Variability of suspended particles properties in Pärnu Bay, Baltic Sea

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Introduction

Standard remote sensing algorithms for water quality parameter retrieval perform well in clear waters (Matthews, 2011) where phytoplankton biomass (usually expressed as concentration of chlorophyll-a, Chl-a) determines the remote sensing signal. Colored dissolved organic matter (CDOM) and suspended particulate matter (SPM) are phytoplankton degradation products and in good correlation with Chl-a. The algorithms usually do not perform well in optically complex coastal and inland waters where the concentrations of optically active substances (Chl-a, SPM, CDOM) vary in wide range and independently from each other and there is no wavelength where only one of the substances affects the water color.

SPM is composed of mineral and organic particles and it scatters light in different directions. It's presence in the water increases the values of the reflectance (> 550 nm) measured by the satellites. More there are particles in the water, higher are the values of the reflectance. It is possible to compute the SPM concentrations using the reflectance spectra but it is not easy. Several factors need to be taken in account: SPM capacity to scatter and backscatter the light, the particles properties like size, shape and nature. Backscattering is difficult to measure in situ, that is why the backscattering ratio bb/b (backscattering/scattering) is used in remote sensing algorithms and it is often taken as constant. Kirk (1981) shows that in most moderately turbid coastal waters the value of 0.019 is valid. In fact, this parameter depends clearly on suspended particles properties like size and shape (Aas et al., 2005). The bigger the ratio, the smaller are the particles. As these properties vary due to composition and flocculation phenomena, the backscattering ratio also changes and is wavelength dependent (Ma et al., 2009). All these parameters need to be studied to understand better how SPM influences the satellite signal.

Study area

There are no previous detailed research about the SPM properties in Estonian coastal waters. The Pärnu Bay is a good place to study particulate matter as there are both, particle flux from the Pärnu River and often lot of resuspension of sediments from the sea bottom due to winds. Pärnu Bay is also one of the three locations belonging to frequent monitoring sites. Thus, there is more data available from this region.

Pärnu Bay is located in the west coast of Estonia and is part of the Baltic Sea (Figure 1). Irregular water level rises and salinity fluctuations are due to its position and location. The mean depth of the bay is 4.7 m (biggest 8 m), salinity is 3-5 psu and current speed is 4-11 cm/s (max 90 cm/s). The bottom of the bay contains fine sand (diameter of >0.063 mm), clay and mud (diameter <0.063 mm) (Kartau *et al.*, 2011), but also some rocky areas. Inflow from the Pärnu River (144 km long, mean discharge 64 m^3/s, catchment area 6920 km2 - biggest in Estonia) and wind derived resuspension of the shallow bottom sediments result in constant higher values of suspended particles in the water column. The quality of water is influenced by the nearby city of Pärnu with 40 000 inhabitants.

Methodology and data

a. In situ optical data

The *in situ* data was collected during four field campaigns in Pärnu Bay (July 2017; April, May and August 2018). A bio-optical package containing WET Labs AC-S, ECO-BB3, ECO-VSF and CTD was used to measure optical properties of the water. AC-S measured spectral absorption and attenuation coefficients of light from which scattering spectra can be calculated. ECO-BB3 and ECO-VSF 3 measured backscattering of light together in 4 angles and 6 wavelengths. VanVeen grab sampler was used to sample and analyze the bottom sediment composition. The WET Labs package data was corrected according to product manuals (ac Meter Protocol Document, ECO-VSF 3 User's Guide, Eco-BB9 User's Guide, Wetlabs). AC-S data was blank corrected, then salinity and temperature corrected and finally scattering corrected. ECO-BB3 and ECO-VSF data was corrected using total absorption data.

b. In situ and laboratory particle characteristics data

A particle size sensor LISST-100X was included in the package during the August 2018 cruise. LISST-100X uses laser diffraction to measure particle size distributions between 2.5 and 500 μm, volume concentrations and attenuation coefficient. In August, it was used to measure particle size distribution profiles and was stabilized under the surface and near the bottom in each station. Only the data from stabilized moments was used to get the normalized volume concentrations to each of the 32 size classes. LISST-100X was also deployed in laboratory setup to analyze particle size distribution after the treatment of the water samples (surface and near bottom) in the ultrasound bath to see if the particles were flocculated. Samples were also extracted from the bottom and analyzed in the laboratory. Two last size classes were not used to calculate the normalized volume concentrations.

