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Section Ecosystem Data Analysis and Modelling
Suspended Matter and Sea Bottom Modelling and Monitoring Group (SUMO)
and
Management Unit of the North Sea Mathematical Models (MUMM)

Analysis of oceanographic profiles taken during RV Belgica campaign ST2019/09

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1. Introduction

In the framework of the ZAGRI-MOZ4 projects, measurement campaigns were carried out in the year 2019, amongst other to investigate the effect of extraction of sand on possible sediment plumes, and to get more insight in the background suspended particulate matter (SPM) concentration in the Hinder Banks region.

In this report, an analysis is presented of the SPM concentrations that were measured during the campaign 2019/09, where profile measurements from the RV Belgica were taken. At three locations profiles were taken over a 10h to 13h cycle, to get more insight into the background SPM concentration. Water samples were taken to calibrate the data that were taken with a Seapoint optical back sensor (OBS).

First, the calibration of the data is presented. Next, the profiles are combined to get some more insight in the variation of the SPM concentration over the water column and during a tidal cycle. Finally, a Van Rijn-Rouse profile is fitted to extrapolate the data to the bottom. A discussion of the data is put forward in the final section.

2. Materials and methods

2.1. *Overview of measurements*

During RV Belgica campaign 2019/09 (see https://odnature.naturalsciences.be/belgica/nl/campaign/1673 for planning and report), that was executed from March 25 to March 29, 2019, measurements were performed at three locations to get more insight into the background SPM concentration. Two cross-banks tracks were sailed and one 13h through-tide measurements was executed.

The position of the tracks between sector 4b and 4c, Oosthinder sandbank and over the sector 4a, Noordhinder sandbank are indicated, as well as the position of the 13-h measurements just south of the sector 4a, Noordhinder, in Figure 1 and Figure 2 (detail). During the cross-bank tracks, every hour, a profile with CTD and Seapoint were taken and water samples were taken at the top of the bank, to calibrate the Seapoint. A total of 10 and 15 water samples were taken for the tracks between 4b and 4c and over 4a respectively. Measurements with a Hach Turbidimeter were taken onboard as an additional proxy for the SPM concentration. During the 13h cycle, a profile and water samples were taken every half hour, at position 51°34.160’N 2°32.42’ E, at the edge of the sector 4a, together with measurements with the LISST-200 to measure the particle size distribution. A total of 27 water samples were taken in this case.

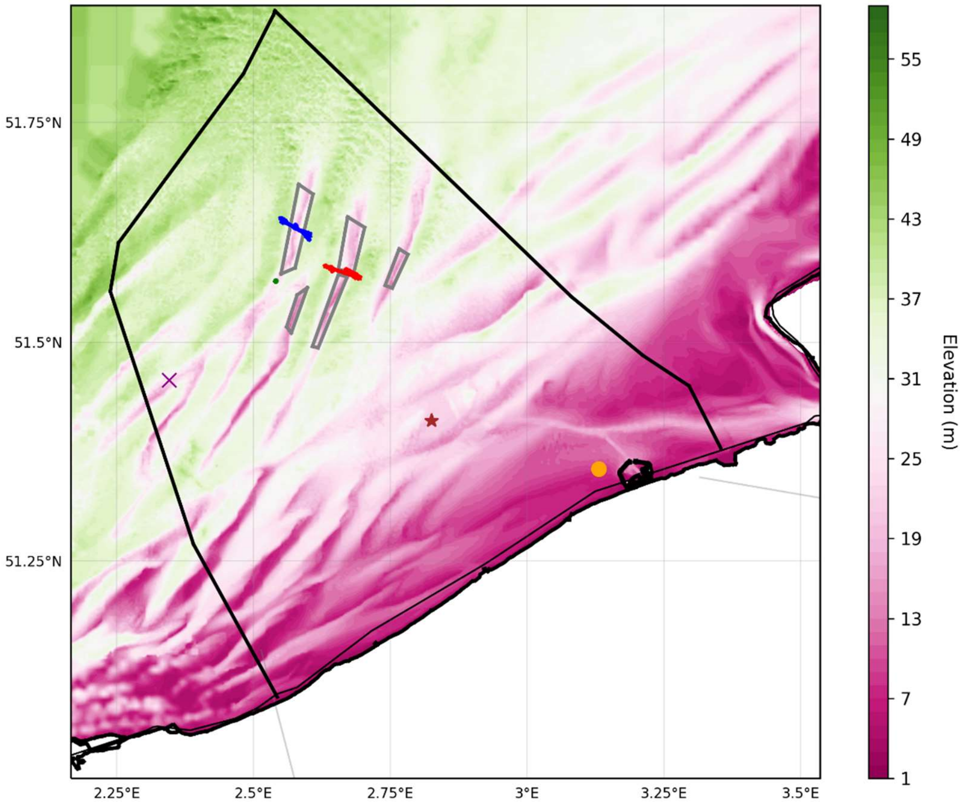

Figure 1: Position of the cross-bank tracks over the Noordhinder sandbank, sector 4a (blue), between

sector 4b and 4c, Oosthinder sandbank (red); position of the 13 h cycle measurements south of sector 4a, Noordhinder (green); position of measuring stations MOW1 (orange dot), W05 (brown star), W08 (purple cross).

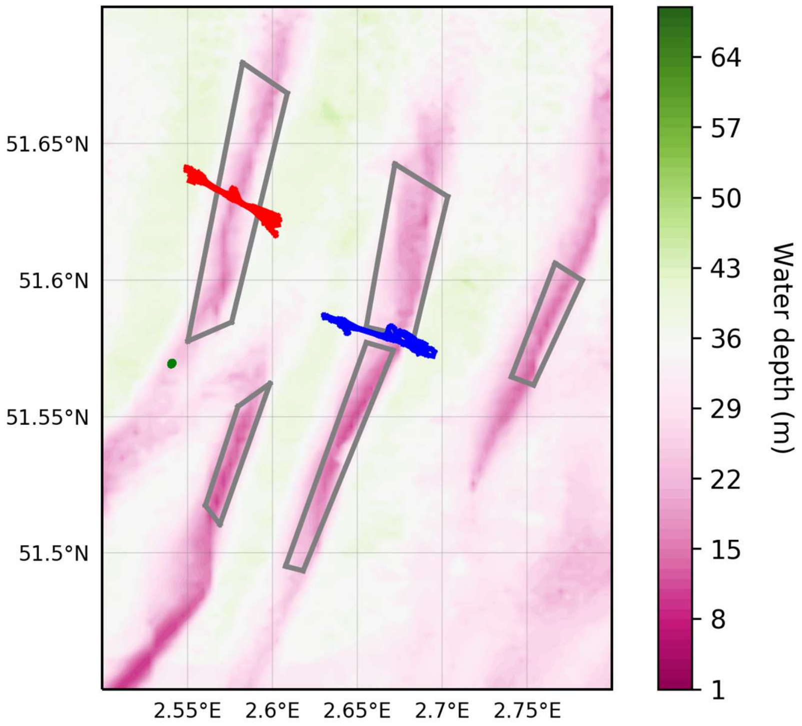

Figure 2: Position of the cross-bank tracks over sector 4a (red), between sector 4b and 4c (blue); position of the 13 h cycle measurements south of sector 4a (green).

2.2. *Water samples*

Water samples were taken for calibration of the continuous registrations (Seapoint OBS, hull-mounted ADCP; bottom-mounted ADCP) using a Niskin bottle of 10 l, mounted on a Seacat profiler (SBE19 CTD system). The latter allowed vertical profiling of oceanographic parameters using CTD for salinity, temperature and depth, and optical backscatter sensor (OBS) for turbidity.

Particle-size distribution (PSD) and volume concentration in the water column was measured using a Sequoia type C 200 X Laser In-Situ Scattering and Transmissometry (LISST). Using an annular ring detector, the instrument derives in-situ particle sizes, in the range 1.2 to 460 µm, from the scattering of particles on 36 rings. PSD are presented as concentration (µl l^{-1}) in each of the 36 log-spaced size bins. Date and time, optical transmission, water depth and temperature are recorded as supporting measurements (http://www.sequoiasci.com).

Water samples were filtered on board for suspended particulate matter (SPM). Mostly, 1.5 to 2.0 l of water was filtered. During the cross-bank transects, almost every hour a profile was taken and filtrations were executed. During the 13-hrs cycle, filtrations were done every half hour. In addition, once per hour, filtrations were taken for determination of particulate organic carbon and nitrogen (POC/PON) (0.250 l), and a bottle of water (0.33 l) was kept for calibration of the conductivity sensor for salinity.

On board, water samples were filtered, in three replicates, using pre-weighted Whatmann GFC filters. These were analysed at the Marine Chemistry Lab (OD Nature, ECOCHEM). Suspended particulate matter concentration (SPMC) (Unit mg l^{-1}) was obtained after drying of the filters for 48 hours, after which weight differences were calculated. A deviation of 12 % between the replicates is acceptable (ECOCHEM Standards). Measuring uncertainty of deriving SPM from filtrations is 17 %. Furthermore, three replicas of the turbidity were also taken on board with a TL 23 Hach Laboratory Turbidimeter. These measurements are used for calibration of the Seapoint OBS or of the filtrations.

POC/PON analyses (Unit g l^{-1}) were carried out in the laboratory using an Interscience Flash EA 1112 Series Element Analyser. Measuring uncertainty is 12 % for POC; 18 % for PON (ECOCHEM AK 7.0). For salinity (Unit PSU), a Laboratory salinometer – Portasal 8410 (Guildline) van Ocean Scientific Int. was used; the measuring uncertainty is 0.15 % (ECOCHEM).

It needs emphasis that water samples were taken at different levels in the water column. Normal procedure is to take a sample at 2m to 4 m above the sea bottom (mab), depending on wave action, hence platform motion. The depth of the water sample is derived from the CTD profiles (see below). Still, there are important uncertainties on the exact sampling depth, as the Seacat frame is easily carried away by the currents.

2.3. *OBS Seapoint measurements*

Since 2017, the OBS3 and OBS3+ turbidity sensors were replaced by the Seapoint OBS sensor, that measure more accurately low SPM concentrations in offshore areas. The Seapoint OBS has a working range from 0 to 125 NTU, which was obtained through the use of a jumper cable that amplified the signal by a factor of 20. As such, the sensitivity was 40 mV/NTU compared to 2 mV/NTU without cable and for the standard range of 0-750 NTU (Sea-Bird Electronics Inc., 2013). Following technical specifications (Sea-bird Electronics Inc., 2013), the following formula was used to convert the voltages into NTU (see Van Lancker et al., 2016):

$$NTU = 25 * Voltage \qquad (1)$$

3. Results

3.1. *Introduction*

In the current section the results of these measurements are discussed. First, the calibration of the Seapoint optical back sensor is discussed, to convert these data into suspended particulate matter concentration. Also, the measurements with the Hach turbidimeter are considered for the calibration.

In a second section the profiles are discussed. The data are extrapolated using a Van Rijn-Rouse profile to get more information on the total SPM concentration (SPMC) and to get more insight in the behaviour of the material near the sea bottom.

3.2. *Calibration of the Seapoint sensor*

3.2.1. Calibration between Seapoint sensor and SPM concentration

Water samples were used to calibrate the turbidity Seapoint sensor and to convert the NTU of the Seapoint, calculated from the output in voltage with the previously mentioned formula, to mg l^{-1}. The SPMC of the water samples was determined in the laboratory and a linear relationship was established between SPMC and the Seapoint output (in NTU) at the same moment. Unfortunately, something went wrong with the time registration of the instrumentation so that the exact moment when the Niskin bottles were closed were not well recorded. This will introduce some uncertainties in the linear regression.

During the cross-bank measurements between sector 4b-4c and over sector 4a, profiles were taken at the top of the sand bank. When taking the profiles during the cross-bank measurements, the CTD and Seapoint were lowered in the water column, to take a profile, was held shortly at depth, and before the CTD and Seapoint were brought on board again, taking another profile, the bottles were closed. The mean time for taking the profile was around 41 seconds for both measurements (to reach 98% of the maximum depth that was obtained with the CTD), while the CTD and Seapoint were held near the bottom for a mean period of 47 or 31 seconds during the cross-bank measurements between sector 4b-4c and over sector 4a respectively. During the 13h measurements, the time to take the profile was a little bit longer, around 71 seconds, and the CTD was left near the bottom for a much longer period, around 22 minutes.

