



Analysis of the sea state dependency of VV and HH surface returns

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Technical Report

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Abstract

C-band scatterometers, such as ASCAT, measure ocean surface winds which prove to very closely align with the local wind vector. Such scatterometers are based on vertical (VV) polarization, whose modulation is well described by the so-called Bragg scattering of e.m. waves. On the other hand, Ku-band scatterometers, although less accurate, provide both vertical and horizontal (HH) polarized measurements. The HH Normalized Radar Cross Section (NRCS) is composed of a Bragg part which depends on the local wind and of a non-Bragg part associated with breaking waves. The dual-polarized NRCS of Ku-band scatterometers can therefore be exploited to detect wave breaking events by analyzing the different HH and VV NRCS response to various sea state and wind conditions.

In this study, we compare the normalized inversion residuals (MLE_{NORM}) from the Haiyang-2C scatterometer (HSCAT-C) against several sea state parameters and surface wind for three different sea state conditions. The MLE_{NORM} is in fact a good noise estimator and it can be exploited to detect a signal not modeled by the Geophysical Model Function (GMF), such as the backscatter signal from breaking waves. The MLE_{NORM} is decomposed into its HH and VV terms, using the measured and simulated NRCS, and the ratio between the two terms is computed in order to highlight any possible increase due to breaking waves.

In the surface wind plots, the $MLE_{\text{NORM,HH}}/MLE_{\text{NORM,VV}}$ ratio (HH/VV ratio) shows higher values for the growing sea condition, followed by the fully developed sea and by the decaying sea, suggesting a more frequent occurrence of breaking waves for wind-dominated conditions compared to swell-dominated conditions. For all sea states, the maximum increase of the HH/VV ratio is observed around 10 m/s.

For the sea state parameters related to wave height and wave period, instead, the variation of the HH/VV ratios as a function of sea state is more complex, perhaps due to the simultaneous combination of several parameters (wind, wave height and wave period). Finally, the HH/VV ratio seems to be rather insensitive to the directional characteristics of the wave spectrum and to the angle between the wind and the waves.

1 Introduction

High-accuracy ocean winds are essential to understand the processes that occur in the ocean and at the sea surface. Because much of the ocean's variability, especially in the top layers, is wind driven, it is crucial to obtain an accurate wind forcing product, which is able to resolve the relevant geophysical dependencies. Scatterometers provide high resolution 10-m-height stress-equivalent wind measurements [1] [2]. C-band scatterometers, such as the Advanced Scatterometer (ASCAT) onboard the Metop series, provide measurements of the Normalized Radar Cross Section (NRCS), commonly referred to as σ_0 , for a vertically polarized signal scattered from the ocean surface (VV). Ku-band scatterometers, instead, can measure both the vertically (VV) and horizontally (HH) co-polarized NRCS. The second generation EUMETSAT C-band scatterometer, EPS-SG SCA, however, will not only measure VV NRCS, but also HH and cross-polarized NRCS (VH and HV) [3]. It is therefore of interest to also investigate the other ocean surface e.m. wave scattering mechanisms associated with horizontally-polarized microwaves.

The VV modulation is well described by the so-called Bragg scattering of e.m. waves on wind-generated gravity-capillary ocean waves. ASCAT winds, which prove indeed to very closely align with the local wind vector [4] [5], are based on VV polarization. On the other hand, the HH NRCS is generally assumed to be the sum of a Bragg part and a non-Bragg part [6]. The response of the sea surface is then based on the short wave spectrum (wavelength from few millimeters to few meters), e.g., [7] [8], and on wave breaking statistics, e.g., [9]. As the non-Bragg scattering is associated with breaking waves and hence the ocean mean slope distribution, longer waves than only the short wave spectrum come into play as they modulate the ocean slopes. This implies that the HH NRCS potentially depends both on the local wind and on the non-locally generated waves that propagate through the scatterometer Wind Vector Cell (WVC).

Recent Synthetic Aperture Radar (SAR) work confirms the different ocean surface scattering mechanisms for VV and HH NRCS co-polarized measurements ([10]). While SAR VV, VH and HH NRCS and Doppler observations are qualitatively in line with the above mechanisms, it is difficult to quantitatively assess the statistical effect. On the other hand, as scatterometers do provide a rather complete distribution of winds and sea states, a quantitative analysis is feasible. In this respect, Ku-band scatterometers are more suitable than C-band scatterometers because of their dual-polarized NRCS measurements, although Ku-band scatterometer vector winds are somewhat less accurate and of lower resolution than ASCAT winds [2], which is partly

related to measurement geometry, wind vector ambiguity, rain sensitivity and noise. Concerning the latter, HH NRCS sea state sensitivity could also play a role, but this has not been evaluated yet. Nevertheless, Ku-band scatterometers provide fore and aft views of both VV and HH NRCS in most WVCs. The wind retrieval then seeks the best fitting WVC wind speed and direction in a given spatial context, defined by 2DVAR ([11]). The WVC solution wind vector is associated with an inversion residual, called Maximum Likelihood Estimator (MLE), which is composed of contributions from all views. Hence the solution MLE compromises both VV and HH NRCS differences in fitting the respective measurements to the VV and HH NRCS Geophysical Model Functions (GMFs). This implies that an unaccounted HH NRCS dependency in the HH GMF, would be compensated in both VV and HH. Hence, both the VV and HH residual contributions to the MLE should be tested for a dependency on the non-locally generated sea state. Note that all locally generated sea state effects due to breaking will be associated with the local wind and hence already implied in the empirical VV and HH GMFs.

In this study, the VV and HH retrieval residuals are analyzed separately and associated with sea state parameters from the ECMWF wave model (WAM). The main aim of this study is to perform an in-depth analysis of the non-locally generated sea state effects on the HH NRCS with a view to improve the HH GMF for Level 2 (L2) wind retrieval. Such information will be particularly useful in preparation for EPS-SG SCA, but also for all the current and past Ku-band scatterometer L2 wind products that actually use HH for wind retrieval. It is expected that the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF) will shortly be processing six scatterometers employing HH at Ku- and/or C-band, either of Indian or Chinese origin.

In Section 2, we describe the datasets used in this study and how they have been collocated. In Section 3, we explain the methodology used to compute the inversion residuals for HH and VV and how we identify different sea state conditions. Section 4 contains the results of the association of the inversion residuals with the sea state parameters. The final remarks and outlook can be found in Section 5.

2 Datasets

2.1 HSCAT

For the Ku-band dual-polarized measurements, we have chosen the data from the rotating pencil-beam scatterometer HSCAT onboard the Chinese Haiyang-2C (HY-2C) satellite. The corresponding OSI SAF L2 dataset is provided by KNMI. The period analysed goes from 21 December 2021 to 21 March 2022, corresponding to a full season (boreal winter), in order to cover a wide range of sea states and wind conditions across the globe. The HSCAT dataset does not only provide the stress equivalent wind vector (U10S), but also many other variables which are used to compute the MLE residuals and to discriminate between the HH and VV signals. More specifically, the HSCAT files provide the following quantities:

- geolocation
- wind speed and wind direction of the selected solution
- measured normalized MLE
- background wind speed and wind direction
- azimuth angle
- incidence angle
- σ_0 (measured NRCS)
- atmospheric correction coefficients
- coefficients to compute Kp_{tot} , which is a noise estimator and a normalization factor for the MLE
- land contamination QC flag
- KNMI_QC and VAR_QC flags, which are two types of wind QC flags

HSCAT data are organized in a swath of 76 equidistant WVCs in the across-track direction (nodes) and about 1775 equidistant WVCs in the along track direction (rows) for each orbit, with grid size of 25 km. The HSCAT instrument has two rotating pencil-beams with different polarizations (HH and VV) and incidence angles. A WVC is generally viewed when looking forward (fore) and a second time when looking aft. As such, up to four views emerge for each WVC: HH fore, HH aft, VV fore and VV aft, as shown in Figure 1.

Because the VV rotating antenna has a higher incidence angle (around 48°) than the HH (around 42°), nodes 1-9 and 67-76 have only VV views, while nodes 10-66 have both HH and VV views. In the figure, different regions with Roman numerals, separated by dashed grey lines, are also indicated according to their wind retrieval skill. Regions I (node numbers 1-9 and 67-76), the so-called outer regions, have a lower retrieval skill because of the VV-only measurements (essentially only two azimuth views). Regions II (node numbers 10-29 and 48-66), the so-called sweet regions, have a higher retrieval skill because of the good azimuth separation between the beams and because they are sampled by both polarized measurements. Finally, region III (node numbers 30-47), the so-called nadir region, has again a lower retrieval skill due to the poor azimuth separation between the beams (i.e., being either too close or approximately 180° separated). We furthermore note that the substantially higher MLE-based QC (about 2%) for Ku-band scatterometers than for C-band scatterometers (about 0.5%) is due to moderate and heavy rain [12], due to the atmospheric droplet distribution.

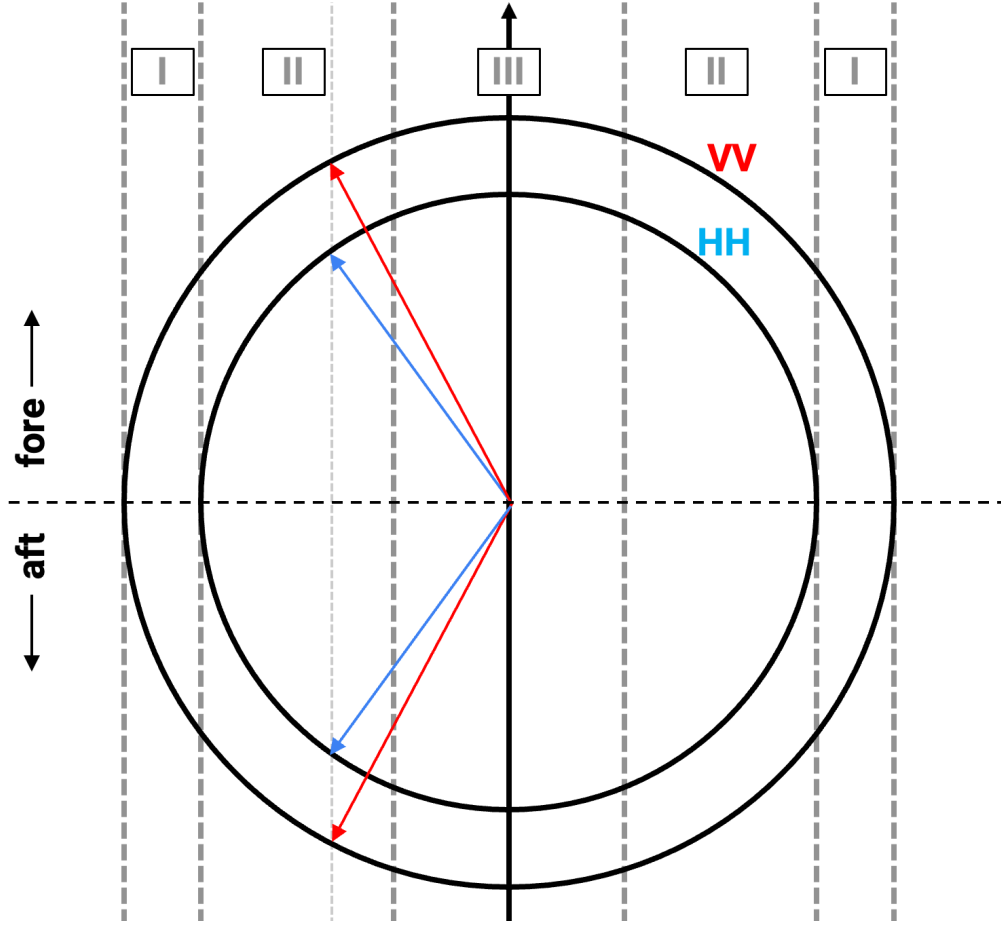


Figure 1: Simplified sketch of HSCAT geometry. The two antenna beams are indicated by the two circles: the inner (outer) circle corresponds to the antenna with HH (VV) polarization. For each WVC in the across track direction (vertical dashed lines) there are up to 4 views (2 fore and 2 aft). The Roman numerals indicate regions with different wind retrieval skills.