Water samples were collected from the surface layer. Suspended matter analyses, including organic/inorganic proportion, were conducted in the lab (ESS, 1993). Samples were collected in August 2018 cruise near the bottom and analyzed the same way.

c. Satellite data

Satellite S3 OLCI sensor data was used to study the suspended particulate matter (SPM) concentration dynamics in Pärnu Bay. To calculate the resuspended particle concentrations, optical water type based SPM algorithms application method was used (Uudeberg et al., 2017). Optical water types classification was based on Reinart et al., 2003 classification that uses optically active substance concentrations which are linked with reflectance spectra features. C2RCC processor was applied to all 2017 and 2018 cloud and ice free Sentinel-3 sensor OLCI L1 images to retrieve water reflectance spectra. Using these spectra, optical water types (Clear, Moderate, Turbid, Very Turbid and Brown) were assigned to all water pixels. The pixel stayed unclassified, if it was statistically too different from the known water types. After the classification, the SPM algorithms described by Kõks (2018) were applied.

Results and discussion

a. Variability of the SPM concentration dynamics

The study showed that three states exist in the Pärnu Bay : 1) dry and calm period when the concentrations in the middle of the bay were low and values near the shore were three times higher (May 2018); 2) raining and snow-melting period, when the concentrations were high near the river mouth and the sediment plume was clearly limited (April 2018); 3) storm period (winds > 11 m/s) when the concentrations were very high everywhere in the bay because of the mixing of the water mass by waves (August 2018). To present rapid changes in Pärnu Bay, the example of the last situation, influenced by the 22 June 2018 storm – wind close to 21 m/s – is shown on Figure 2. It was similar to the event seen during the August 2018 measurement campaign, but no cloud-free images are available from this period. The variability of optical water types show that the optical properties of the water column are also different and they vay both in time and space. This is one reason why the use of only one algorithm does not give good results. It was also seen that the situation changed fast and in 5 days the concentrations of SPM were as low as 5 days before the storm. These kind of fluctuations are impossible to monitor with traditional in situ measurement campaigns and can be well monitored only by remote sensing in cloud-free conditions.

b. Variability of the sediment nature

The sediment samples analyses of the August 2018 campaign are shown on Figure 3. The bottom was composed of fine grained anoxic black mud in the Pärnu River (S) and close to the river mouth (M). The south-eastern side of the bay was sandy, with coarse sand in the dredged sediment disposal area (P2) and fine sand more in the south (station K4). The bottom was covered with brownish clay mud in K5, in the trajectory of the river discharge, and K21, at the exit of the bay. Only gravels could be extracted in station K7. The variability of the bottom cover indicates that the resuspended sediment sizes vary at large scale. There are large quantities of fine grained (< 63 µm) clay. If they are resuspended, the particles stay in water column longer than sand.

c. Particle size distributions

In situ particle size distribution measurements were conducted the day after a strong west wind influence which had brought material from the Baltic Sea into the Pärnu Bay and had mixed intensely the water mass. Because of this, in situ particle size distributions and volume concentrations were similar in surface and in bottom layers (Figure 4). Particle size distributions show three cases. The fine (< 50 µm) and coarse (>200 µm) particles are dominating the particles size distribution in stations K21 and K7 that are located near the bay's exit. The spectra of these two stations are similar because of the influence of the Baltic Sea water mass entrance. The particles were evenly distributed in all size classes with a little increase of volume concentration between 100 to 200 µm in stations K5 and P2. The same is seen in K4, but with higher concentrations of fine particles of 50 µm. The only place, where there was a difference between the surface and the bottom measurements, was inside the river (S). The particles were evenly distributed in all size classes in the bottom layer and fine particles with large particles dominated the size distribution in the surface layer. The volume concentration of the particles bigger than 200 µm was high even above the muddy bottom. That indicates that fine single particles may have agglomerated into bigger flocs. The laboratory experiment confirms that, as after deflocculating in ultrasound bath, the volume concentrations of the particles from 8 to 20 µm were highest and the particles between 20 and 200 µm were absent.