To get a representative Seapoint value that can be compared with the results of the filtrations, the mean Seapoint reading during 11 seconds was considered first, just before the CTD was hauled on board again. Since the exact time of the closure was not known, this time of closure was estimated manually (see Figure 3 to Figure 5).

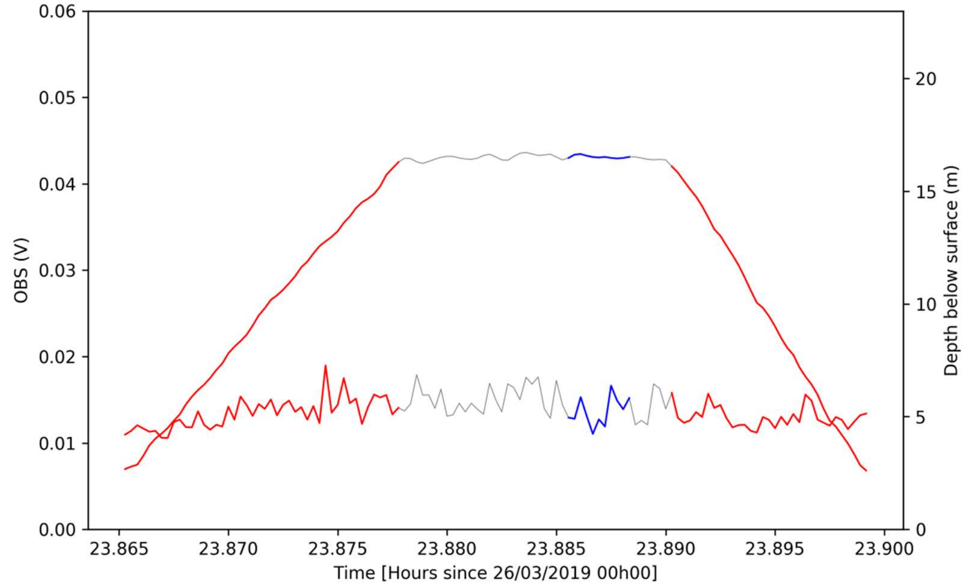

Figure 3: OBS voltage output and depth below surface as a function of time for the second profile taken during the cross-bank measurements between sector 4b-4c (Oosthinder). Blue: 11 seconds during 'closure of the bottle'; red: the profile downwards and upward (until 98% of maximum depth is reached).

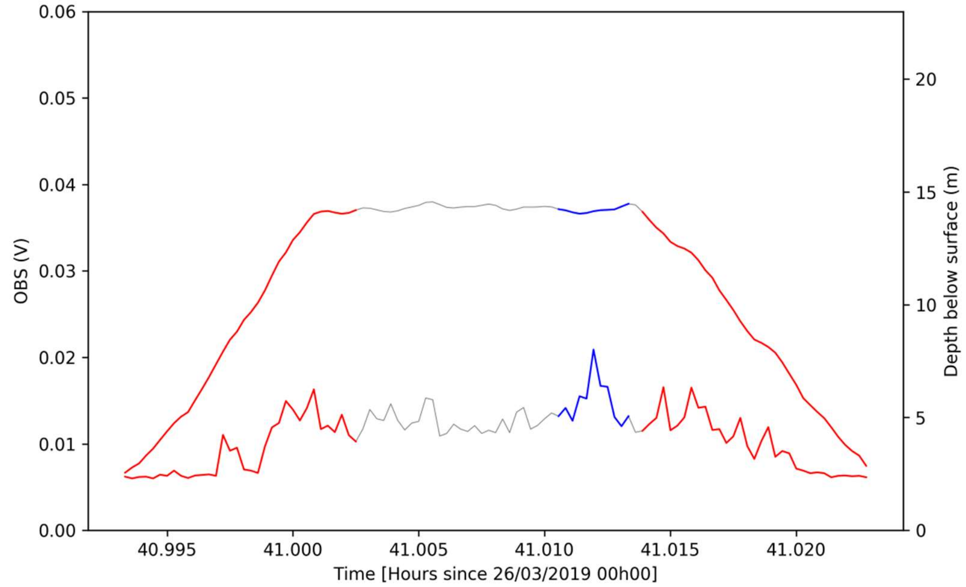

Figure 4: OBS voltage output and depth below surface as a function of time for the second profile taken during the cross-bank measurements between sector 4a (Noordhinder). Blue: 11 seconds during 'closure of the bottle'; red: the profile downwards and upward (until 98% of maximum depth is reached).

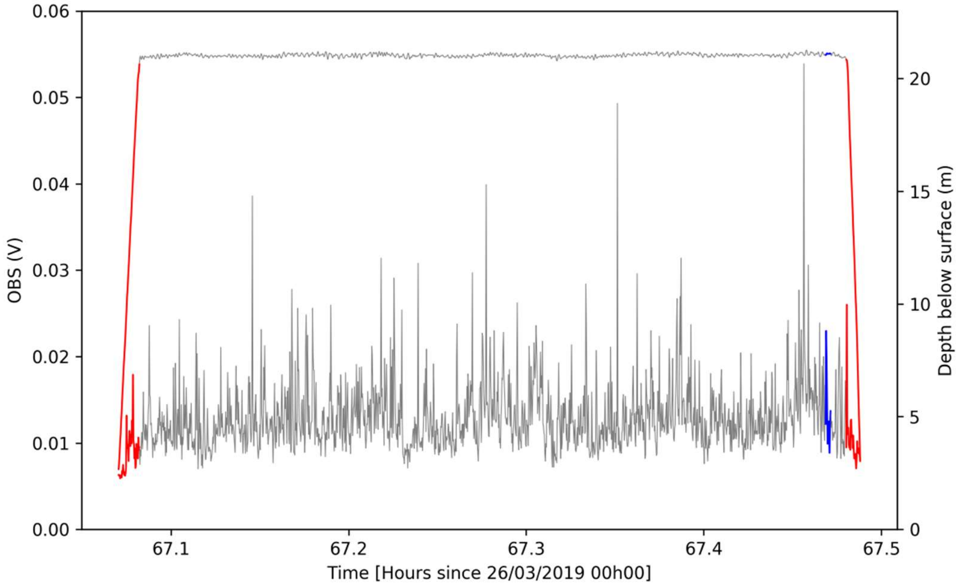

Figure 5: OBS voltage output and depth below surface as a function of time for the second profile taken during the 13-h tidal cycle measurements south of sector 4a (Noordhinder). Blue: 11 seconds during 'closure of the bottle'; red: the profile downwards and upward (until 98% of maximum depth is reached).

One can see that during the 11 seconds that the bottle is closed the OBS voltage can still vary over some range. The exact moment of the closure of the bottles is however not known. Taking the mean over 11 seconds just before the upwards profile is taken seems to be a reasonable solution. Remark that other methods were tested to get an estimate of the OBS reading during the closure of the bottoms, but these tests did not change the results significantly.

A total of 52 profiles and water samples were taken during the entire campaign: 10 over the sector 4b-4c, 15 over the section 4a, and 27 south of sector 4a. For each of the water samples, three water filtrations were taken that were weighted in the laboratory. When the relative standard deviation (RSD) is smaller than 12 % between the three results, the results are reported without error code. When the RSD is higher than 12 %, the outlier is reported suspected when the RSD is without the outlier below 12 %. If with removing an outlier, the RSD is never below 12 %, all data are reported suspected. During this campaign, only 16 of the 52 SPM concentration measurements were reported without error code, while 25 measurements had one outlier and 11 of the data had all suspected values. This rather low quality of the measurements is probably mainly a result of the low values in the water, which make accurate measuring more difficult. Additionally, it needs emphasis that on sandbank environments sand grains are found in the water samples, weighing disproportionally on the result of the filtration. Human errors are not excluded as well.

In Fettweis et al. (2019) a thorough discussion is found on the uncertainties related to gravimetrical measurements of the SPM concentration, by filtering and weighing. The removal of salt in the filters, if not well done, could lead to an overestimation of the SPM concentration (Neukermans et al., 2012). In high turbid waters, the difficult homogenization of a sample prior to subsampling and filtering (Fettweis, 2008) could lead to errors, but this is not the case here. Fettweis et al. (2019) mention an uncertainty of 8.5 % for sample values lower than 5 mg l^{-1}.

An overview of the gravimetrical measurement of the SPM concentration of the water samples is presented in Figure 6. It can be seen that four high values (higher than 15 mg l^{-1}) are taken during the cross-bank measurements over sector 4a and five high values are taken during the 13h cycle, south of sector 4a. All the measurements are taken relatively short after each other, which give some consistency in these results. Moreover, most of the high values measured were not categorized as suspicious values.

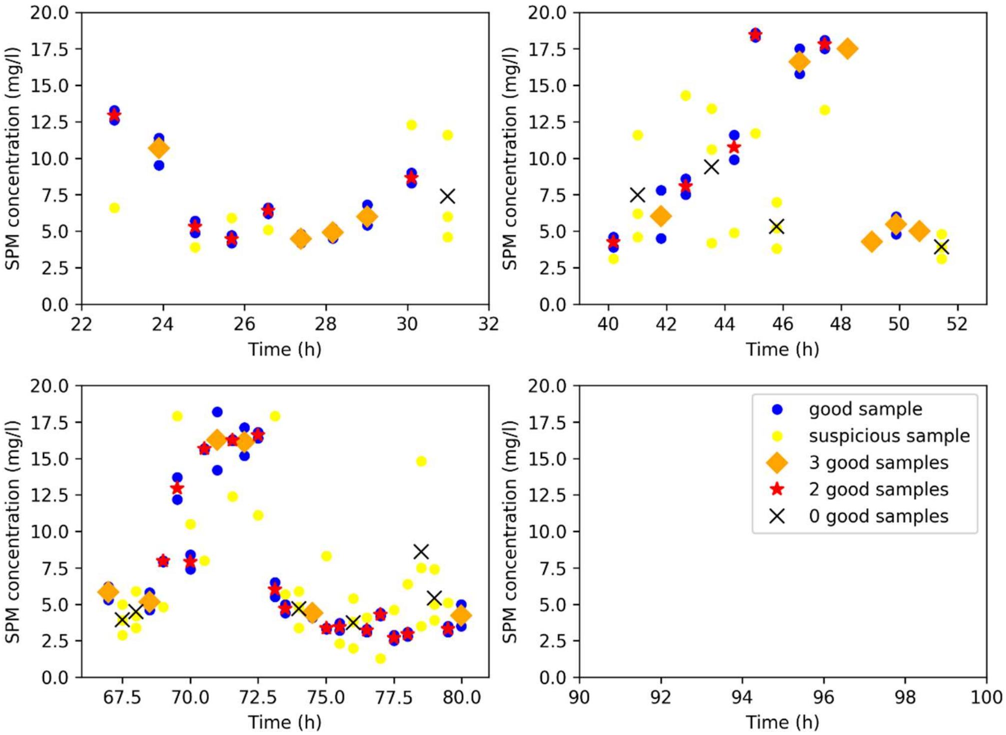

Figure 6: Overview of the results of the three gravimetrical measurements for the water samples taken during the campaign. Blue dots: good samples, yellow dots: suspicious samples (see above). Orange diamonds: red stars: mean of the two good samples, black cross: mean of three suspicious samples, these data are not used.

The difference between taking the mean over all samples and taking the mean over two samples only, removing the outlier, is shown in Figure 7. The overall differences remain acceptable. It seems therefore reasonable to take the mean of the good samples into account for the calibration of the OBS sensor. The samples with three suspicious values are not considered in the further analysis. Therefore, 11 samples were removed from the analysis. Only for 16 samples, no suspicious values were found.