2.2 WAM Model

The sea state parameters from the ECMWF WAM model are downloaded from the ECMWF online MARS archive. They cover the same period of the HSCAT dataset and they are chosen to distinguish sea state conditions with and without the presence of swell. More specifically, the downloaded variables, together with their description (taken from the ECMWF online parameters database), are:

- **swh**: significant height of combined wind waves and swell
This parameter represents the average height of the highest third of

surface ocean/sea waves generated by wind and swell. It represents the vertical distance between the wave crest and the wave trough. More strictly, this parameter is four times the square root of the integral over all directions and all frequencies of the two-dimensional wave spectrum.

- **shts:** significant height of total swell
This parameter represents the average height of the highest third of surface ocean/sea waves associated with swell. It represents the vertical distance between the wave crest and the wave trough. More strictly, this parameter is four times the square root of the integral over all directions and all frequencies of the two-dimensional total swell spectrum. The total swell spectrum is obtained by only considering the components of the two-dimensional wave spectrum that are not under the influence of the local wind.
- **pp1d:** peak wave period
This parameter represents the period of the most energetic ocean waves generated by local winds and associated with swell. The wave period is the average time it takes for two consecutive wave crests, on the surface of the ocean/sea, to pass through a fixed point. This parameter is calculated from the reciprocal of the frequency corresponding to the largest value (peak) of the frequency wave spectrum. The frequency wave spectrum is obtained by integrating the two-dimensional wave spectrum over all directions.
- **mpts:** mean period of total swell
This parameter is the average time it takes for two consecutive wave crests, on the surface of the ocean/sea associated with swell, to pass through a fixed point. It is the mean over all frequencies and directions of the total swell spectrum.
- **dwps:** wave spectral directional width for swell
This parameter indicates whether waves associated with swell are coming from similar directions or from a wide range of directions. It is a measure of the range of wave directions for each frequency integrated across the two-dimensional spectrum. It takes values between 0 and the square root of 2. Where 0 corresponds to a uni-directional spectrum (i.e., all wave frequencies from the same direction) and the square root of 2 indicates a uniform spectrum (i.e., all wave frequencies from a different direction).
- **mwd:** mean wave direction
This parameter is the mean direction of ocean/sea surface waves. The

units are degrees true, which means the direction relative to the geographic location of the north pole. It is the direction that waves are coming from, so 0 degrees means "coming from the north" and 90 degrees means "coming from the east".

We convert **mw**d, that indicates the wave direction with respect to the north, to the more useful direction relative to the wind and rename it as **rw**d.

2.3 SST

An additional parameter needed to correct the simulated MLE is the SST (sea surface temperature), which is downloaded from the ERA5 reanalysis dataset available from the MARS archive.

2.4 Collocations

The three previously mentioned datasets (HSCAT, WAM and SST) are collocated using the Pencil-beam Wind Processor (PenWP), a software package specifically developed by KNMI to process Ku-band pencil beam scatterometer data ([13]). WAM parameters and SST are linearly interpolated to the HSCAT locations and times using the two closest forecasts for WAM (± 1 hour) and the two closest analyses for SST (analysis times at 00 and 12 UTC).

3 Methodology

3.1 Data filtering

The collocated dataset is pre-processed to filter out the invalid WVCs. In particular, we only keep the WVCs with a valid number of ambiguities, a valid selected solution, no land contamination, a positive SST (no ice) and valid sea state parameters values. Regarding the latter, note that, since the sea state parameter data (WAM output) are spatially and temporally interpolated to the HSCAT acquisitions, some WVCs close to the coast do not have enough sea state data surrounding them, which leads to the assignment of invalid values.

Two different sets are considered using the KNML.QC flag: the KNML.QC-passed category (no rain contamination) and the unfiltered category (rain contamination allowed).

3.2 MLE computation

The OSI SAF HSCAT-C L2 data files contain the selected winds, which can be used to simulate the VV and HH NRCS values for each view (fore/aft and VV/HH for Ku-band, i.e., up to 4 views for each WVC). The ocean-calibrated and SST-corrected measured NRCS values are then subtracted from the simulated NRCS values. The quadratically summed departures of all views in each WVC constitute the inversion MLE as follows:

$$\text{MLE} = \sum_{i=1}^4 \frac{(\sigma_{\text{GMF}i}^0 - \sigma_{\text{meas}i}^0)^2}{K_{p_i}} \quad (3.1)$$

where:

- i is the view number: $i = 1$: fore HH, $i = 2$: fore VV, $i = 3$: aft HH, $i = 4$: aft VV;
- σ_{GMF}^0 is the simulated NRCS;
- σ_{meas}^0 is the measured NRCS (calibrated);
- K_p is the noise estimator which is used as a normalization factor.

The values of σ_{GMF}^0 , σ_{meas}^0 and K_p are computed with the same methodology used in the PenWP code. σ_{GMF}^0 is computed with lookup tables (LUT) that take into account the polarization type (pol), the wind speed (U), the relative wind direction (ϕ_{rel}) and the incidence angle (θ). The σ_{GMF}^0 obtained from

the LUT is then multiplied by a correction factor (k_{SST}) that depends on the quantities above and on SST. The correction factor is estimated again with another LUT:

$$\sigma_{\text{GMF}_{\text{uncorr}}}^0 = \text{LUT}(\text{pol}, U, \phi_{\text{rel}}, \theta) \quad (3.2)$$

$$k_{\text{SST}} = \text{LUT}(\text{pol}, U, \phi_{\text{rel}}, \theta, \text{SST}) \quad (3.3)$$

$$\sigma_{\text{GMF}}^0 = \sigma_{\text{GMF}_{\text{uncorr}}}^0 * k_{\text{SST}} \quad (3.4)$$

σ_{meas}^0 is read from the HSCAT files, but it needs to be corrected for atmospheric effects and a calibration factor, and then linearized before being used in Equation 3.1, using the other parameters provided in the files:

$$\sigma_{\text{corr}}^0 = \sigma^0 + k_{\text{pol}} + k_{\text{att}} / \cos(\theta) \quad [dB] \quad (3.5)$$

$$\sigma_{\text{meas}}^0 = \text{sign}_{\sigma_0} * 10^{(\sigma_{\text{corr}}^0/10)} \quad [linear] \quad (3.6)$$

where σ^0 is the measured, uncorrected NRCS, k_{pol} is the ocean calibration correction factor which depends on the polarization, k_{att} is the atmospheric attenuation coefficient, and θ is the incidence angle. A sign correction is also used in Equation 3.6 using the values from sign_{σ_0} .

The term K_p is computed from a series of coefficients provided in the files (K_{p_a} , K_{p_b} , K_{p_c}) and quadratically depends on σ_{meas}^0 :

$$K_p = (K_{p_a} - 1) (\sigma_{\text{meas}}^0)^2 + K_{p_b} \sigma_{\text{meas}}^0 + 10^{(K_{p_c}/10)} \quad (3.7)$$

It is important to stress at this point that the terms on the right-hand side of Equation 3.1, namely σ_{GMF}^0 , σ_{meas}^0 and K_p , are computed for each WVC of the swath and for each view ($i = 1, 2, 3, 4$). Because we are interested in analyzing the HH and VV contributions separately, the MLE is then split in two terms, one for HH ($i = 1, 3$) and one for VV ($i = 2, 4$):

$$\text{MLE}_{\text{HH}} = \sum_{i=1,3} \frac{(\sigma_{\text{GMF}_i}^0 - \sigma_{\text{meas}_i}^0)^2}{K_{p_i}} \quad (3.8)$$

$$\text{MLE}_{\text{VV}} = \sum_{i=2,4} \frac{(\sigma_{\text{GMF}_i}^0 - \sigma_{\text{meas}_i}^0)^2}{K_{p_i}} \quad (3.9)$$

Such separation is only possible for those WVCs that contain both polarization measurements (i.e., the inner swath WVCs), that are usually found in nodes 10-66. Sometimes the nodes at the edges of this interval, i.e. nodes 10 and 66, contain VV views only, instead of HH and VV views. In order to exclude those cases, we filter according to the incidence angle θ : for the

Table 1: Identification of HH and VV σ^0 measurements based on the incidence angle of the first view (θ_1).

	view 1	view 2	view 3	view 4
$\theta_1 < 45^\circ$	HH	VV	HH	VV
$\theta_1 > 45^\circ$	VV	VV	VV	VV

first view ($i = 1$), in fact, θ_1 is always $< 45^\circ$ if the measurement is HH, while θ_1 is always $> 45^\circ$ if the measurement is VV. The other three views change accordingly, as shown in Table 1. As such, we only keep those WVCs for which θ_1 is $< 45^\circ$.

The mean total MLE computed for the full analysis period (boreal winter of 2022) and its decomposition into the HH and VV terms, as a function of node number, are shown in Figure 2.