d. Variability of the backscattering ratio

The backscattering ratios are influenced by the particles properties, like size, shape and nature. They were calculated from the data collected during three field-campaigns, June 2017, April and May 2018. The August scattering and backscattering data was not analyzed yet. The backscattering ratios show high variability between stations and within the stations during different measurement periods, as it is demonstrated by the river mouth station M (Figure 5). The backscattering ratio varies also spectrally being especially high between 400 nm (0.01) and 600 nm (0.038) in station K7. As seen above, the single fine particles may agglomerate into bigger flocs, which have different random shapes. The bigger size of flocs influences light scattering and backscattering differently than in the case of single particles. In remote sensing algorithms, the backscattering ratio is often taken as a constant because it is difficult to measure.

Therefore, the situation in coastal waters is more complex and the particles properties, scattering and backscattering phenomena need to be taken into account to generate working algorithms for complex waters.

Conclusions

The suspended particulate matter concentration dynamics and characteristics vary strongly in both time and space, in Pärnu Bay. Traditional *in situ* measurements don't cover all the variability and dynamics, extreme events can stay out of attention. This is when remote sensing becomes a great tool to accompany *in situ* measurements. A novel method of SPM concentration calculation using optical watertype based SPM algorithms was used to map rapid fluctuations of the suspended particles dynamics by Sentinel-3 OLCI imagery near-by the 22th June 2018 storm. The situation changed already in couple of days.

To use the satellite data correctly in complex waters (coastal areas, river mouths), optically active substances need to be studied in detail. This study focused on the variability of the backscattering ratio and the size distributions of suspended particles. The backscattering ratio varied spectrally but it was also different during various seasons for one station. This showed clearly that this parameter can't be used as a constant in remote sensing algorithms. The backscattering ratio can be linked to the particle size. There were no differences between bottom and surface layer of the water column after the particle size distribution measurements because of the mixing of the water column by waves. Therefore particles of all size classes between 2.5 and 250 μm were present (single particles and flocs). The bottom sampling also indicated the difference of the nature and the composition of the particles, which means that other particle size distribution measurements need to be carried out during different situations (snow-melting, raining, dry period).

The next step of this study is to correlate backscattering ratios with particle size distributions.

Also, the collection of particle size distribution, scattering and backscattering data has to be continued. Finally, the particles shape needs to be measured by other technics based on image analysis. All this helps to generate methods to retrieve more valid satellite products for optically complex coastal waters.

Acknowledgments

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Figures

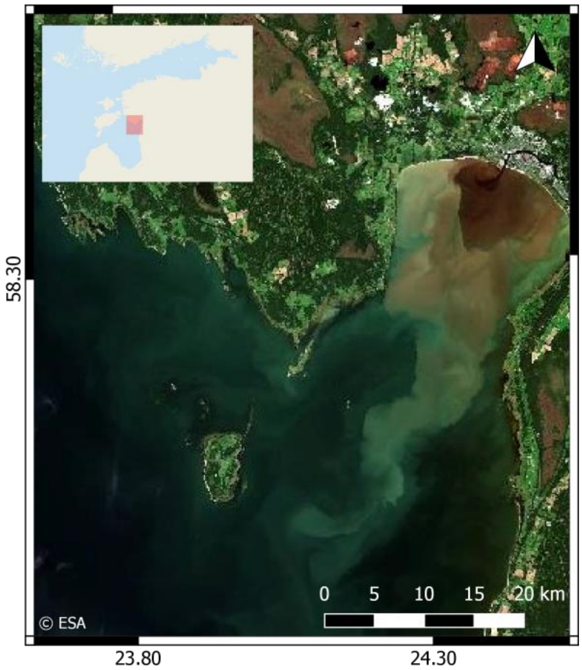

Figure 1: Location of the Pärnu Bay, Baltic Sea, on Sentinel-2 MSI 28.08.2016 satellite image.