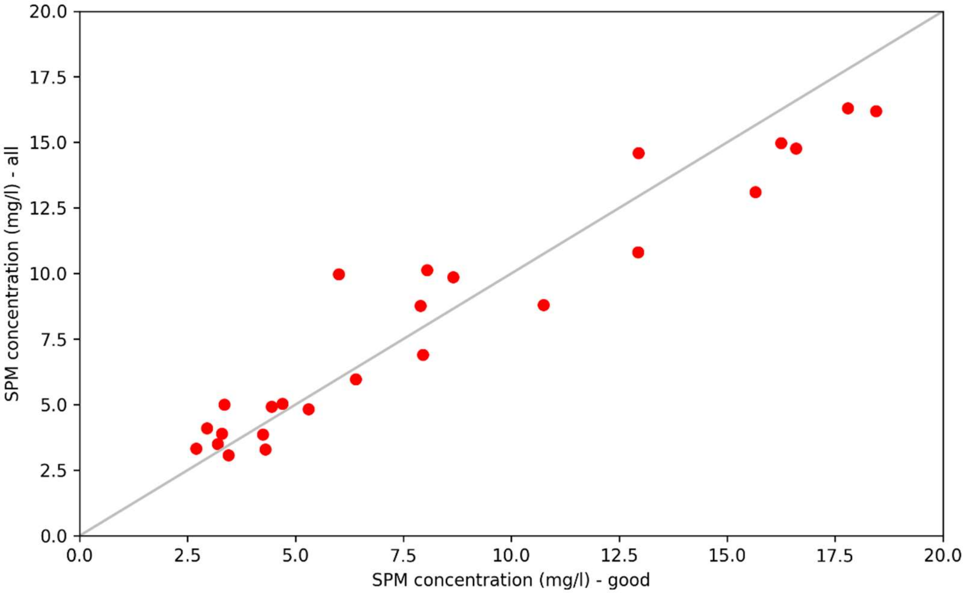

Figure 7: Mean SPM concentration when taking only the two samples into account without error code, compared to the mean SPM concentration when taking all three samples into account, including the outlier.

In Figure 10, the time series of the SPM concentration, as determined by the water samples are presented. The differences between taking only the good samples into account, or taking all water samples into account are not very big. Only during the track over the Noordhinder one data point gives a much lower value, when all data points are considered, around hour 46. During the 13h-cycle, a second small peak in SPM concentration is visible when all data are considered between hour 77 and 80, which is not apparent, when only the good filtrations are accounted for.

A linear regression is calculated between the Seapoint OBS voltage readings, converted to FTU, via the formulae above, and the SPM concentrations, obtained via filtrations. Only the 41 non-suspicious results were used. These were compared with the OBS readings at the closure of the bottles. The results are shown in Figure 9. The correlation coefficient R is even negative, with a coefficient of determination R^2 of 0.001.

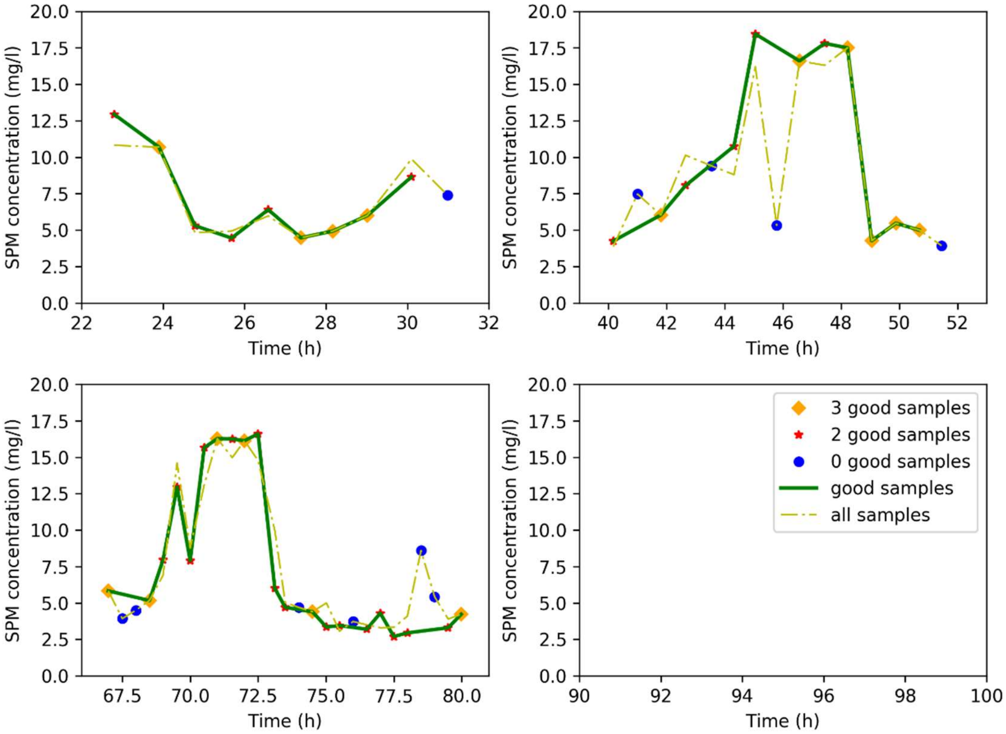

Figure 8: Overview of the results of the three gravimetrical measurements for the water samples taken during the campaign.

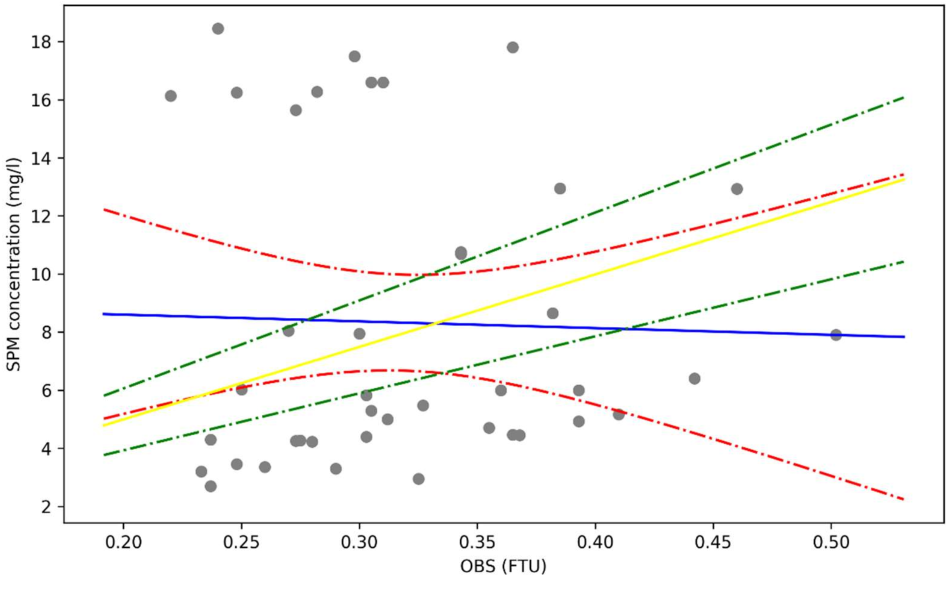

Figure 9: SPM concentration as a function of the OBS reading during (11 seconds of) closure of the bottle. Only 41 water samples, with only good values, are considered. Blue line: linear regression, red lines: 95 % confidence interval; yellow line: linear regression through the origin, black lines: 95 % confidence interval.

This could be due to the nine water samples having SPM concentrations that are higher than 15 mg/l, for rather low OBS readings. If the linear regression is calculated for the three tracks separately (Figure 10), the results are quite different. Mainly the measurements during the 13h cycle give unreliable results with a negative slope and a coefficient of determination of 0.002. The bad results are again mainly due to the four water samples with high SPM concentrations for low OBS voltages. The coefficient of determination R^2 for the tracks at sector 4b-4c (OH) and sector 4a (NH) are 0.18 and 0.04 respectively. When removing the nine samples that have SPM concentrations higher than 15 mg l^{-1} improves the correlation, resulting in a coefficient of determination of 0.28. This is however still low. Furthermore, there is no obvious reason to remove those results.

Other tests have been executed by using the tracks over the sector 4b-4c and 4a the mean OBS reading, when the sensor is near the bottom, and by using all the SPM concentration measurements, without removing the measurements with more than one outlier. That however did not improve the results.

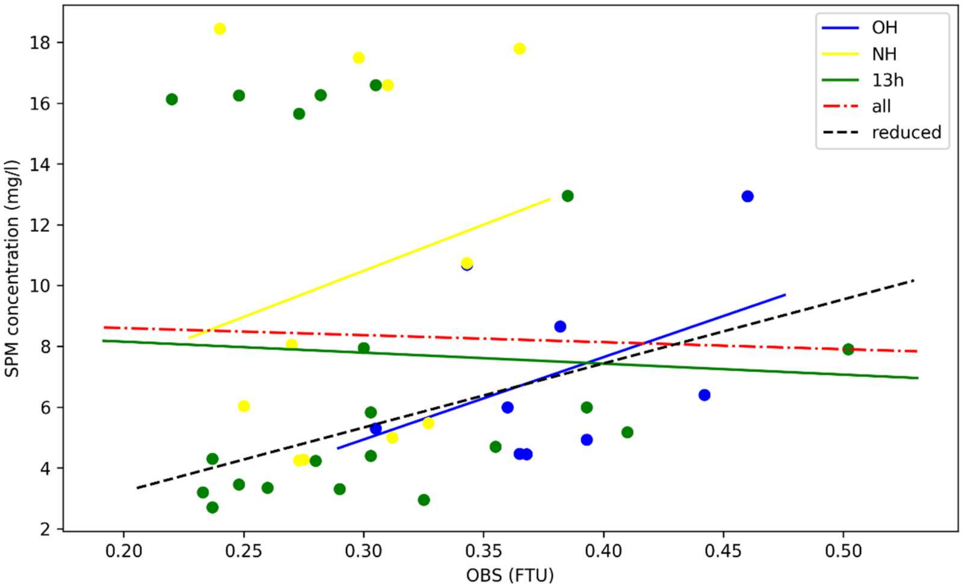

Figure 10: SPM concentration as a function of the OBS reading during (11 seconds of) closure of the bottle. Only 41 water samples with good filtrations are considered. Blue: data from measurements between 4b-4c (OH); yellow: data from measurements at 4c (NH), green: data from 13h tidal cycle (13h); red: linear regression for all data; black: linear regression for the reduced data set.

A negative slope for the relation or a slope of zero is not useful. For a slope of zero, the SPM concentration is constant during the entire time. Therefore, also the regression is calculated, forced through the origin. The results are shown in Figure 11.

Following relation, when all data are considered, is found:

$$SPMC\ (mg\ l^{-1}) = 24.96 * OBS\ (FTU) \qquad (2)$$

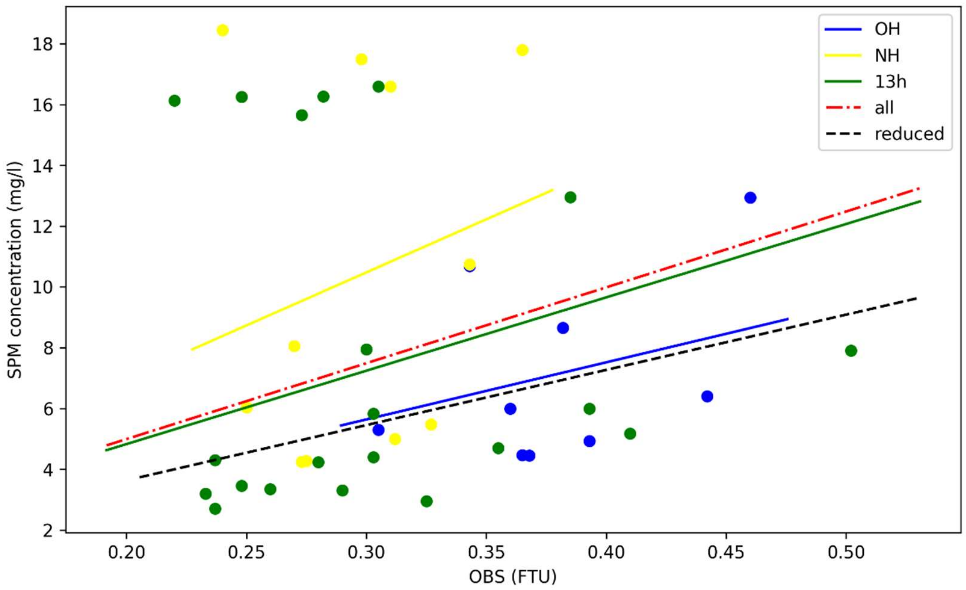

Figure 11: SPM concentration as a function of the OBS reading during (11 seconds of) closure of the bottle, but forced through the origin. Only 41 water samples are considered. Blue: data from measurements between 4b-4c (OH); yellow: data from measurements at 4c (NH), green: data from 13h tidal cycle (13h); red: linear regression for all data; black: linear regression for reduced data set.