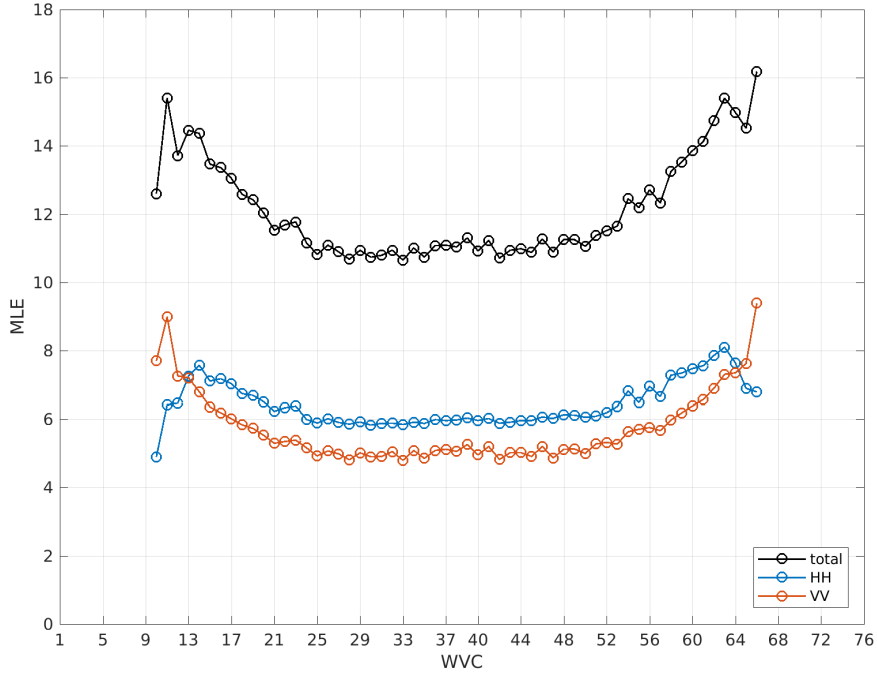


Figure 2: Mean total MLE (black curve) and its decomposition into the HH and VV terms (blue and red curves, respectively) as a function of node number for the boreal winter of 2022.

3.3 Normalized MLE

Due to non-linearities in the inversion and some misestimation of the measurement error (K_p), the MLE presents an across-swath dependency (Figure 2). This dependency is mitigated by empirically normalizing the MLE as a function of wind speed and node number. The resulting normalized residual, MLE_{NORM} , is a very useful parameter for wind retrieval and quality control purposes ([14]). The HSCAT files already contain the estimated normalized MLE, but to separate its HH and VV contributions, we need to estimate them using another quantity called the expected MLE, which is in fact the MLE that is expected for a particular node number and wind speed. The expected MLE cannot be directly estimated from the information contained in the L2 files since it depends on the closest-to-background wind speed solution. The latter is often replaced after the 2D-VAR ambiguity removal step by the selected ambiguity, which is not necessarily one of the original inversion solutions (or minima) due to the use of the multiple solution scheme in PenWP ([15]). As such, the expected MLE is deduced as follows:

$$\langle \text{MLE} \rangle = \frac{\text{MLE}}{\text{MLE}_{\text{NORM}}} \quad (3.10)$$

such that the HH and VV contributions to MLE_{NORM} can be estimated as follows:

$$\text{MLE}_{\text{NORM,HH}} = \frac{\text{MLE}_{\text{HH}}}{\langle \text{MLE} \rangle} \quad (3.11)$$

$$\text{MLE}_{\text{NORM,VV}} = \frac{\text{MLE}_{\text{VV}}}{\langle \text{MLE} \rangle} \quad (3.12)$$

Figure 3 shows the normalized MLE (total, HH and VV) as a function of node number for the same period of Figure 2.

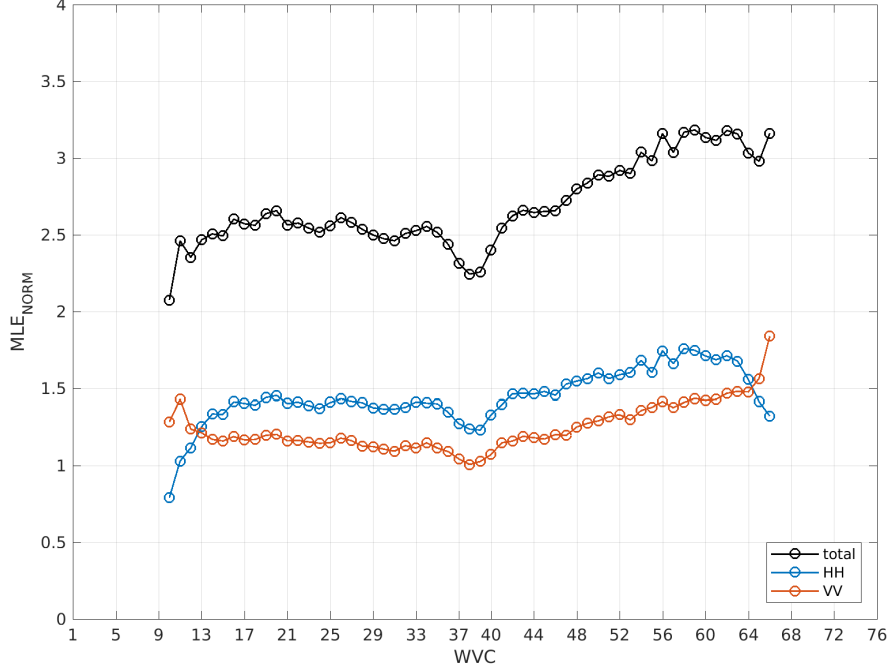


Figure 3: Mean total normalized MLE (black curve) and its decomposition into the HH and VV terms (blue and red curves, respectively) as a function of node number for the boreal winter of 2022.

The MLE_{NORM} is in fact a noise estimator for wind measurements, and we want to exploit this property to highlight a possible unmodeled effect, such as the non-local wave breaking contribution to the NRCS, which would translate into noise and therefore in a higher MLE value. Since such effect is assumed to be of second order, we focus the analysis on the regions of the swath in which the estimated MLE is a good noise estimator. These are the so-called sweet regions of the swath (i.e., node numbers 14-29 and 48-63), for which there is an optimal azimuth diversity, with azimuth separation between the fore and aft views between 60° and 150° .

3.4 Sea state conditions

In order to perform the analysis for different sea state conditions, we use the method from [16], which is based on the wind speed and the significant wave height information. First, the significant wave height for fully developed sea

is computed as follows:

$$H_S^{\text{FD}} = 0.22 \frac{U^2}{g} \quad (3.13)$$

where U is the HSCAT wind speed (U10S) and g is Earth's gravitational acceleration. Then, the three sea state conditions are identified as follows:

$$\text{growing sea :} \quad H_S - H_S^{\text{FD}} \leq -0.44 \frac{U}{g} \Delta U \quad (3.14)$$

$$\text{fully developed sea :} \quad |H_S - H_S^{\text{FD}}| < 0.44 \frac{U}{g} \Delta U \quad (3.15)$$

$$\text{decaying sea :} \quad H_S - H_S^{\text{FD}} \geq 0.44 \frac{U}{g} \Delta U \quad (3.16)$$

where H_S is the significant wave height from the WAM model and $\Delta U = 1.3$ m/s is the typical HSCAT wind difference with buoy measurements. We find that, according to this segregation algorithm, the decaying sea is the most common sea state with 74.8% of the occurrences, followed by the fully developed sea (21.1%) and the growing sea (4.1%).

4 Results

Each sea state parameter downloaded from the WAM model (Section 2.2) is associated with the normalized MLE and its two terms (HH and VV) for each sea state condition (Section 3.4). The U10S speed from HSCAT is also associated with the normalized MLE to assess the dependency of the inversion residuals on wind speed. The normalized MLE is averaged over all the WVCs of the sweet region (node numbers 14-29 and 48-63) and an additional averaging is performed bin by bin over the range of each parameter, using a total of 60 bins.

4.1 U10S

The top panel of Figure 4 shows the averaged MLE_{NORM} vs U10S for the unfiltered winds (no QC flags applied), regardless of the sea state condition: the total MLE_{NORM} is in black, while the HH and VV terms are in blue and red, respectively. The plot also shows the distribution of the U10S values in green. In general, $\text{MLE}_{\text{NORM,HH}}$ is always higher than $\text{MLE}_{\text{NORM,VV}}$, as already seen in Figure 3, while the two curves (blue and red) seem to follow each other as they vary along the wind speed range. **This implies that the weights of VV and HH are different in the MLE due to different noise and to a different GMF sensitivity to the wind vector for VV and HH. The sensitivity depends on U10S, hence changes in the MLE may be explained by this or by U10S-dependent GMF errors. I.e., not necessarily by wave breaking characteristics.**

In order to better highlight a possible unusual change in the HH term relative to the VV term, we computed the ratio $\text{MLE}_{\text{NORM,HH}}/\text{MLE}_{\text{NORM,VV}}$, which is expected to increase if the HH component includes a signal which is unaccounted for in the GMF, for example a wave breaking based backscatter signal. The ratio is shown in the bottom panel of Figure 4 (black line) and is rather constant in the interval from 1.5 to 18 m/s, where most of the U10S occurrences are found. The ratio increases between 18 and 25 m/s, perhaps suggesting a correlation between higher wind speeds and non-local wave-breaking scattering. Alternatively, these VV and HH MLE disparities may be caused by the distinct rain attractors in VV and HH NRCS data [17] in the QC-rejected (rainy) data. At the tails of the distribution, i.e., below 1.5 m/s and above 25 m/s, the ratio becomes noisy due to the lower number of samples.