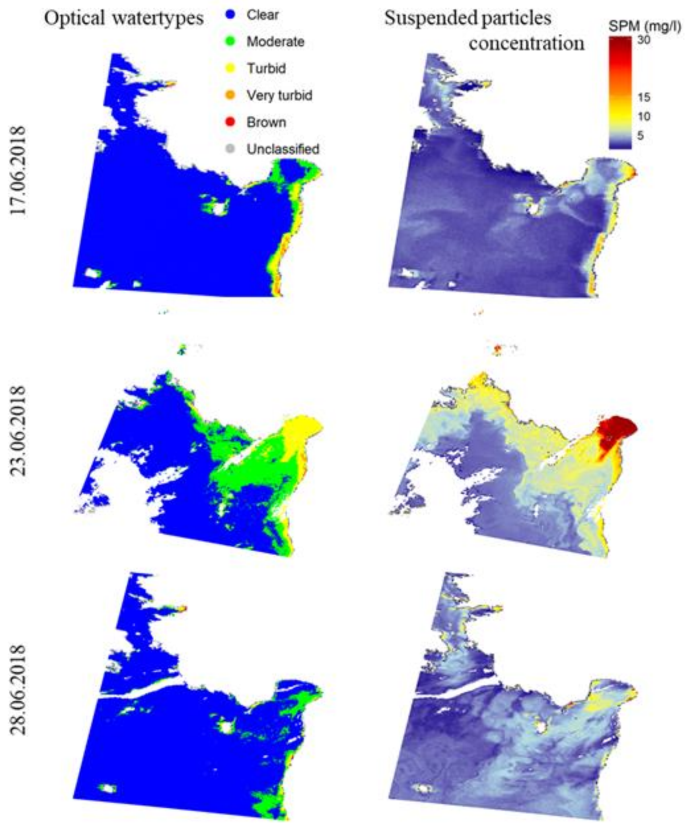

Figure 2: Optical water types (left) and suspended particles concentrations (right) variation before and after the 22.06.2018 storm in Pärnu Bay, Baltic Sea (Sentinel-3 OLCI images).

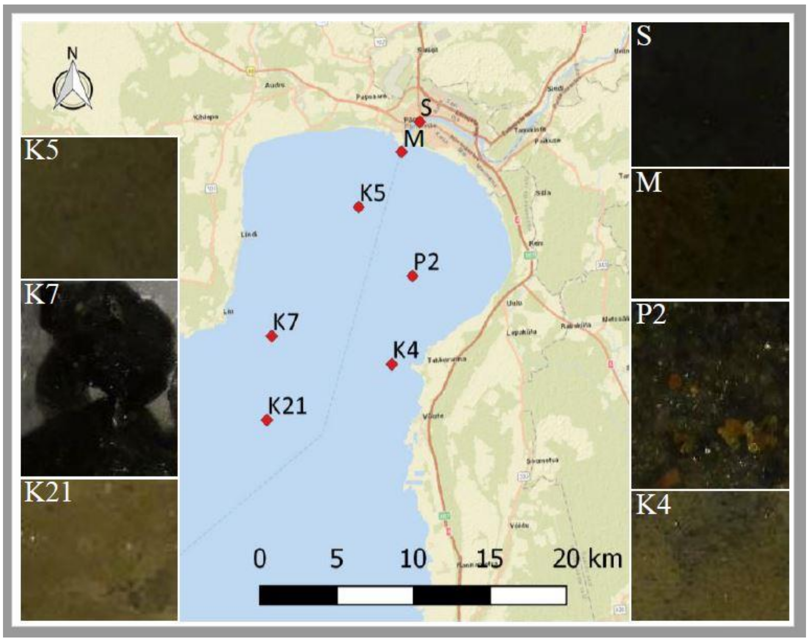

Figure 3: The map of bottom sediment distribution in Pärnu Bay, Baltic Sea, 28.08.2018. S, M, K5 and K21 are composed of fine mud, P2 of coarse sand, K4 of fine sand and K7 of gravels.