3.2.2. Calibration between Seapoint sensor and Hach

Instead of correlating the readings of the Seapoint sensor to the SPM concentrations that were derived from the water samples, a second possibility exists in relating the reading of the Seapoint sensor to the measurements with the Hach turbidimeter, which was used using water samples on board of the ship. This eliminates possible human errors during the filtrations of the water samples on board or in the laboratory. It however assumes a good correlation between the SPM concentration and the Hach turbidimeter. Since, Fettweis et al. (2019) found a stable relationship between Hach water sample turbidity and sample SPM concentration for different locations, this relationship was considered in further analyses.

3.2.2.1. Relation OBS-Hach

In Figure 12, the linear regression between the Seapoint OBS readings (converted to FTU) and the Hach readings are shown for the different tracks and the 13h-cycle measurements.

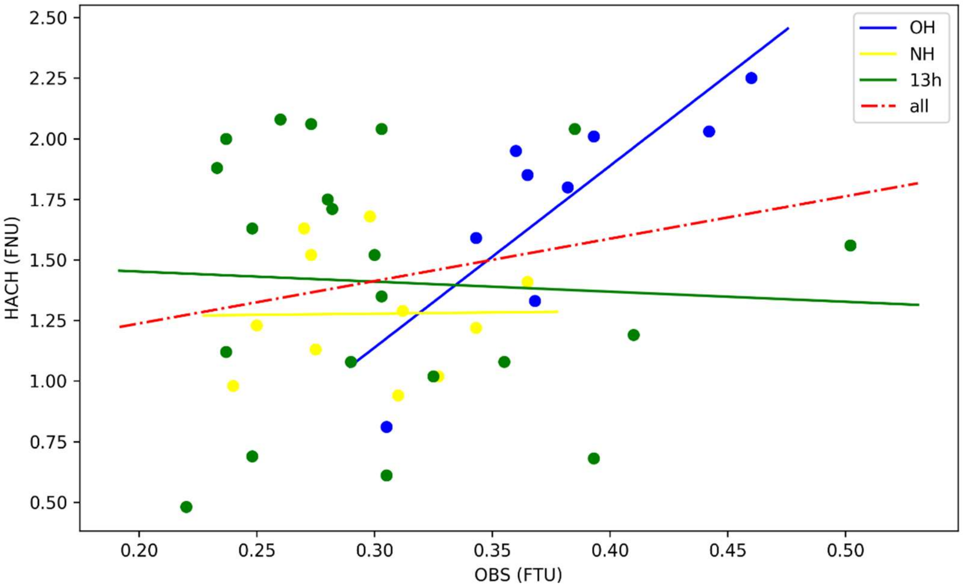

Figure 12: Linear regression between the Seapoint OBS readings and the Hach measurements for the different tracks and the 13h-cycle measurements.

Only for the measurements at the Oosthinder (track between section 4b and 4c), the coefficient of determination R^2 is relatively high, at 0.66. For the other tracks or for all data, the correlation coefficients are low. Also, for the relation through the origin, the correlation coefficients, as defined by Kozak and Kozak (1995), are very low (not shown here).

Since the relation between the OBS Seapoint and the Hach is not a clear relationship with a high correlation, this method of conversion was not taken forward for deriving SPM concentrations.

3.2.2.1.1. *Relation Hach-SPM concentration*

Also, the relation between the SPM concentration and the Hach has been looked at. In Figure 13, the linear regression between the Hach turbidimeter and the SPM concentrations, obtained in this campaign were shown. Again, the best results were found for the measurements at the Oosthinder, but overall the correlation is not good. For all measurements, the correlation is even negative, with higher Hach readings indicating lower SPM concentrations. The stable relation between Hach and SPM concentration clearly is not reproduced in this case.

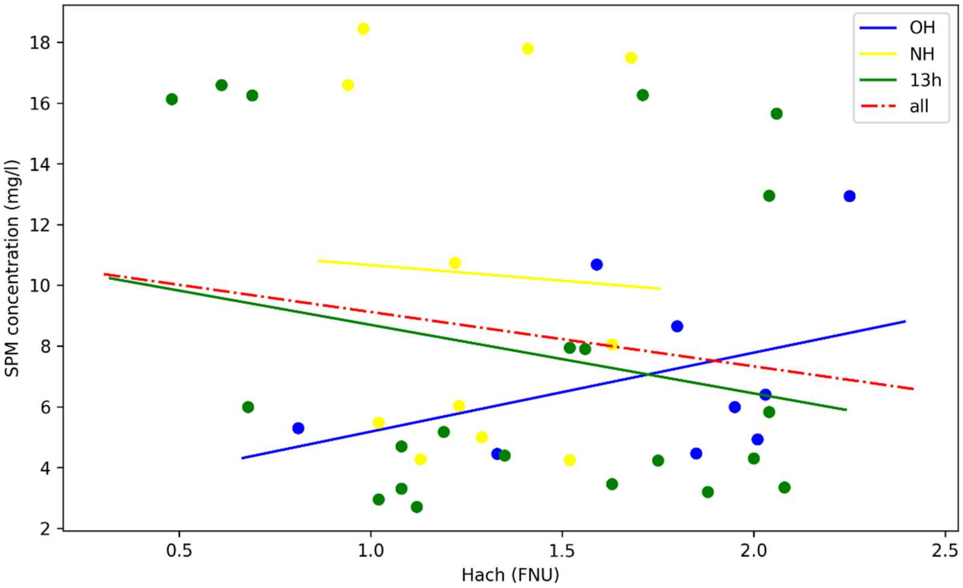

Figure 13: Linear regression between the Hach measurements and the SPM concentration measurements for the different tracks and the 13h-cycle measurements.

When the linear regression is forced through the origin (Figure 14) it seems that the found relation indicate a higher SPM concentration that was indicated by the stable relationship, that was derived from all measurements, using the Hach, on the Belgian Part of the North Sea (Figure 13). This relationship, which is forced through the origin, reads:

$$SPMC = 1.29 * Hach \quad (3)$$

It is clear that this stable relationship is very useful for large OBS values, as has been shown by Fettweis et al. (2019). However, this relationship is likely less useful for lower values of SPM concentrations.

To test this stable relationship for lower OBS values, all data that were obtained during the measuring campaigns in 2019 and 2020 so far were looked at. During these campaigns, a total of 1013 matching measurements have been executed where the Hach measurements could be compared with SPM concentrations. The measurements were taken at three stations, i.e., MOW1, W05 and W08. The position of these three stations are indicated in Figure 1. While the MOW1 is near the coast, near the harbour of Zeebrugge, the W05 is more offshore, while the W08 station is furthest offshore, to the west of the marine aggregate concession zone 4. The relationship for the results in the different stations is shown in Figure 15. Remark that the subplots in this figure have different scales.

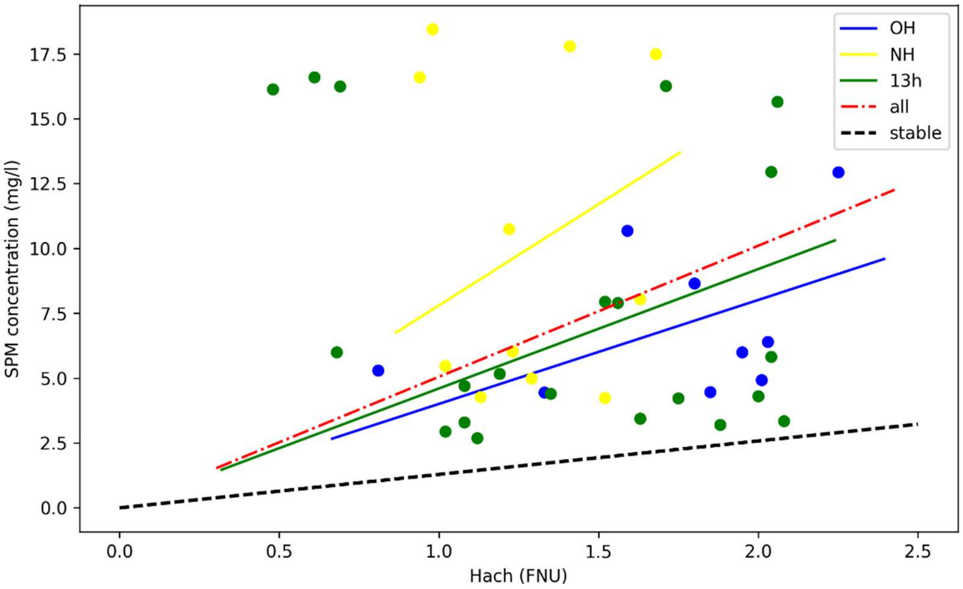

Figure 14: Linear regression through the origin between the Hach measurements the SPM concentration measurements for the different tracks and the 13h-cycle measurements.

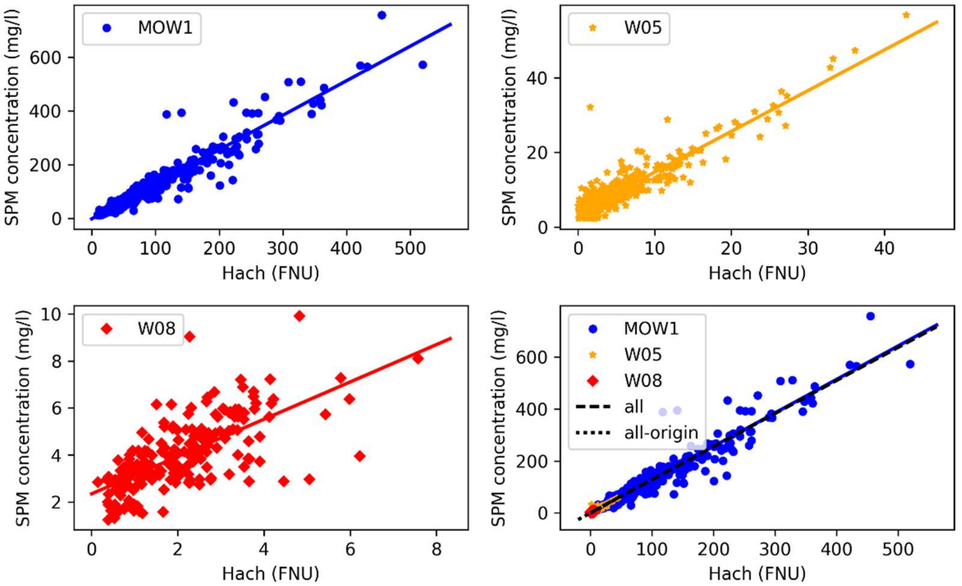

Figure 15: Relationship Hach – SPM concentration for different stations MOW1, W05 and W08. Different scales for the different figures.

Whilst for the data at MOW1, the coefficient of determination R² between the Hach and the SPM concentration is 0.92, this correlation coefficient decreases for the W05 to 0.85 and for the W08 to 0.46. The slope of the regression line is respectively 1.29, 1.09 and 0.79, see Table 1. The slope between the Hach and the SPM concentration for MOW1 and for all the data is close to the relation that Fettweis et al. (2019), which are of course, partly based on these data. The relation for the W05 and the W08 stations however has lower slopes, indicating lower SPM concentration values for the same Hach reading than would be obtained using the overall relationship. Remark however that the intercept is relatively high at 3 mg/l for the data from W08. When a relation through the origin is forced, the slope is higher for the W05 and W08 stations and even higher than the results for the MOW1 station.

Table 1: Slope and intercept for linear regression and correlation coefficient for the relation between Hach and SPM concentration for stations MOW1, W05 and W08. Also *slope_0*: slope of the linear regression through the origin.