By introducing the sea state categories, we want to identify the conditions for which the $\text{MLE}_{\text{NORM,HH}}/\text{MLE}_{\text{NORM,VV}}$ ratio is particularly high due to non-local sea state. Figure 5 shows the MLE_{NORM} for growing sea (top left),

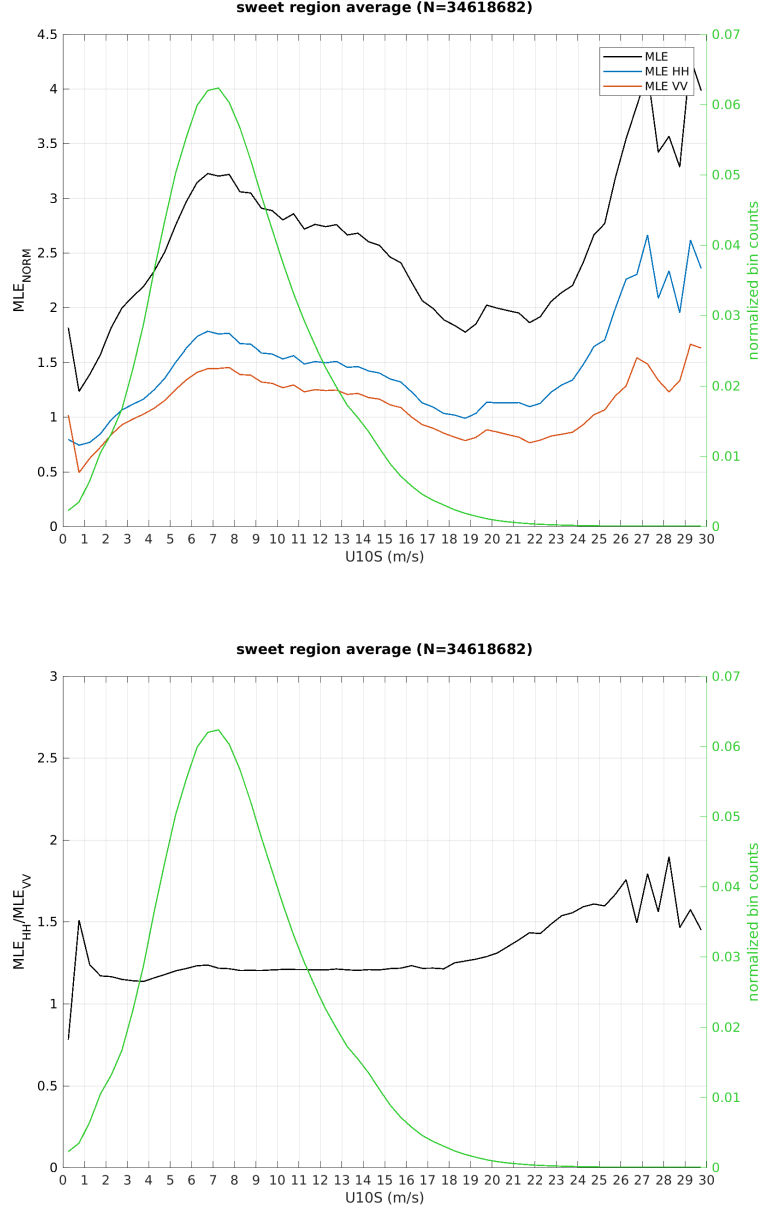


Figure 4: **Top:** MLE_{NORM} (total in black, HH in blue and VV in red) vs $U10S$ averaged over the sweet region for the unfiltered winds. **Bottom:** $MLE_{NORM,HH}/MLE_{NORM,VV}$ ratio vs $U10S$ (i.e., the ratio of the blue and red curves from the top plot). The green line in both plots shows the number of points in each horizontal bin of width 0.5 m/s relative to the total number of points.

fully developed sea (top right) and decaying sea (bottom left) categories for the unfiltered winds. The distribution of the U10S values is different for the three sea state categories. The growing sea has on average higher wind speeds with the peak of the distribution around 14 m/s. The fully developed sea has intermediate wind speeds with the peak of the distribution around 10 m/s, while the decaying sea has lower wind speeds with the peak of the distribution around 7 m/s. In the bottom right panel of Figure 5 the $\text{MLE}_{\text{NORM,HH}}/\text{MLE}_{\text{NORM,VV}}$ ratio is shown for each sea state category: on average, in the range up to 16 m/s, the ratio is higher for the growing sea (blue line), followed by the fully developed sea (red line) and by the decaying sea (yellow line), perhaps suggesting an enhanced non-local wave-breaking scattering for wind-dominated sea conditions and a reduced non-local wave-breaking scattering for swell-dominated sea conditions, which is counterintuitive, as one would expect swell to contribute to non-local effects. For all three categories, there is a peak in the ratio around 6-7 m/s, which suggests an enhanced GMF inconsistency between VV and HH. Above 16 m/s an increase of the ratio as a function of wind speed is again noticeable for all sea state conditions.

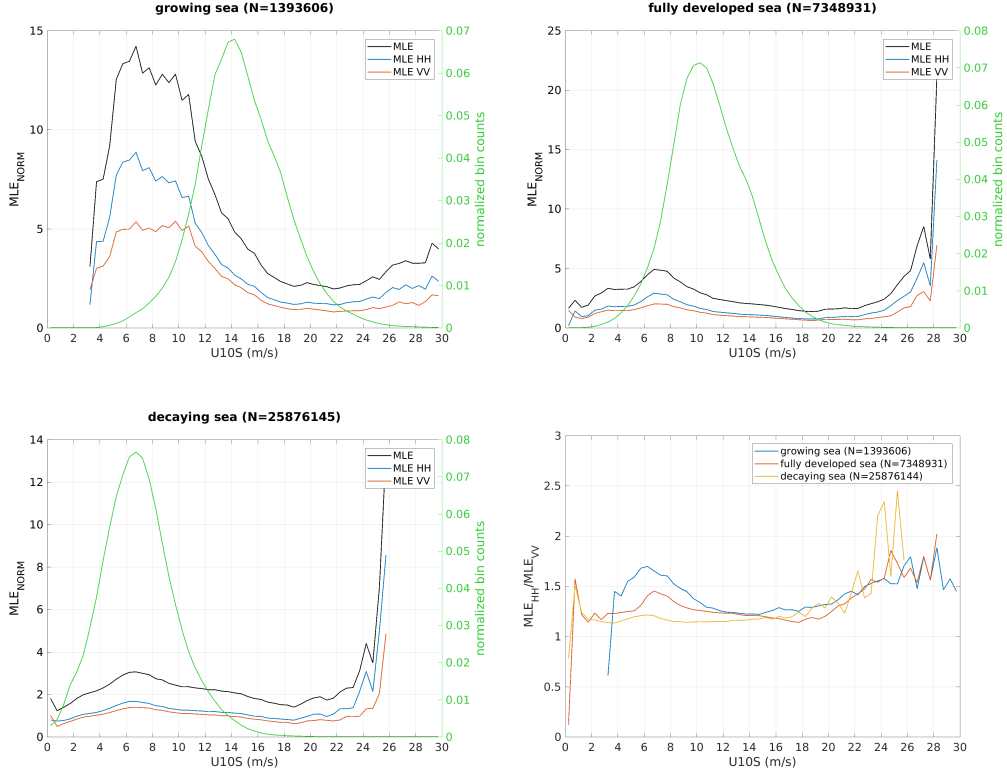


Figure 5: MLE_{NORM} vs U10S for different sea state categories for the unfiltered winds: growing sea (top left), fully developed sea (top right) and decaying sea (bottom left). The $MLE_{NORM,HH}/MLE_{NORM,VV}$ ratios are shown in the bottom right panel for the growing sea (blue), fully developed sea (red) and decaying sea (yellow). The green line in the first three plots shows the distribution of the U10S values.

The same plots from Figure 5, which are derived with unfiltered winds, have been generated but for the KNMI.QC-passed winds only in Figure 6. The KNMI.QC flag is related mainly to moderate and heavy rain, occurring most often in the tropics (associated with decaying seas). The QC has a clear effect on the MLE_{NORM} , reducing its values for all categories and reducing the gap between $MLE_{NORM,HH}$ and $MLE_{NORM,VV}$. While it is still possible to observe a separation between the ratios (bottom right plot of Figure 6) in the interval from 4 to 14 m/s, such separation is minimized compared to that of the unfiltered winds case. Moreover, in the rest of the wind speed range, the ratios are close to one as they overlap with each other, suggesting the absence of a distinct wave-breaking signal in the HH component of the MLE_{NORM} . As rain has a distinctly different effect on VV and HH [17] and KNMI.QC has been effectuated to reject about 4.5% of rainy WVCs, it is not surprising that

VV and HH differences show up in rainy cases, and in fact, disappear in case the QC is used. Furthermore, the KNMI_QC is most active in the tropical region, associated with low and median winds. In cases of moist convection leading to moderate and high rain rates, fast-evolving wind updrafts and downdrafts will be associated with it [18], which are generally not resolved in the ECMWF winds forcing WAM and hence not represented in the wave parameters we use here.

In any case, for all three categories, there is a peak in the ratios around 10–11 m/s, more prominent for the growing sea state. There is no increase of the ratio as a function of wind speed after 16 m/s, in contrast to what observed for the unfiltered winds in Figure 5, because the KNMI_QC filter effectively removes the rainy WVCs associated with high winds, which contaminate the MLE_{NORM} .

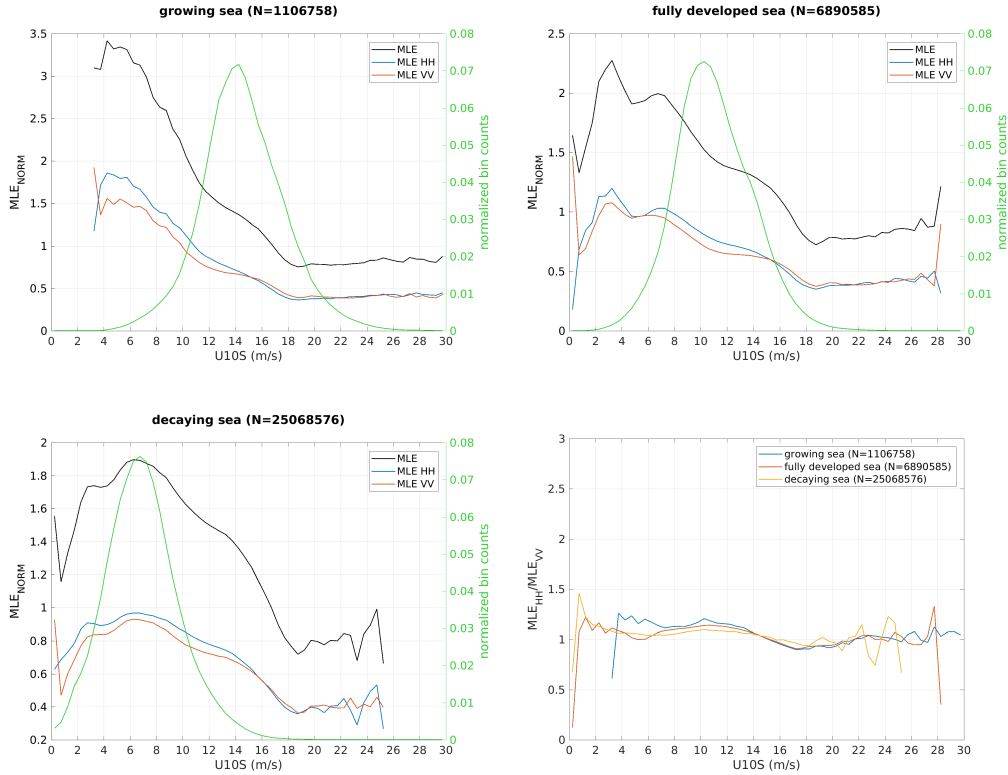


Figure 6: Same as Figure 5 but for KNMI_QC-passed winds only.

Hereafter, we focus the analysis on the KNMI_QC-passed winds only to avoid the known effect of rain on the MLE_{NORM} components (HH and VV), which could be much larger than any sea state effect, misleading the interpretation of the results. For completeness, we report the corresponding

plots for the unfiltered winds category in the appendix.