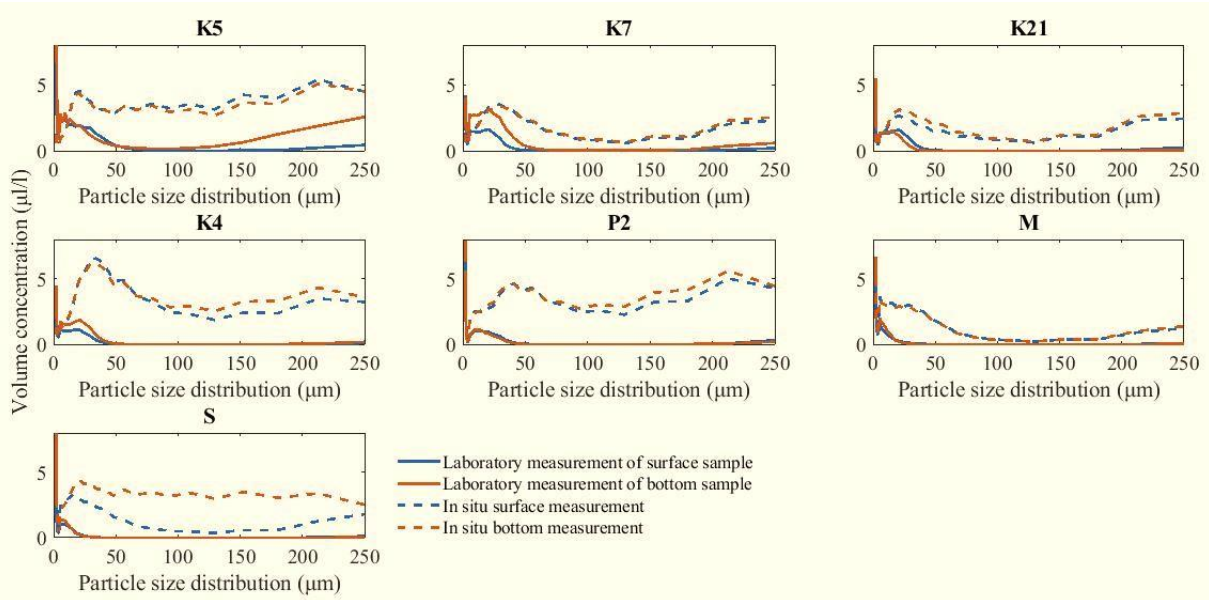

Figure 4: Particle size distribution measured from surface and bottom layer *in situ* and in laboratory on 28.08.2018 in 7 stations of the Pärnu Bay, Baltic Sea.

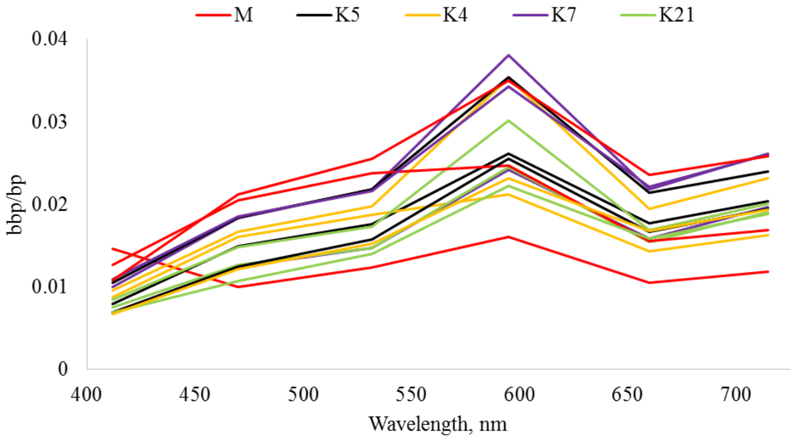

Figure 5: The variability of the backscattering ratio, dependent on wavelength, in five stations of Pärnu Bay, Baltic Sea, measured during 3 field campaigns (July 2017, April and May 2018).