	Data	Slope (mg/l/FNU)	Intercept (mg/l)	Correlation	Slope_0 (mg/l/FNU)
MOW1	464	1.29	-1.29	0.92	1.28
W05	347	1.09	3.80	0.85	1.40
W08	199	0.79	2.34	0.46	1.62
Winter	303	1.29	-0.76	0.95	1.29
Spring	223	1.31	2.94	0.97	1.34
Summer	224	1.38	0.24	0.90	1.37
Autumn	260	1.11	2.98	0.97	1.12
All	1010	1.28	1.21	0.95	1.28

A possible reason for these deviations is the uncertainty in the results when filtering the water for SPM concentrations for lower concentrations. An effect of the seasons could be important as well. These linear regressions for the different seasons are therefore shown in Figure 16. The parameters for the linear regression are shown in Table 1.

Although there are differences shown for the different seasons, the differences are less important than the differences for the stations, where the slope is much lower and the intercept higher for the stations W05 and W08 than for the stations MOW1. All results are summarized in Figure 17 and Figure 18, where the different linear regressions are shown on a log-log scale and for the range 0-20 FNU and 0-20 mg/l respectively. While the intercept is below zero for the winter and the MOW1 data, the intercept is above zero for all the data and for the other seasons and stations. On a log-log scale the difference in slope for the different linear regressions is not very apparent. Also, from Figure 18, it is clear that the intercept seems to have a more important influence than the difference in slope between the different regressions, at least for the lower ranges.

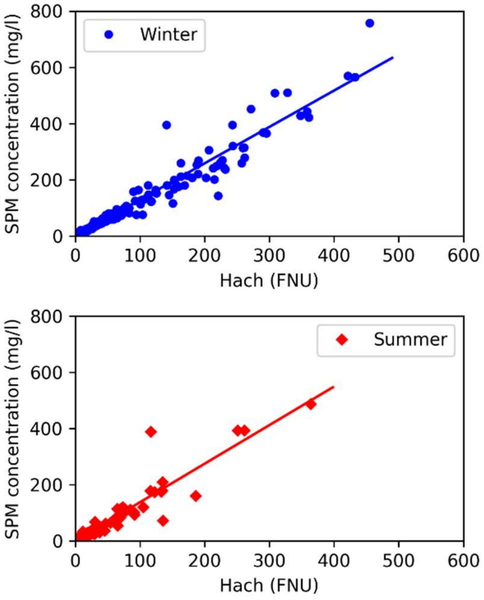

Figure 16: Relationship Hach – SPM concentration for different seasons

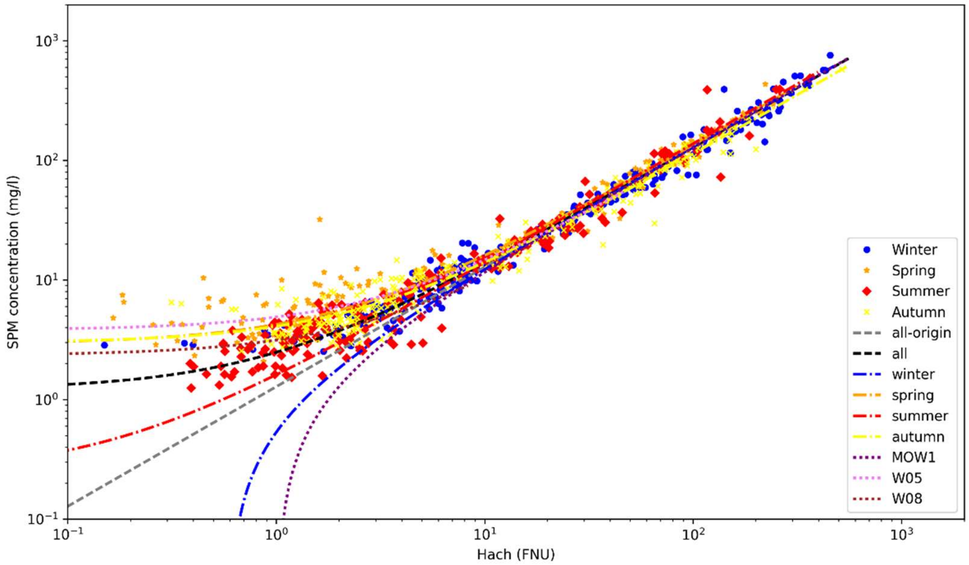

Figure 17: Relationship Hach – SPM concentration for different seasons and for different MOW1, W05 and W08 on a log-log scale

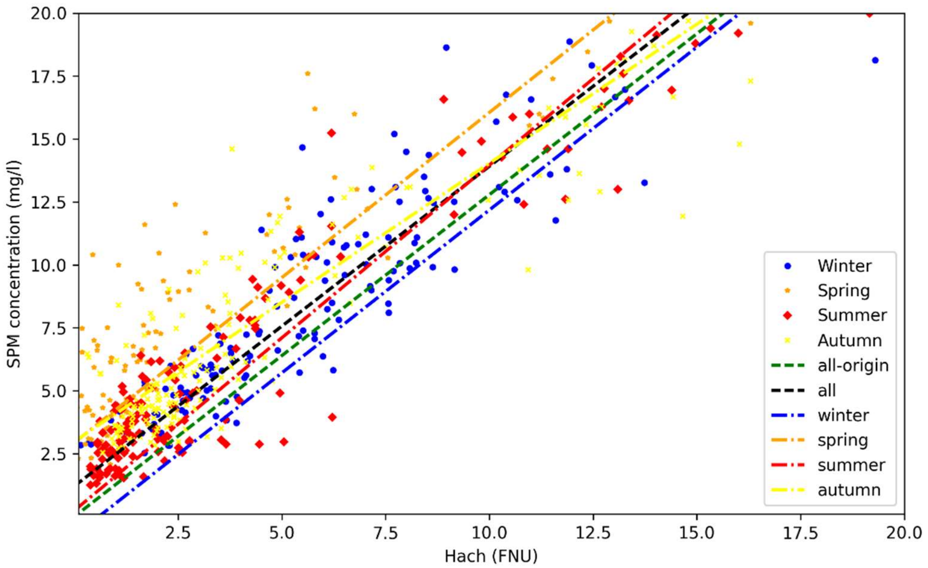

Figure 18: Relationship Hach – SPM concentration for different seasons and for the different locations MOW1, W05 and W08 for the range 0-20 FNU and 0-20 mg/l.

3.2.2.2. *Discussion*

Also, the use of the Hach-SPM concentration relation does not give good results for the calibration of the Seapoint OBS measurements. First of all, there does not seem to be a good correlation between the OBS Seapoint FTU and the Hach FNU. Furthermore, the stable relationship between Hach and SPM concentrations, as put forward by Fettweis et al. (2019) is not very accurate for very low SPM concentrations, as found at the Hinder Banks.

3.2.3. Conclusions

Since no good correlation was found between the Seapoint and the SPM concentrations, or between the Seapoint and the Hach values, no easy calibration of the Seapoint was found. Therefore, one solution could be using the calibration curve (Figure 19), that has been set up previously, using data from the RV Belgica ST1502 and ST1507 campaigns (Van Lancker et al., 2016), during which measurements took place in sector 4b (Hinder Banken), Westhinder and an area near the Kwinte Bank. Good results were obtained during these campaigns and the correlation coefficient is in this case 0.92. The results of the regression were:

$$SPMC = 4.731 * \text{NTU} + 3.556 \tag{4}$$

The correlation and the 95% confidence limits are presented in Figure 19. This relationship is not forced through the origin and therefore indicates a minimum SPM concentration value of 3.6 mg l^{-1}.

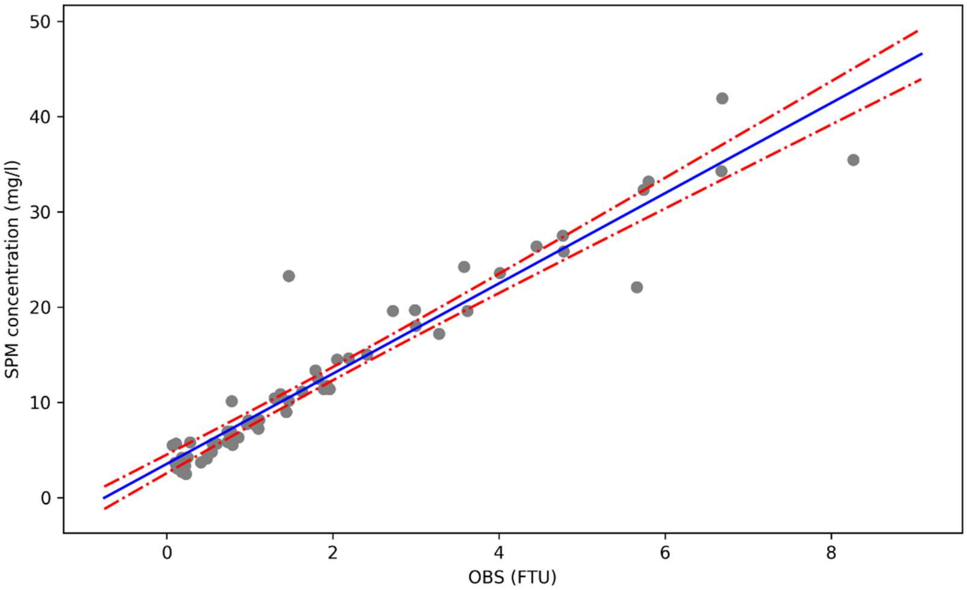

Figure 19. Calibration curve of the Seapoint OBS, using data from RV Belgica campaigns ST1502 and ST1507. A regression was fitted (black line) with the top (blue) and bottom (red) 95 % confidence intervals. Results regression: SPM = 4.7314 * NTU + 3.5599; R2 = 0.9218; 61 data points used.

Another solution could be to use regression through the origin using the actual data (Eq. 1). In Figure 20. Three profiles in OBS voltage (brown) and in SPM concentration after conversion using Equation 1 (red) or conversion using Equation 4 (blue). Left up: downward profile 1 at Oosthinder; Right up: downward profile 1 at Noordhinder; left down: downward profile 1 during the 13h cycle. Black diamond: SPM value after conversion at closure of bottle, using Equation 1: green star: SPM value after conversion at closure of bottle, using Equation 4; purple circle: SPM value of filtration on board.

Figure 20 some OBS voltage profiles and SPM profiles, after conversion, are shown for the first downward profiles during the three measurements. Also, the SPM concentration (after conversion) during the closure of the bottles is shown, together with the SPM concentration from the filtrations. The conversion using Equation 4 gives much less variation and overall lower values, although with lower OBS voltages, this conversion can give higher SPM concentrations. The error between the OBS voltages, at the moment of the closure of the bottles, converted to SPM concentration following the two equations, and the SPM concentration, as found by the filtrations is presented in Figure 21. Both the differences and the squared differences are smaller, using the Eq. 1 for converting the OBS voltages to SPM concentrations, than using the more general Eq. 4, although the differences can be quite high. Therefore, this conversion is used in the remainder of the study.

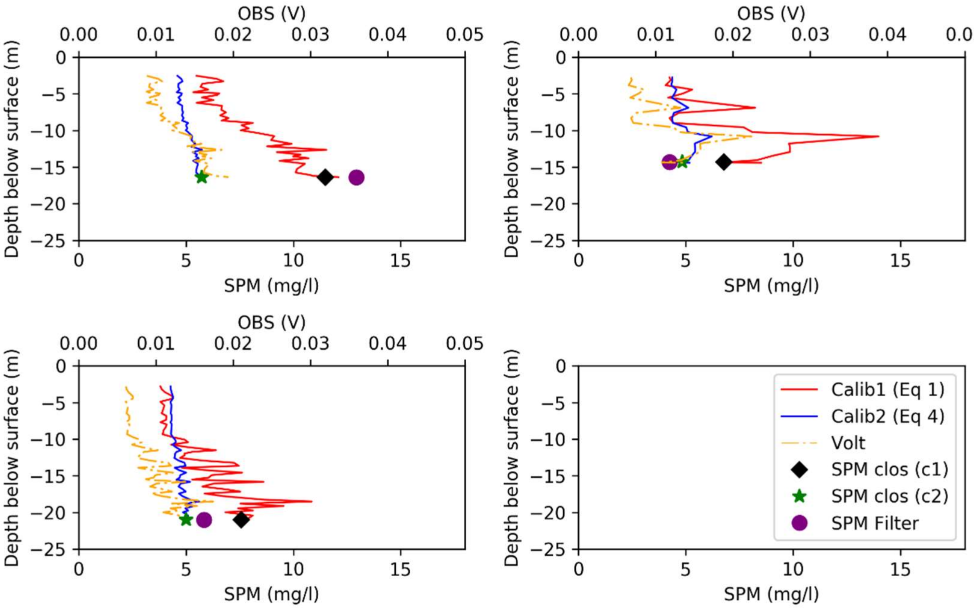

Figure 20. Three profiles in OBS voltage (brown) and in SPM concentration after conversion using Equation 1 (red) or conversion using Equation 4 (blue). Left up: downward profile 1 at Oosthinder; Right up: downward profile 1 at Noordhinder; left down: downward profile 1 during the 13h cycle. Black diamond: SPM value after conversion at closure of bottle, using Equation 1: green star: SPM value after conversion at closure of bottle, using Equation 4; purple circle: SPM value of filtration on board.