4.2 swh

Figure 7 shows the same as Figure 6, but for significant wave height (swh). The peak of the distributions is between 2 and 3 m for all sea states. For the decaying sea, the distribution is narrower with less values near zero, as expected from swell-dominated conditions.

The $\text{MLE}_{\text{NORM,HH}}/\text{MLE}_{\text{NORM,VV}}$ ratios (bottom right plot) are different for each sea state category. The growing sea (blue curve) has higher ratios for smaller values of swh and they decrease after about 1.5 m. The fully developed sea (red) and the decaying sea (yellow) follow a similar behaviour, but their curves are shifted towards the right (larger swh values), with their peaks at about 2.5 m and 4.5 m, respectively. Some portions of the curves show ratios below 1, which occur after 3.5 m for the growing sea and after 5.5 m for the fully developed sea. A ratio below 1 indicates a $\text{MLE}_{\text{NORM,VV}}$ greater than the $\text{MLE}_{\text{NORM,HH}}$, however, since their values are almost identical (their difference is very small), their ratio can be practically considered equal to 1.

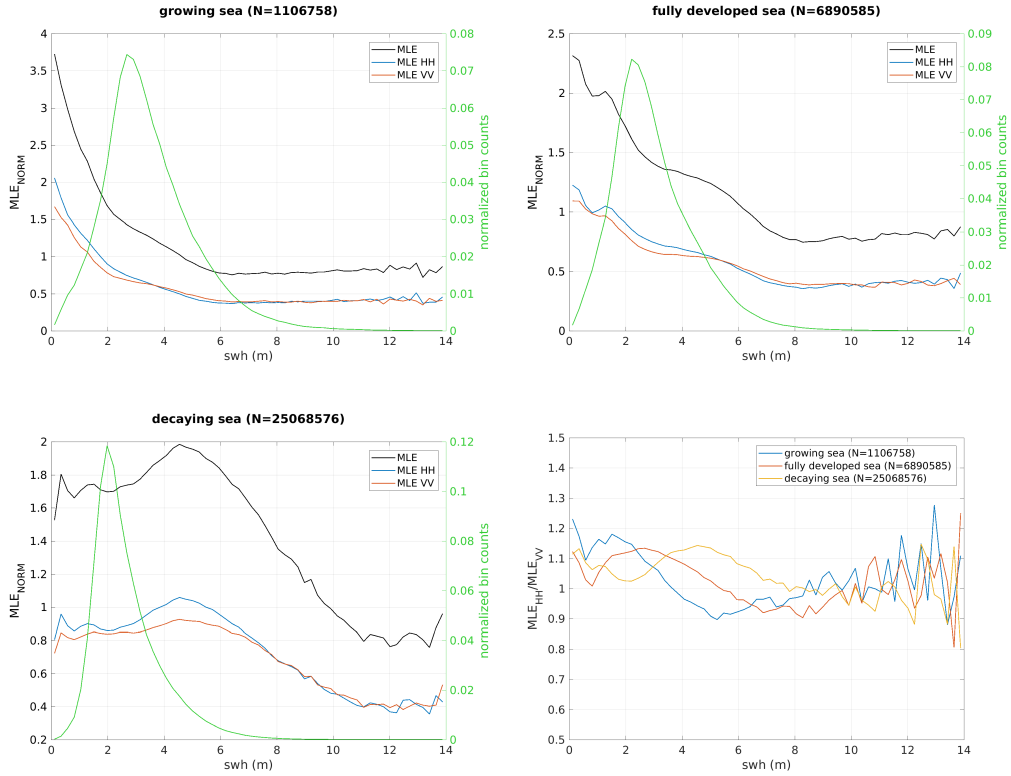


Figure 7: Same as Figure 6 but for swh.

4.3 shts

Figure 8 shows the same as Figure 6, but for significant height of total swell (shts). This parameter is similar to swh but it excludes the waves generated by the local wind and the distributions for the growing sea and the fully developed sea are narrower and more shifted to the left.

The $MLE_{NORM,HH}/MLE_{NORM,VV}$ ratios (bottom right plot) have a similar behaviour to the ones for swh (Figure 7), but the curves for the growing sea (blue) and for the fully developed sea (red) have smaller values and their peaks are more shifted towards the left. The curve for the decaying sea (yellow) corresponds more to the one in Figure 7 (maximum value of 1.15 at 4.5 m) because for such sea state most of the waves are swell waves, hence swh is almost equal to shts.

The decaying seas with large swell heights ($shts > 3$ m) show large MLE (bottom left plot), which appears to show an effect (non-local) independent of U10S. $MLE_{NORM,HH}$ appears elevated here with respect to $MLE_{NORM,VV}$, as also indicated by their ratio (bottom right plot).

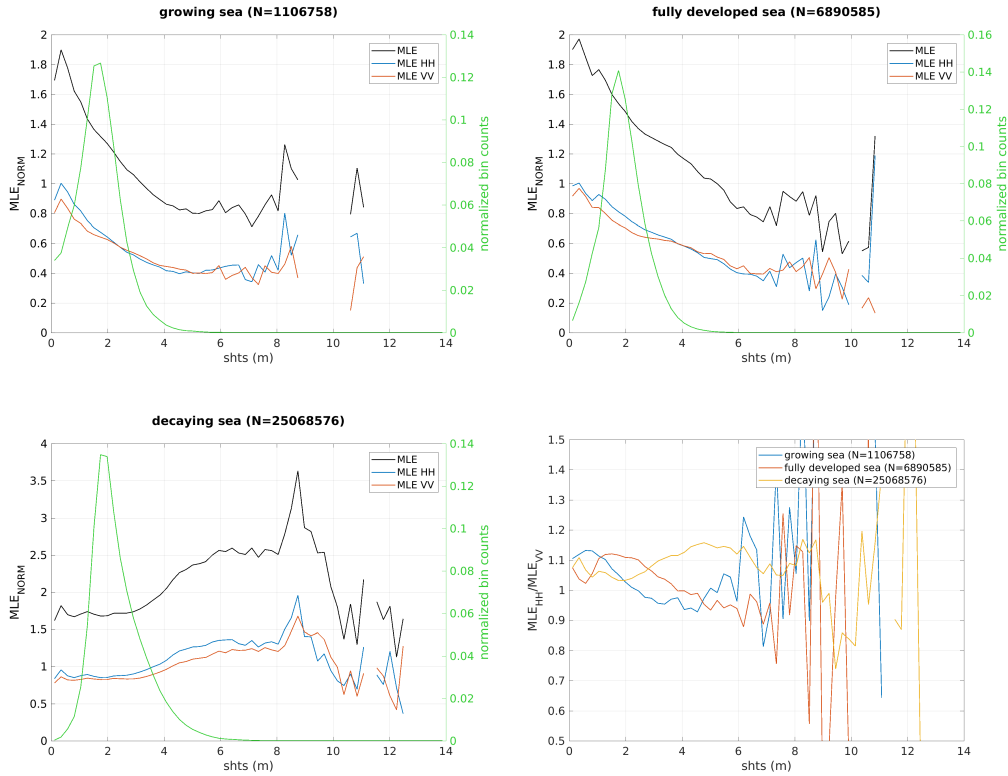


Figure 8: Same as Figure 6 but for shts.

4.4 pp1d

Figure 9 shows the same as Figure 6, but for the peak wave period (pp1d). The peaks of the distributions occur at relatively short periods (8 s) for the growing sea, at intermediate periods (9 s) for the fully developed sea, and at longer periods (12 s) for the decaying sea.

The $\text{MLE}_{\text{NORM,HH}}/\text{MLE}_{\text{NORM,VV}}$ ratios (bottom right plot) are different for each sea state category. The growing sea (blue curve) is in counterphase with respect to the other two sea states: when the blue curve reaches its maximum around 5.5 s, the other two curves reach their minimum, and when the blue curve decreases to reach its minimum around 10 s, the other two curves increase to reach their maximum. Therefore, it seems that for the growing sea the breaking-waves contribution occurs at shorter periods while for the older sea states it occurs at longer periods.

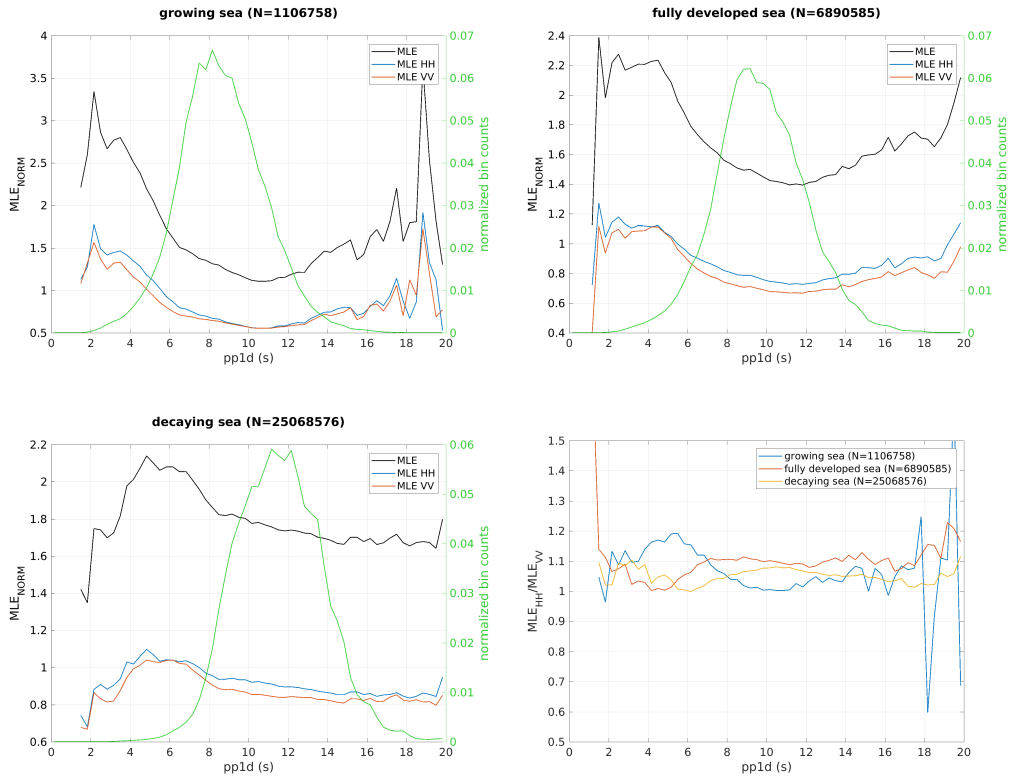


Figure 9: Same as Figure 6 but for pp1d.

