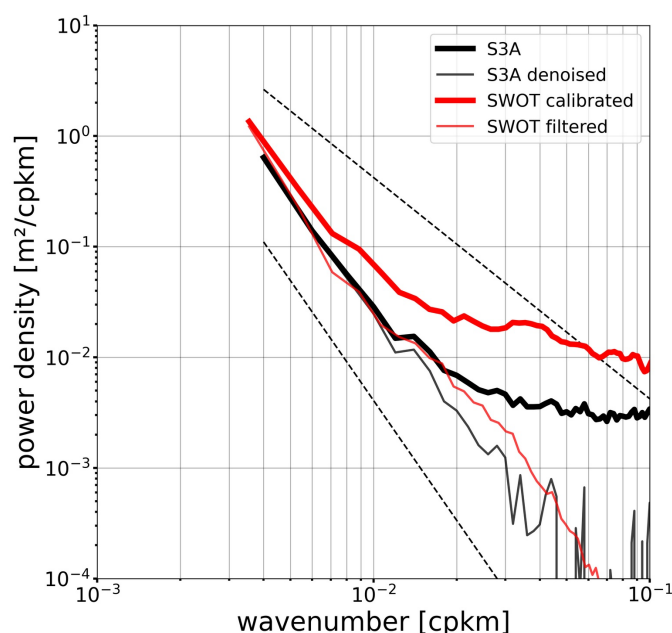


Figure 5: SSH spectra over the SNC region. In red line for the T4 SWOT swath crossing the SNC region during the fast-sampling phase. Spectrum for the calibrated SWOT data is in thick line whereas spectrum for the filtered SWOT data is in thin line. In thick black line for the few S3A tracks close to the Swot swath (Thick tracks in Fig.2). The thin black line is for the denoised S3A spectrum. The characteristic wavenumber slopes k^{-2} and $k^{-3.6}$ are represented by the dotted black lines.

6. Discussion and conclusion

Altimeter satellite along-track products are commonly used for scientific oceanographic purposes and in operational oceanography with a 1 Hz sampling (SSHA_LR). Their effective resolution is limited to spatial scales with wavelengths > 100 km, which only allows accessing to large-scale mesoscale dynamics. Based on a classical SSH wavenumber spectral methodology, this study highlights the potential of HR (20/40 hz) SSHA products in accessing wavelengths smaller than 100 km, providing insights into small mesoscale and submesoscale dynamics.

Three different altimeter missions (J2, SRL, S3A) are considered on a specific region south of New Caledonia featuring dynamically complex circulation with high mesoscale activity and internal tides. The use of HR data requires a dedicated/tailored processing that involves a threshold editing procedure based on standard validation flag parameters and a nonlinear iterative editing filter. Once applied, the HR products provide more accurate data even at scales as large as ~100 km compared to LR data. But for J2 the error level is still too high and prevents mesoscale observation at fine scales. When using SRL or S3A, the signal to noise ratio is improved with HR data down to wavelengths of 40-60 km and mesoscale resolution



capability is improved by a factor of 2 compared to J2 and LR dataset (40 km against 80 km). Finally, SSHA_HR data from SRL and S3A may be used with success to infer submesoscale and internal tide signatures for wavelengths down to 40 km.

485 A description of the fine scale dynamics at work south of New Caledonia is attempted from regional-averaged SSHA wavenumber spectra. A mesoscale slope around -3.7 extends down to 60 km wavelength. It highlights the dominant SQG dynamics in the surface layers, particularly present in austral winter while QG dynamics (k^{-4} mesoscale slope) prevail in austral summer, consistent with model results (Bendinger et al., 2023). A second k^{-2} spectral slope emerges at smaller scales down to 30 km wavelength in accordance with SSH slope of the Garret and Munk spectrum for internal gravity waves. Internal tides are particularly energetic just south of New Caledonia sampled by a limited number of altimetric tracks. Because of the
490 orientation of the altimetric tracks with regard to the direction of internal tide energy beam propagation, the spectral internal tide signatures are not characterised by specific peaks as one might expect but extend over a broad range of wavelengths up to 150 km. Internal tide signatures are particularly visible in austral summer when submesoscale activity is less energetic. This illustrates the potential of along-track HR data from SRL and S3A satellite missions to document a specific region. This regional analysis brings new information compared to global diagnosis that already exist where along-track LR data are
495 sampled inside larger regional boxes.

The region south of New Caledonia has been chosen in the SWOT-AdAC Consortium (d'Ovidio et al., 2019) as a cal/val site for SWOT during the Fast Sampling Phase. Despite the high quality of SWOT exceeding prelaunch expectations (Fu et al., 2024; Archer et al., 2025; Wang et al., 2025a), further validation from independent measurements is needed. The increasing
500 observability of the finest wavelengths in HR along-track products could extend the use of along-track SSHA data for SWOT validation purposes. The comparison of along-track SWOT SSH spectrum with S3A SSHA_HR spectra (similar results are obtained with SRL spectra) illustrates a good consistency between both altimetric measurements for small scale down to 20 km wavelength. These first comparisons give us an initial insight into the consistency or inconsistency between the spectral content of the nadir datasets over a reference period and that of the SWOT data over a significantly shorter period. It points
505 out the interest of such HR along-track data to document fine scale dynamics over a long time period. Also, the assimilation of SWOT data in operational forecasting system is on the way (Fouchet et al., 2025). A part of the submesoscale signals in SWOT data not captured by LR along-track data could be now accessible from HR along-track data. This raises the opportunity of their assimilation in such operational system in conjunction with SWOT data or once the SWOT mission will be completed.

510 Code and data availability

The SWOT data, as well as the Jason, SARAL/AltiKa and Sentinel-3a L2P altimeter products, were provided by CNES (<https://www.aviso.altimetry.fr/en/data.html>). The MSS15 can be downloaded from the AVISO website



(<https://www.aviso.altimetry.fr>). Model data is available through Bendinger et al. (2023). the wavenumber spectra are computed with a python function named *scipy.signal.welch* (Welch 1967).

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Author contributions

LG and NA designed the experiments and carried them out. MLD developed the model code on spectral analysis. AB provided the model simulations. FL and OV provided the altimetric datasets. RM and SC prepared the manuscript with contributions from all co-authors.

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Competing interests

The authors declare there are no conflicts of interest for this manuscript.

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