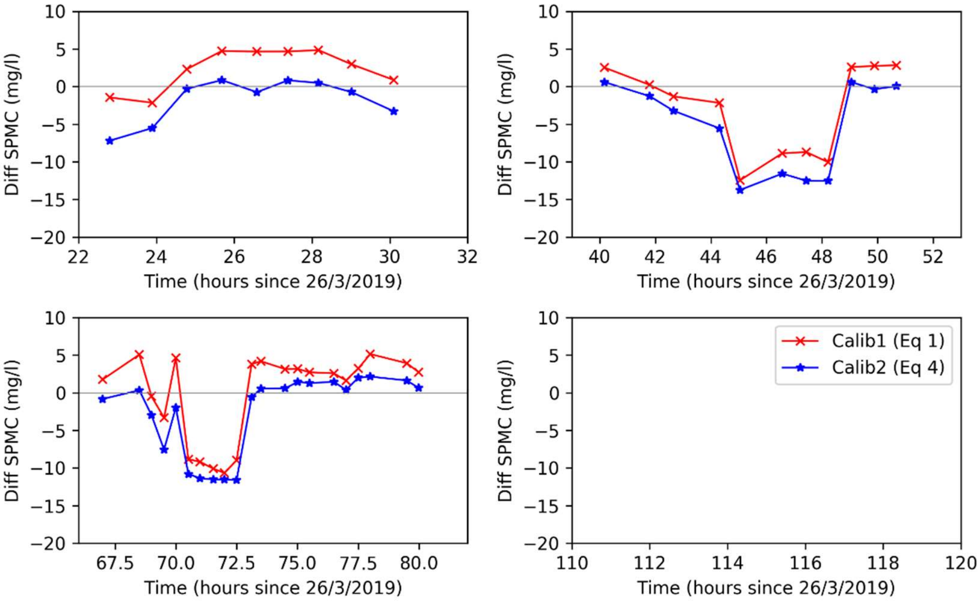

Figure 21. Difference between SPM filtrations and SPM concentration from OBS readings at the time of closure of the bottom. Positive is overestimation of the SPM from OBS sensor, compared to the filtration.

3.3. *Variation of the SPM concentration*

3.3.1. Combination of profiles

To get insight in the variation of the SPM concentration, the time series of the profiles that were taken are combined. First of all, the downward and the upward profiles are combined together to get one profile for each hour in the case of the tracks, or to get one profile for each half hour, in the case of the 13h cycle. In the first case, the two profiles at the beginning and the end of the measurement are taken. The time difference between these profiles is around 90″ or around 74″ for the tracks over Oosthinder and Noordhinder respectively. For the 13h cycle, the time difference between the downward track and the next upward track is much longer, because the CTD is held near the bottom during around 23 minutes. In this case the time difference between the upward profile and the next downward profile is much less, only around 386″, thus round 6 to 7 minutes. In this case, these two profiles are combined. Some examples of these combined profiles are shown in Figure 22.

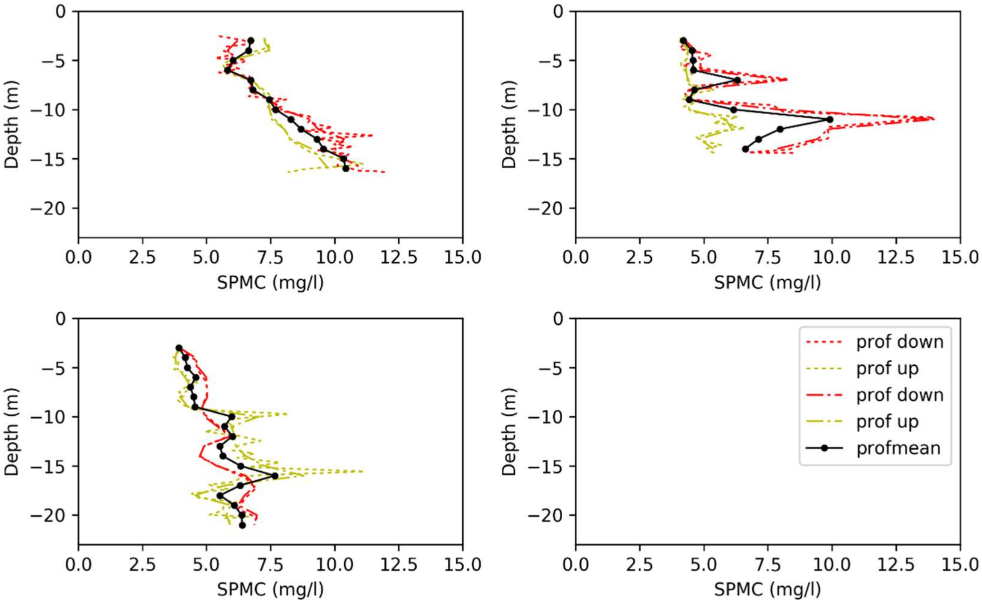

Figure 22. Sediment concentration profiles for the first profile at Oosthinder (upper left), Noordhinder (upper right) and 13h cycle (down left). Dotted lines: profiles each second; dashed: profiles averaged over 1 m (below surface); full line: average between profile up and profile down.

Although the time difference between the two profiles that are compared to each other is low, the differences can however still be important with differences up to 4 mgl^{-1} (Figure 23). However, the mean difference is close to zero and the mean absolute difference remains less than 1 mgl^{-1}, which is acceptable.

3.3.2. Overall profiles

The overall mean profile (Figure 24) shows higher concentration near the bottom than at the surface. The SPM concentrations are higher at the Oosthinder than at Noordhinder and south of Noordhinder, during the 13h cycle. However, the Oosthinder profiles are taken closer to maximum spring tide. Surprisingly, both the SPM concentration seems to decrease again near the bottom for both the measurements at Noordhinder and south of Noordhinder.

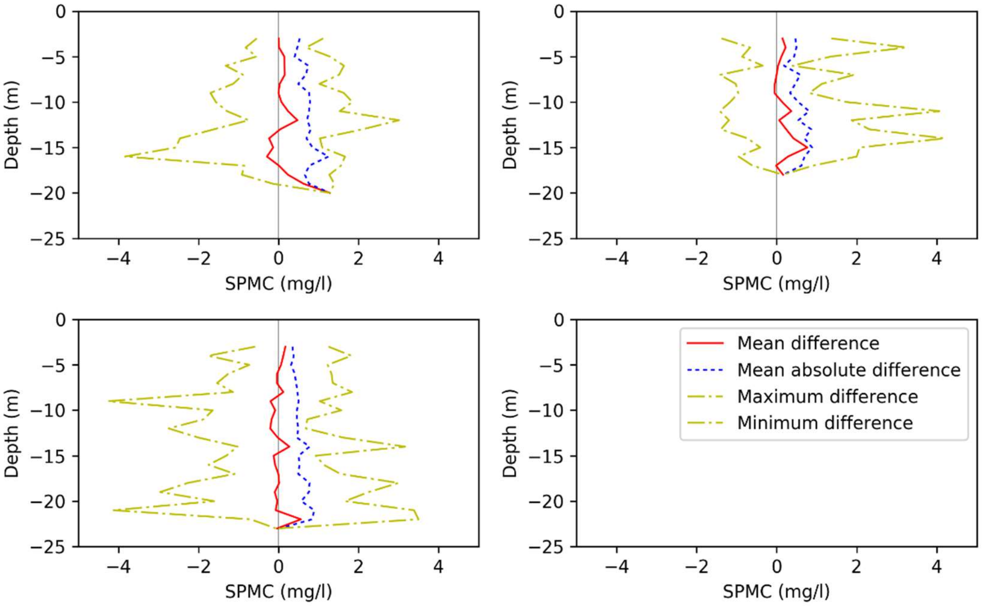

Figure 23. Mean difference in two SPM concentration profiles that are combined (red full line), mean absolute difference (blue dotted line) and minimum and maximum difference (yellow dashed line). Left upper: measurements at Oosthinder: right upper: measurements at Noordhinder; left down: measurements during 13h cycle.

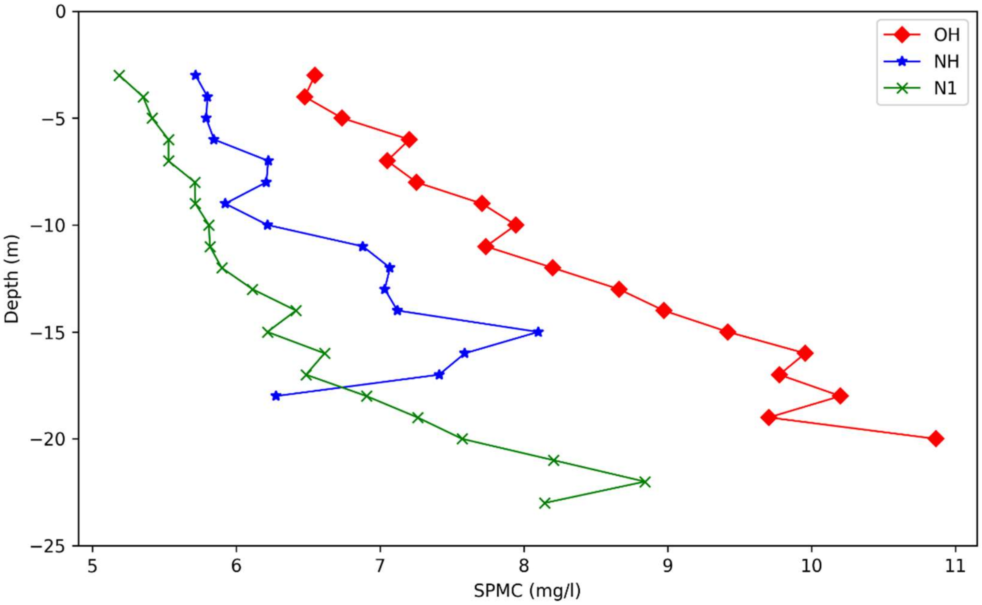

Figure 24. Overall mean SPM concentration profiles. Red: measurements at Oosthinder (OH); blue: measurements at Noordhinder (NH); green: measurements during 13h cycle (N1).

3.3.3. Variation over time and depth

To get an overall view, also the entire water column needs consideration. Since the measurements are done from the ship, the profile measurements are always with respect to the water level. To get the depth above the bottom, the total water depth is needed. The Online Data Acquisition System (ODAS) of the RV Belgica logs the total water depth. The water height during the sailing of the tracks over the Oosthinder and Noordhinder are varying over more than 20 m, from 15 m water depth, to more than 40 m. The profiles are taken on the top of the sand bank. During the measurements at Oosthinder, the water depth, during the taking of the profiles can also vary over several meters. During the 13h measurements, the RV Belgica was anchored at the same position, and the variation of the water depth is mainly due to the tides and the drift of RV Belgica.