4.5 mpts

Figure 10 shows the same as Figure 6, but for the mean period of total swell (mpts). This parameter is similar to pp1d but represents the average period over all the swell waves rather than being the period of the most energetic waves. The spread of the values of the peaks of the distributions is more limited compared to those of pp1d, with all the peaks occurring between 9 and 10 s.

The $MLE_{NORM,HH}/MLE_{NORM,VV}$ ratios for mpts (bottom right plot) are very similar to those of pp1d (Figure 9) and analogous conclusions to those made in Section 4.4 can be drawn.

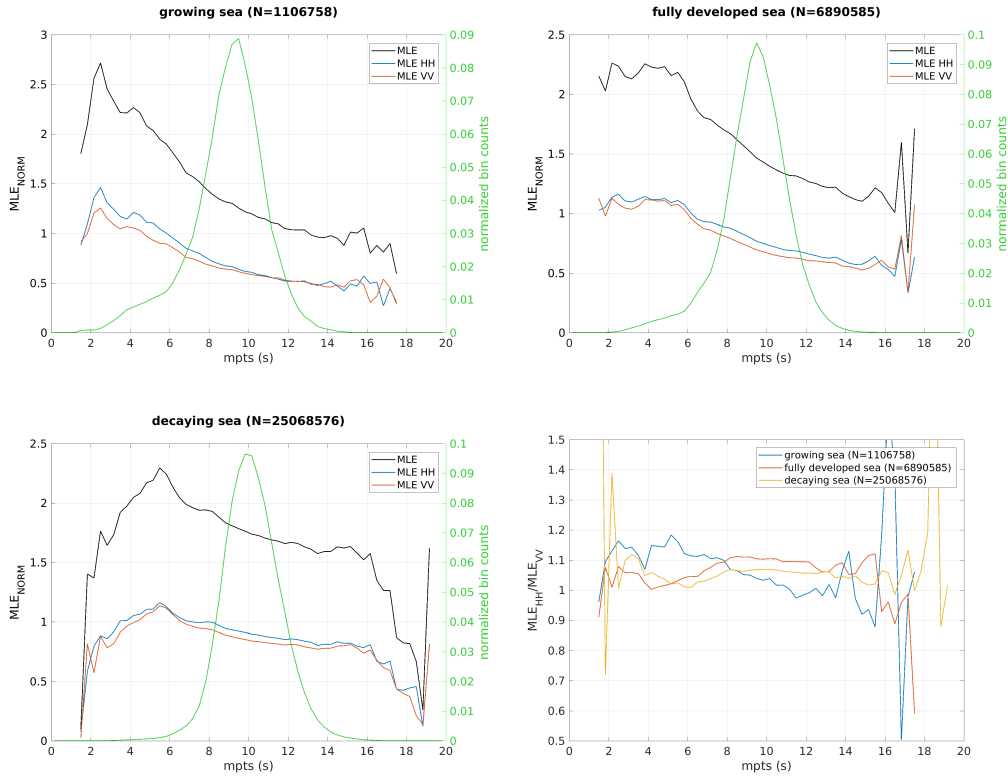


Figure 10: Same as Figure 6 but for mpts.

4.6 dwps

Figure 11 shows the same as Figure 6, but for the wave spectral directional width for swell (dwps). This parameter indicates whether the waves associated with swell come from the same direction or from a wide range of directions. It is possible to see from the distributions that there are almost no cases where all the waves come from the same direction ($\text{dwps}=0$) or from all directions equally ($\text{dwps}=\sqrt{2} \approx 1.4$).

For all three sea states, the $\text{MLE}_{\text{NORM,HH}}/\text{MLE}_{\text{NORM,VV}}$ ratios are rather constant over the dwps range. The fully developed sea has a higher ratio compared to the other two sea states, except for dwps values less than 0.2, where the ratio is larger for the growing sea.

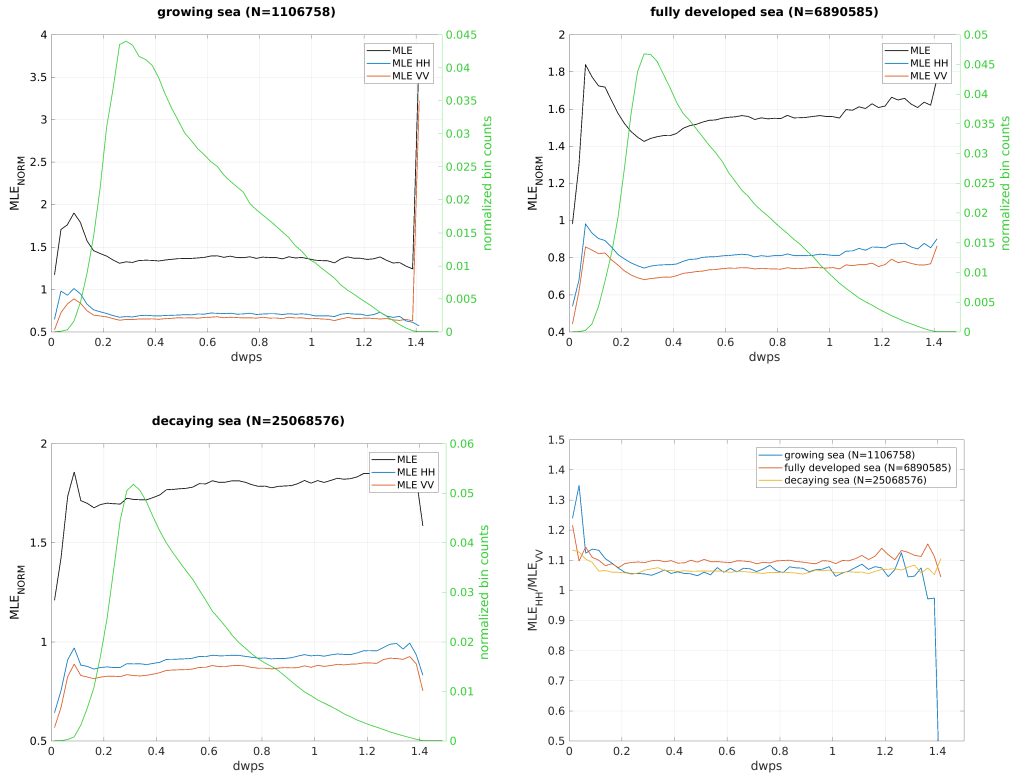


Figure 11: Same as Figure 6 but for dwps.

4.7 rwd

Figure 12 shows the same as Figure 6, but for the relative wave direction (rwd), which is the relative angle between the wind and the mean wave direction. The shape of the distributions shows that most of the points have low angles, meaning that most of the waves travel nearly in the same direction as the wind.

The $\text{MLE}_{\text{NORM,HH}}/\text{MLE}_{\text{NORM,VV}}$ ratios are rather constant over the rwd range, with the curve of the fully developed sea higher than the other two, similarly to what already seen for dwps.

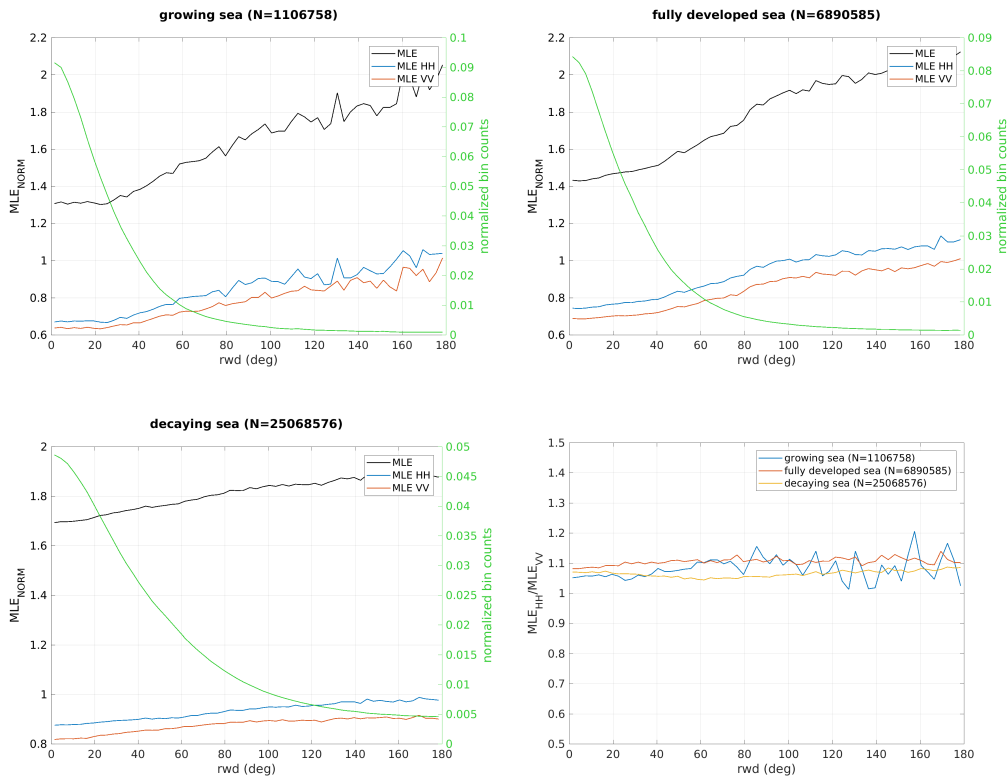


Figure 12: Same as Figure 6 but for rwd.

5 Final remarks and outlook

The main aim of this study is to analyze whether, in contrast to VV NRCS, the HH NRCS potentially depends not only on the local wind but also on the non-locally generated waves that propagate through the scatterometer Wind Vector Cell (WVC). For such purpose, a thorough analysis of the ratio between the HH and VV inversion residuals (MLE) of the Ku-band HSCAT-C NRCS and their potential correlation to several sea state parameters is carried out. We analyze six different sea state parameters (swh, shts, pp1d, mpts, dwps, rwd) from the ECMWF WAM model and, in addition, the U10S wind speed measured by the HSCAT-C scatterometer. The residuals (MLE_{NORM} after normalization) are divided into their HH and VV terms and averaged over a period of time (boreal winter of 2022) for each WVC belonging to the sweet region, a part of the satellite swath with a higher retrieval accuracy.

The QC wind flag is known to result in a distinct HH to VV MLE ratio due to rain droplet scattering and this can be observed comparing the results with and without QC. For this reason, only the results with the QC flag applied are presented (i.e., without rain).

A categorization based on sea state is introduced to potentially identify the most favourable conditions for wave-breaking occurrence.

For U10S we find that, in the range up to 14 m/s, the HH to VV ratio of MLE_{NORM} is higher for the growing sea condition, followed by the fully developed sea and finally by the decaying sea, perhaps indicating anomalous wave-breaking occurrence for wind-dominated conditions compared to more average behaviour in swell-dominated conditions, well described by the wind GMF. Each sea state shows a peak in the ratio around 10 m/s, suggesting an inconsistency in the VV and HH GMFs.

Four of the sea state parameters analyzed (swh, shts, pp1d, mpts), similarly to U10S, seem to have specific values for which the HH to VV MLE_{NORM} ratio suddenly increases. Such values that enhance the GMF inconsistency also vary depending on the sea state, with smaller wave heights and shorter periods for the growing sea and larger wave heights and longer periods for the more mature sea states. The inconsistency may be related to wave breaking occurrence at certain combinations of wind speed (U10S), wave height (swh, shts) and wave period (pp1d, mpts).

The other two sea state parameters, dwps and rwd, instead, show a more uniform response across their range of values with no clear, isolated peaks or trends. Moreover, the $\text{MLE}_{\text{NORM,HH}}/\text{MLE}_{\text{NORM,VV}}$ ratio of these two parameters is higher for the fully developed sea compared to the other two sea states.

These conclusions are based on the main assumption that the $\text{MLE}_{\text{NORM,HH}} / \text{MLE}_{\text{NORM,VV}}$ ratio is a valid method for identifying the GMF anomalies. However, this assumption remains untested. If the GMF, either VV or HH, is wrong for a particular condition, then the consistency of the whole retrieval will suffer as it compromises the differences between measured and simulated NRCS values for all different views, i.e., it likely increases both $\text{MLE}_{\text{NORM,HH}}$ and $\text{MLE}_{\text{NORM,VV}}$ with respect to other conditions in order to minimize the total MLE, which implies the GMF error may not be visible in the ratio. To first order, a GMF error, for example due to sea state, will increase all differences and hence increase the total MLE. To counteract the U10S dependence of MLE, one could make a ratio $\text{MLE} / \langle \text{MLE}_{\text{U10S}} \rangle$, which should not depend on U10S anymore. If this variable would depend on independent sea state variables, then this indicates that sea state may have an effect, irrespective of U10S. This could be part of future investigation.

In summary, it is clear that a nice property of the ratio $\text{MLE}_{\text{NORM,HH}} / \text{MLE}_{\text{NORM,VV}}$ is its insensitivity to wind speed, while the retrieval itself will compromise unusual changes in the HH GMF with both adaptations to the HH and VV MLE terms in order to minimize/balance the total MLE. This implies for Figure 6 that the larger MLEs for growing seas, in particular for winds below 10 m/s could indicate an HH GMF sea state effect, which would increase both $\text{MLE}_{\text{NORM,HH}}$ and $\text{MLE}_{\text{NORM,VV}}$. The effect remains somewhat visible for the ratio around 5 m/s, perhaps further indicating an HH GMF error. Collocations with ASCAT may show whether the larger MLEs in growing seas are associated with larger wind errors too. Nevertheless, the ASCAT MLEs may also be enhanced in growing wind sea conditions due to enhanced variability conditions. Figure 5, on the other hand, may indicate that the effect in Figure 6 is mainly due to remaining rain contamination. This could be verified in the future with a newly developed QC filter (see Section 5.1).

5.1 Future work

In this study we applied a QC filter that rejects about 4.5% of the data. In the meantime, a new QC has been developed by KNMI which rejects less data (about 2%) and with more rain included. Moreover, the new QC rejects less good-quality high winds. It would be interesting to repeat the analysis with the new QC to remove even more efficiently the rain effects on the polarization ratio and to verify whether the observed discrepancies are indeed caused by wave breaking. Also, because the QC (both old and new) is mostly active in the tropics, it would be better to separate the analysis by geographical region, i.e., considering the tropics and the extratropics separately.

The 3 months period analyzed in this study, corresponding to boreal winter 2021-2022, seems sufficient for investigating the HH NRCS signal, relative to VV, for most sea state conditions. It would be interesting to extend such analysis to other seasons and years to verify whether a similar HH to VV behaviour is found or not. Moreover, the EUMETSAT OSI SAF processes intercalibrated ASCAT, ScatSat-1 and HY-2 scatterometer winds, such that many collocations between VV-only and combined VV/HH scatterometers may be analyzed. Most collocations appear between ASCAT and ScatSat, which were in a very similar orbit for a period of time, while today's inclined orbit HY-2C and HY-2D scatterometers may provide further collocations with ASCAT.

For C band, [19] [5], among others, investigated non-local sea state effects in ASCAT to conclude that these are negligible. On the other hand, the ASCAT MLE has been associated with local wind variability, most probably due to the mismatch between the footprints of the different views. A mismatch of view footprints is expected to be more prominent for Ku-band scatterometers. From this point of view, it appears of interest to evaluate VV and HH NRCS residual contributions in collocated data sets of ASCAT and Ku-band scatterometers to be able to more fully understand the differences in VV NRCS for C-band and Ku-band. This will be helpful to understand how potential sea state effects in the HH NRCS manifest in the VV and HH NRCS residual contributions.

Finally, note that different models exist on the stress balance between winds and waves, i.e., the balance between wind input and wave feedback, where some suggest a substantial net effect of the waves on the winds and others do not [4]. Scatterometry appears to confirm that such feedback is insubstantial, since the VV NRCS employed by ASCAT has not been found to depend on non-locally generated waves [4] [5].

Here we also find non-local HH sea state effects to be limited. This may be further verified in future studies.

6 Appendix

In this appendix we show, for completeness, the plots for the unfiltered data (no KNMI_QC applied) for the six sea state parameters.

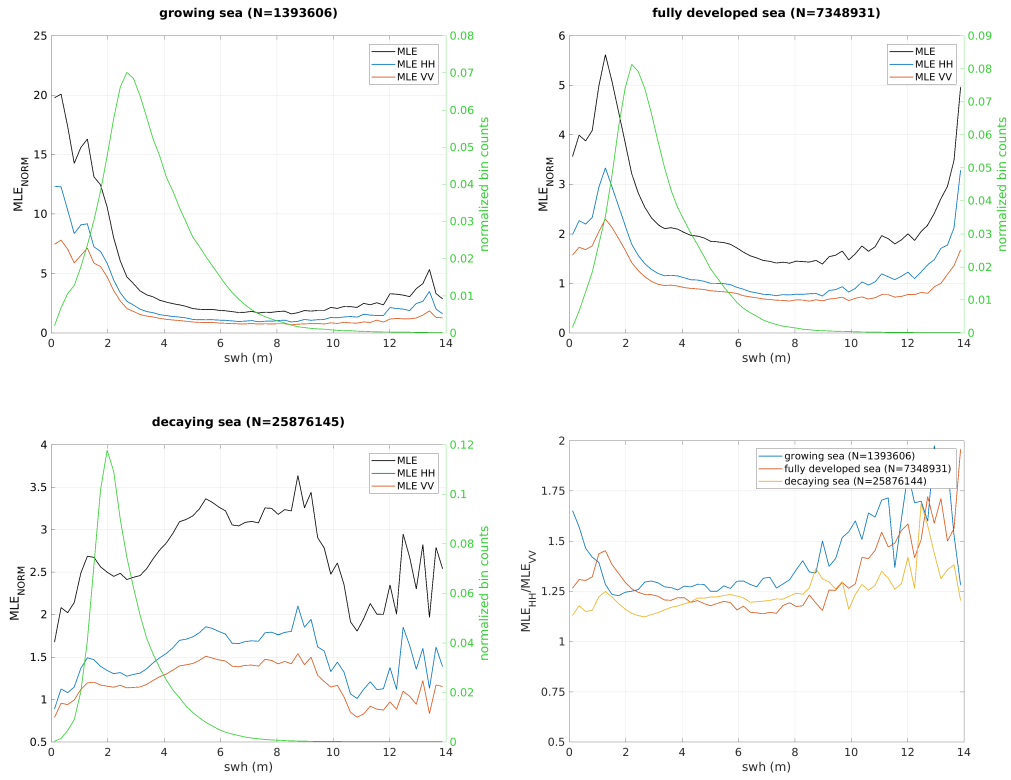


Figure 13: Same as Figure 5 but for swl.

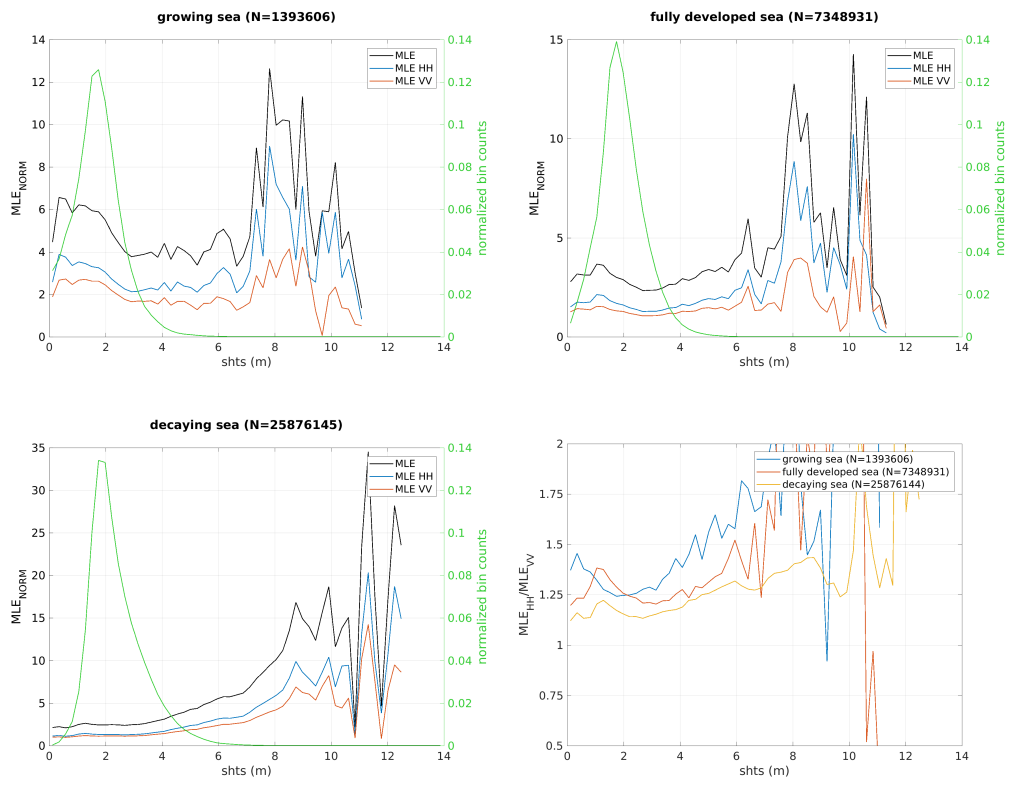


Figure 14: Same as Figure 5 but for shts.