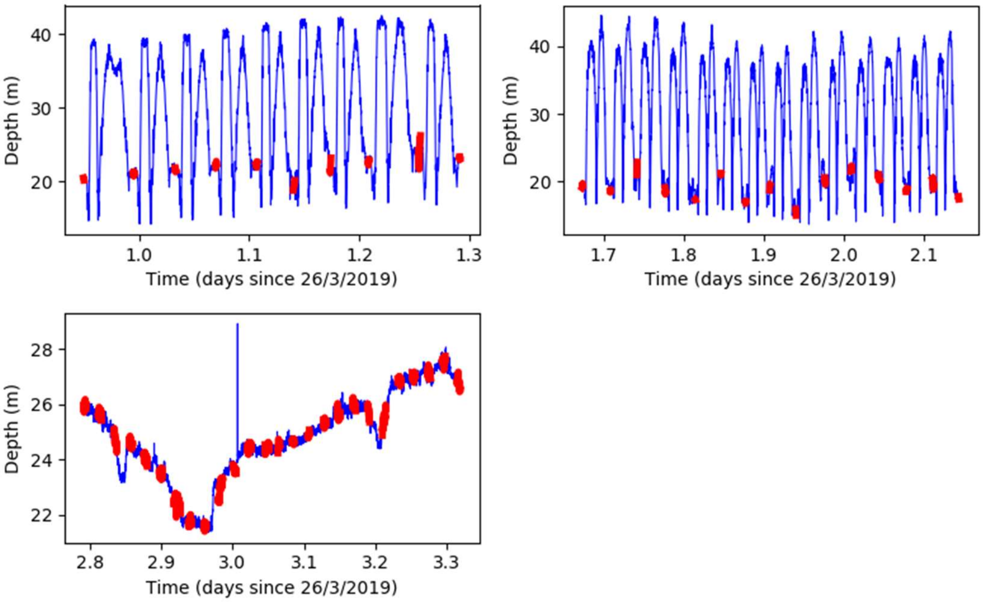

Figure 25. Total water depth during the measurement at Oosthinder (left upper), Noordhinder (right upper) and the 13h cycle, south of Noordhinder (left down). Blue curve: continuous water depth; red curve: water depth during the taking of the profiles.

The contour plots of the variation over time and depth at the three sites are shown in

Figure 26 to

Figure 28.

The measurements at Oosthinder show the highest SPM concentrations, with higher concentrations near the bottom at high tide up to more than 13 mg/l. During low tide, the concentration decreases, certainly at the bottom.

The measurements at Noordhinder are not very clear, and it is not clear from the total water depth, when the measurements at high tide and low tide are taken. This is mainly due to the fact that the measurements were not taken exactly at the same position. One can expect that the high tide is around profile 14, when the SPM concentrations are clearly higher, certainly at the bottom.

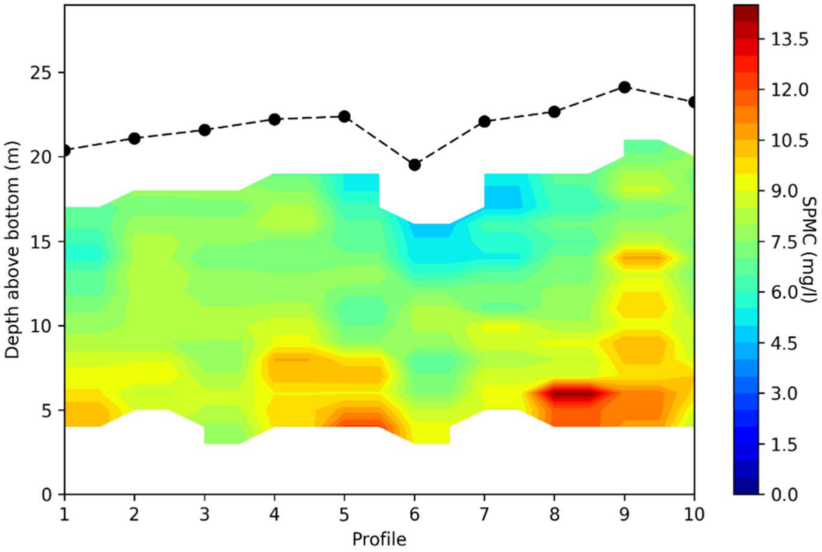

Figure 26. Variation of SPM concentration over depth and time at station Oosthinder. Time between the different profiles is approximate 1 hour. The black line is the indication of the water depth.

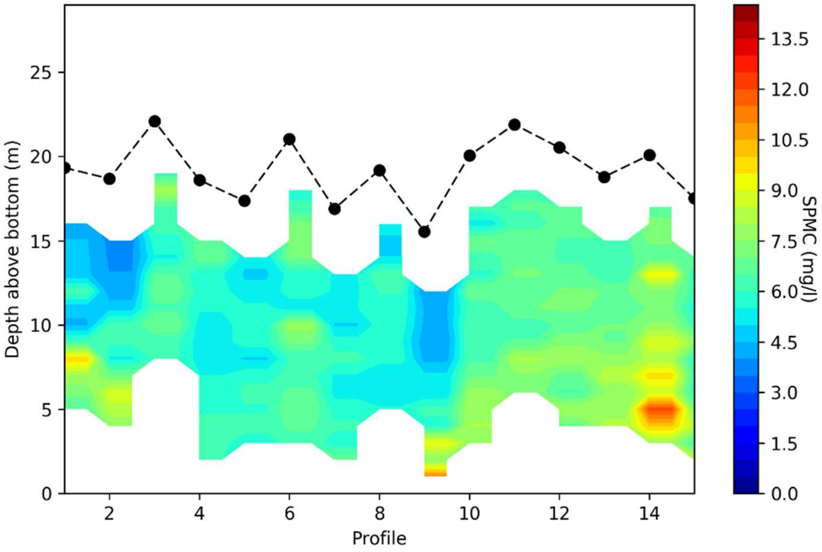

Figure 27. Variation of SPM concentration over depth and time at station Noordhinder. Time between the different profiles is approximate 1 hour. The black line is the indication of the water depth.

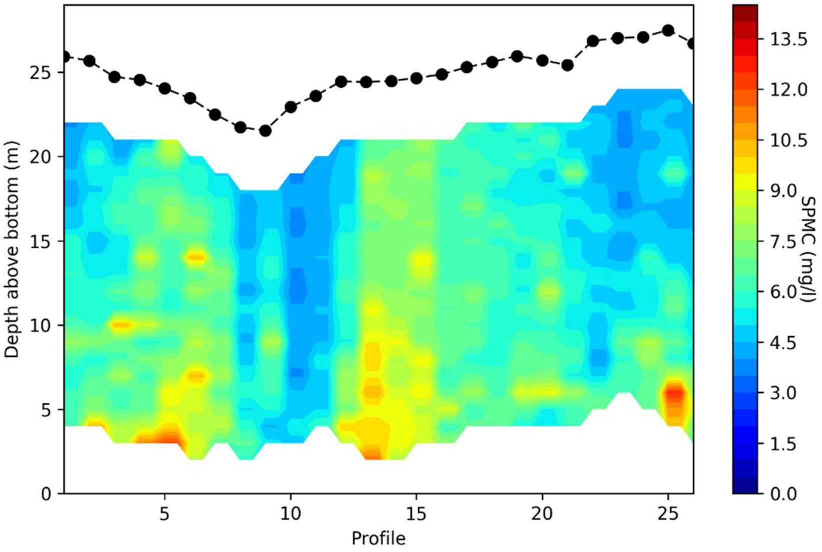

Figure 28. Variation of SPM concentration over depth and time during 13h cycle south of Noordhinder. Time between the different profiles is approximate 0.5 hour. The black line is the indication of the water depth.

The measurements during the 13h cycle show profiles each half hour and are more detailed. These measurements are taken almost at the same position and the high water and low water tides are clearly visible in the total water depth. During low tide, the concentration is clearly lower, with more constant concentration over the water column. During high water the concentration near the bottom is the highest, but surprisingly with a stronger gradient, and with lower SPM concentrations near the water surface.

3.3.4. Extrapolation of SPM concentration profiles

During oceanographic profiling, the SPM concentration near the surface is not considered, due to spikes and disturbances of the measurements. Also, near the bottom, no data are available, due to the fact that the equipment may not risk hitting the bottom, where it could be damaged. To get more information, certainly at the bottom, the profiles can be extrapolated by fitting the data to a SPM concentration profile.

The well-known Rouse profile is based on an equilibrium between fall velocity and diffusion, with an eddy diffusivity which is assumed to vary parabolically with the height. The Van Rijn (1984) profile on the other hand, assumes that the eddy diffusivity varies parabolically in the lower half of the water column, but that it is constant in the upper half of the water column. He obtains the following profile:

$$c(z) = c_a \left[\frac{z}{z_a}\frac{(h-z_a)}{(h-z)}\right]^{-\beta} \qquad \text{for } z_a < \mathrm{z} < \frac{h}{2} \qquad (5)$$

$$c(z) = c_a \left[\frac{z_a}{(h-z_a)}\right]^{\beta}.\exp\left[-4\beta\left(\frac{z}{h}-\frac{1}{2}\right)\right] \qquad \text{for } \frac{h}{2} < \mathrm{z} < \mathrm{h}$$

with	$c(z)$	SPM concentration as a function of depth
	z	depth above the sea bottom
	z_a	reference height near the sea bed at which height the reference concentration c_a is calculated
	c_a	reference concentration
	h	total water depth
	β	Rouse parameter or suspension parameter = $w_s/\kappa u_*$
	w_s	fall velocity
	κ	Von Karman's constant (=0.40)
	u_*	shear velocity or friction velocity

Soulsby (1997) argues that the Van Rijn profiles are more suitable to be used at sea, since the Rouse profile results in a prediction of zero sediment concentration near the surface, which is in contradiction with observations, especially when waves are present. The Van Rijn profile probably best corresponds to data. This profile is therefore used to extrapolate the data.

The agreement between the data and the Van Rijn profile is good. The Goodness-of-Fit Q (Press et al., 1992) is for all profiles near 1. The agreement is good for both profiles that have a very low gradient, as for profiles having a high gradient (Figure 29).

Vi

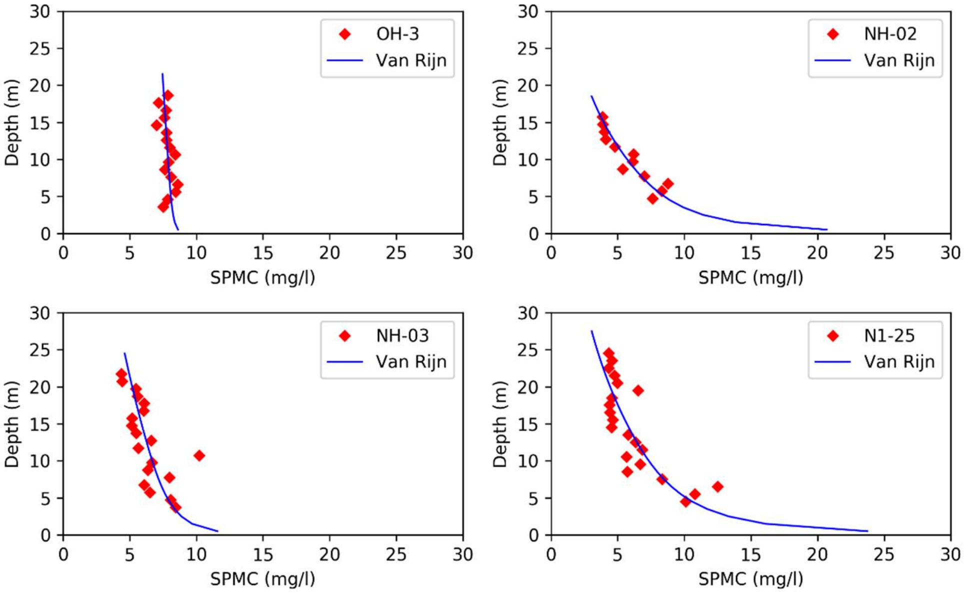

Figure 29. Examples of the fitting of the data with a Van Rijn (1984) SPM concentration profile.

The variation of the reference concentration near the bottom and the Rouse parameter, being an indication of the gradient in the SPM concentration, is relatively similar, indicating that the low gradient profiles are occurring for low concentrations near the bottom, while higher gradients are occurring for higher reference concentrations (Figure

30). The reference concentration at 0.1 m above the bottom is varying between 5 mg/l to up to 40 mg/l. The Rouse parameter varies between less than zero to almost 0.4. in these figures, a clear tidal cycle is apparent. This has to be confirmed by model results.