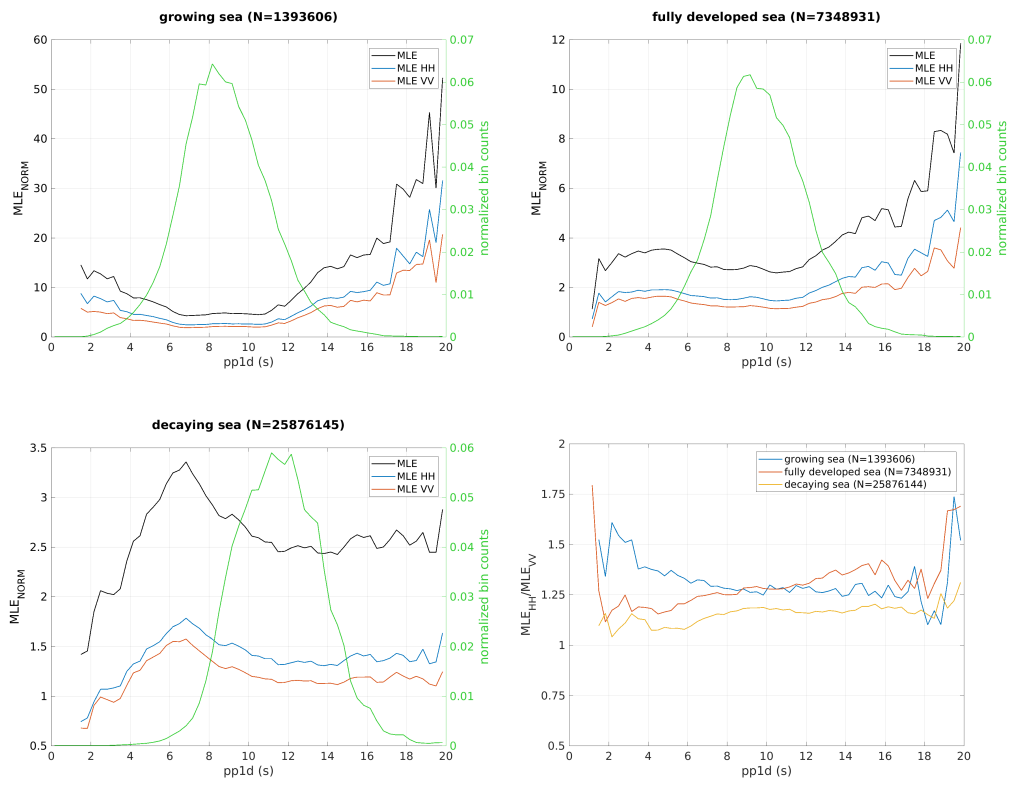


Figure 15: Same as Figure 5 but for $pp1d$.

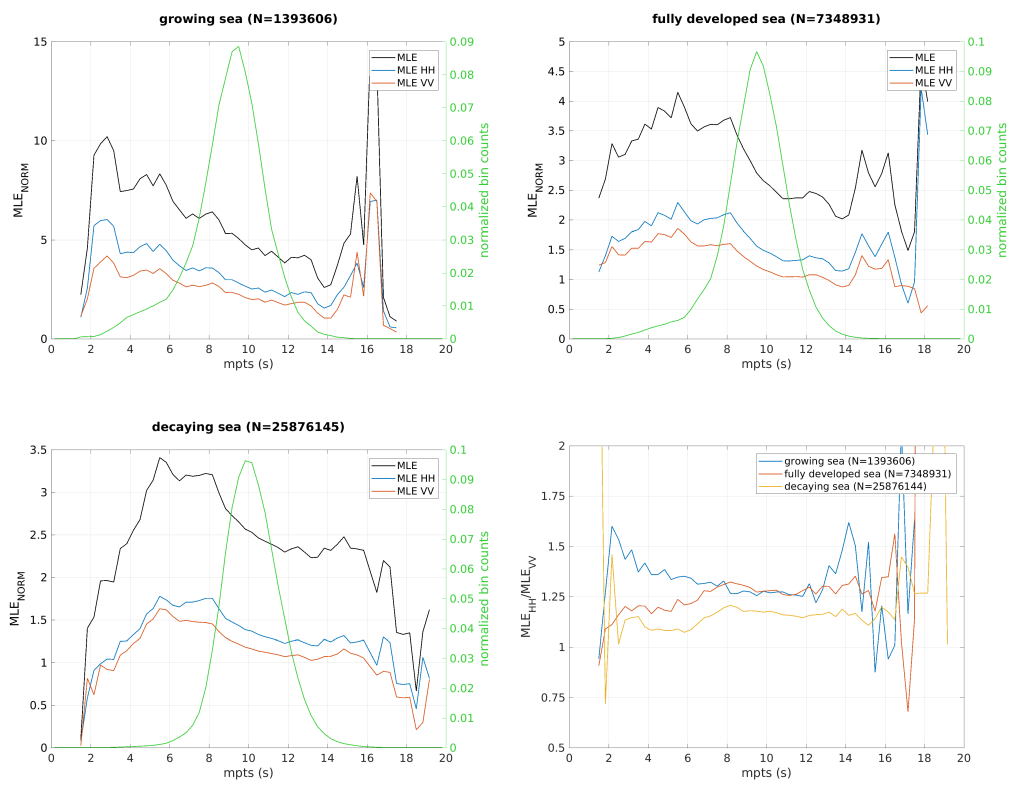


Figure 16: Same as Figure 5 but for mpts.

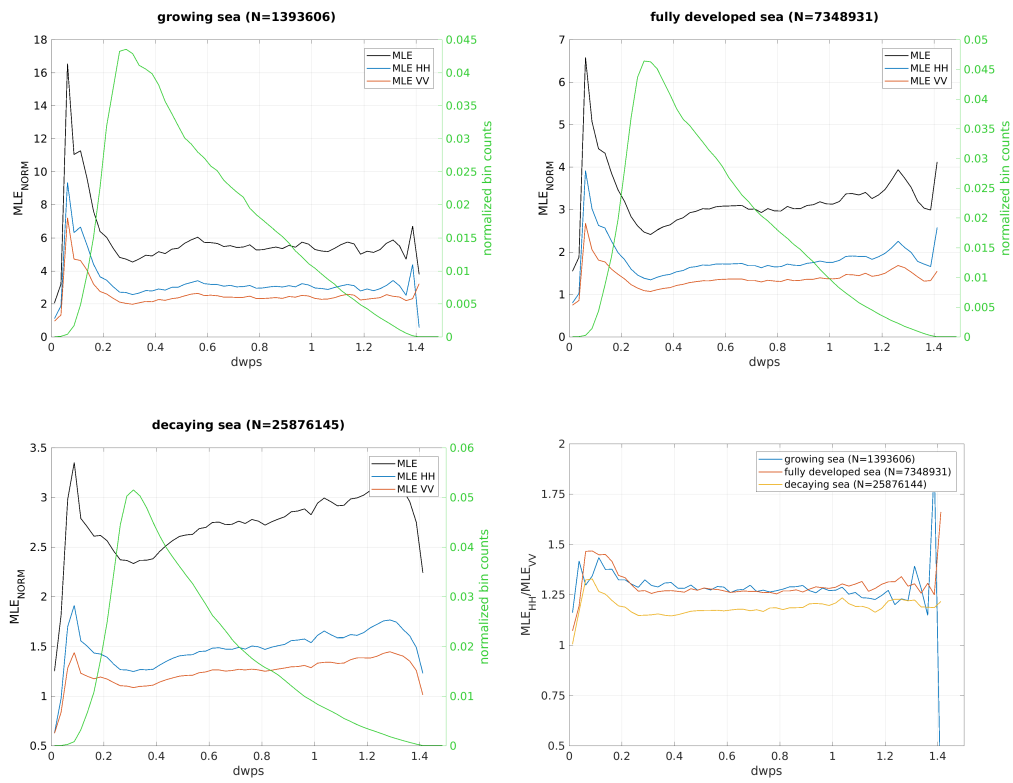


Figure 17: Same as Figure 5 but for dwps.

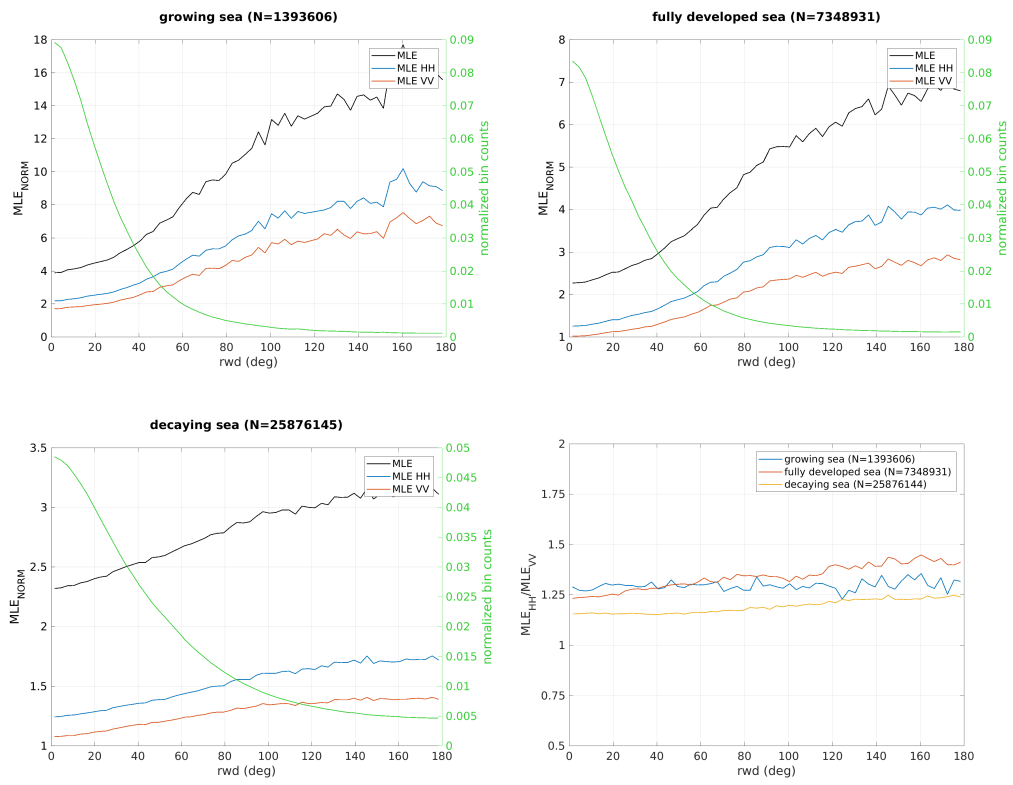


Figure 18: Same as Figure 5 but for rwd.

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