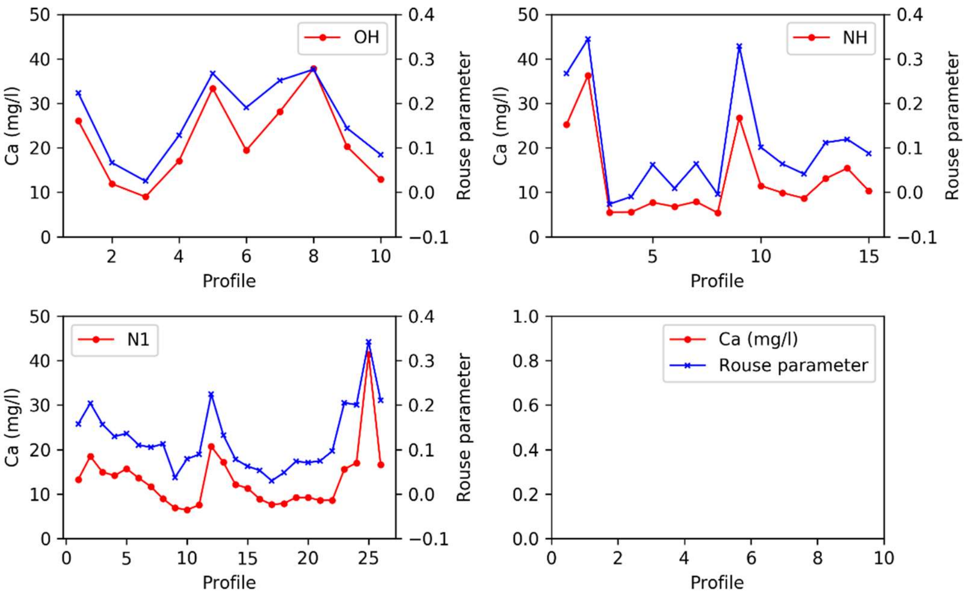

Figure 30. Variation of reference concentration at 0.1 m above the bottom and of the Rouse parameters at the different locations.

The final contour plots with the variation of the SPM concentration over time and over the depth, after smoothing out and extrapolation by using the Van Rijn profile are given in Figure 31 to Figure 33. The plots are smoother and have higher concentrations near the bottom, due to the extrapolation.

Due to the changing position (Figure 34), the total water depth is changing as well, mainly influencing the total water depth at the Noordhinder. For the quasi stationary measurements during the 13h cycle, the drift of RV Belgica, is clearly visible around the anchor position. For the track measurements, the position of the profiles can differ more, influencing also the total water depth.

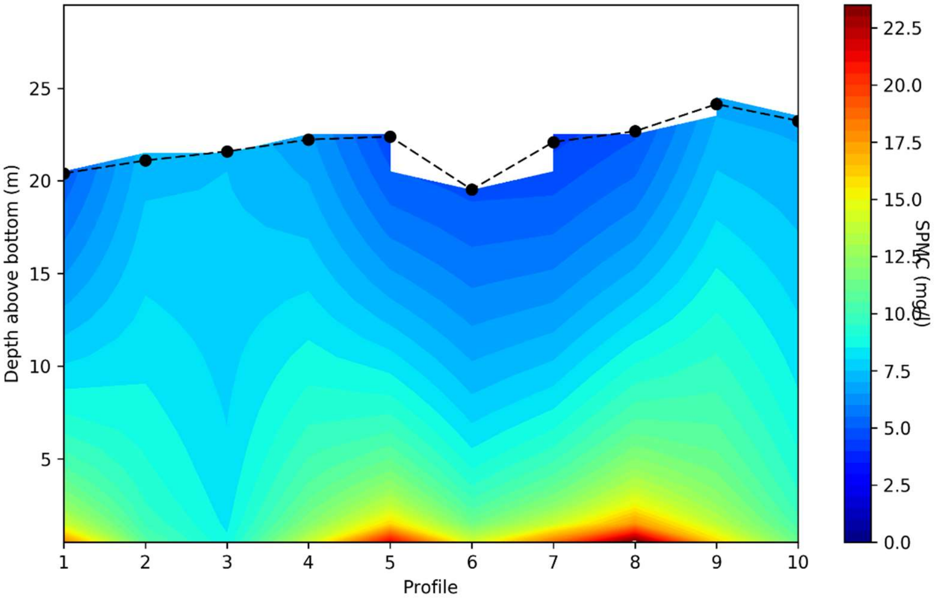

Figure 31. Variation of SPM concentration over depth and time at station Oosthinder. Time between the different profiles is approximate 1 hour. The black line is the indication of the water depth.

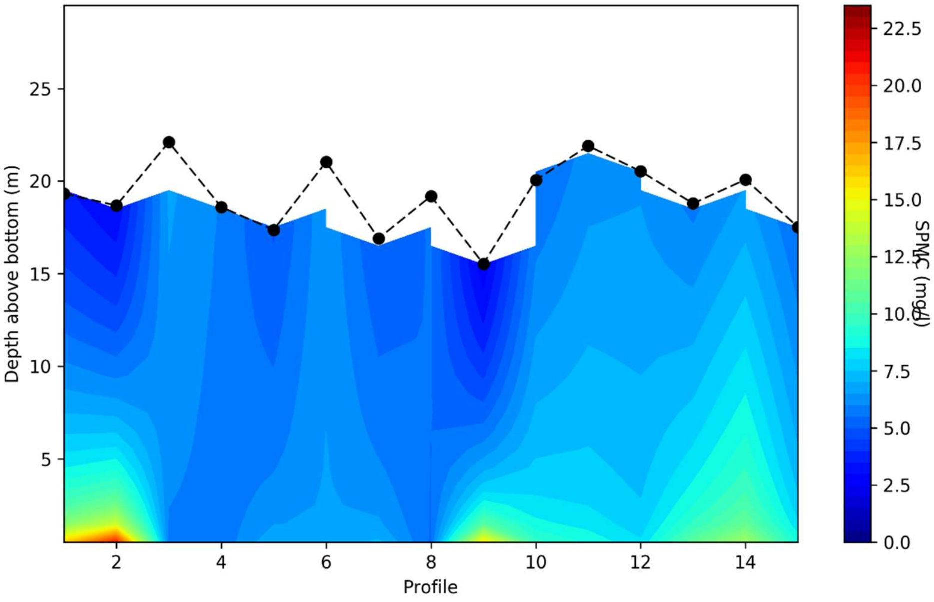

Figure 32. Variation of SPM concentration over depth and time at station Noordhinder. Time between the different profiles is approximate 1 hour. The black line is the indication of the water depth.

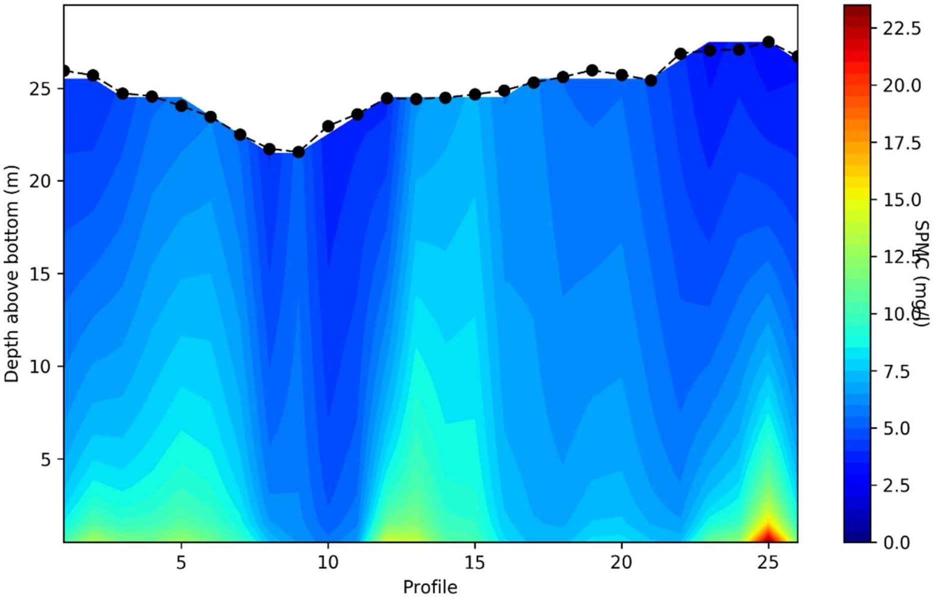

Figure 33. Variation of SPM concentration over depth and time during 13h cycle south of Noordhinder. Time between the different profiles is approximate 0.5 hour. The black line is the indication of the water depth.

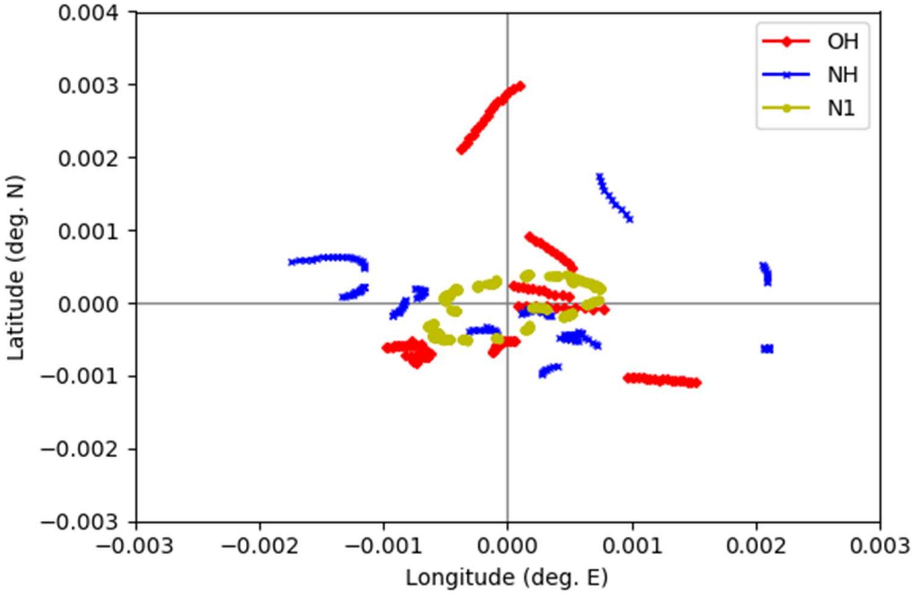

Figure 34. Variation of position around the central position of the measurements for the three locations.

4. Conclusions

In the present report, the CTD and OBS measurements taken during RV Belgica campaign 2019/09 were analysed. A cross-bank trackline was sailed over the Oosthinder, while taking profiles over the water column and taking water samples at the top of the sand bank each hour. Similar measurements were taken when sailing cross-bank tracklines over the Noordhinder. Finally, a 13-hour measurement cycle was measured at a position south of the extraction zone 4a, Noordhinder sandbank. Here, profiles and water samples were taken each half hour.

To calibrate the OBS Seapoint sensor, water samples were taken that were filtered on board of RV Belgica, and measurements were taken with a Hach turbidimeter as well. Unfortunately, no good correlation was found, both between the OBS sensor readings and the SPM filtrations, and between the Hach turbidities and the SPM filtrations. Therefore, no good calibration could be set up between the Seapoint measurements and the SPM concentrations in the water column. Furthermore, the datasets in the offshore Hinder Banks with lower SPM concentrations in the water column, showed that the stable relationship between the Hach turbidity results and the SPM concentrations, as put forward by Fettweis et al. (2019), was not really applicable. The same conclusion was drawn for the relationship that was found by Van Lancker et al. (2016) between the Hach turbidity results and the SPM concentration. Finally, a relationship based on a linear regression, forced through the origin, was used to convert the OBS Seapoint voltages to SPM concentrations.

Final results show a clear variation of the SPM concentration over the water depth and over the tide, with higher concentrations near the bottom and during high water. The overall concentrations seem higher than expected. Data are extrapolated to the sea bottom, using the Van Rijn profile. Results show a clear tidal cycle variation with concentrations up to almost 40 mg/l at 0.1 m above the bottom. The highest concentrations are found at the Oosthinder, although the measurements at the Noordhinder were made in shallower water conditions. However, it is not clear yet whether this is due the timing of the measurements of the Oosthinder profiles taken closer to maximum Spring tide, or whether a higher turbidity characterizes this sandbank.

5. Acknowledgments

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COLOPHON

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