Seasonal variability of suspended particulate matter observed from SeaWiFS images near the Belgian coast

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Suspended Particulate Matter (SPM) surface concentration maps in the Belgian/Dutch coastal zone are retrieved from SeaWiFS images and are corrected using in situ measurements to obtain depth-averaged SPM concentration maps. A spatial correlation analysis of the derived maps shows that the area could be divided into three sub-regions where the correlations between the SPM concentrations are higher than 70%. Examination of in situ SPM concentration measurements reveals that during about 1/3 of the tidal cycle the SPM concentration is significantly higher than during the rest of the cycle. Strong vertical gradients are sometimes observed during periods with increased SPM concentration. A satellite image taken during such a period would underestimate the depth-averaged SPM concentration. Images taken during other periods better represents (except for some small corrections) the averaged SPM concentration. The methodology for obtaining the depth-averaged SPM concentration maps from surface SPM distributions derived from SeaWiFS images is positive but can be further improved.

1. INTRODUCTION

Near the Belgian coast (Southern Bight of the North Sea, see Fig. 1), the harbours and navigation channels are situated in a high turbidity zone. Suspended Particulate
Matter (SPM) concentrations of up to a few hundred mg/l are common, resulting in very high deposition of fine sediments (mainly mud). To maintain access for ships, more than 10 million tons of dry matter are dredged on average every year. In the harbour of Zeebrugge the sedimentation rate is estimated at 3.8 ton/m²/year, which corresponds to about 2.9 m/year when assuming a density of 1.3 ton/m³ (Van Lancker et al., 2003). Knowledge of suspended sediment processes in the Belgian coastal zone is therefore needed to provide a sustainable management of the dredging and dumping activities.

The influence of tides and the neap-spring tidal cycle on the distribution of mud on the bottom and in suspension and the different sources of fine-grained matter in the area are discussed in Fettweis and Van den Eynde (2003) using numerical model results and field measurements. However, the development of a regional cohesive sediment transport model is -- besides the difficulty of incorporating a detailed description of all processes -- limited by the lack of field data. Very often the available data consist of measurements in one or several points during a limited time (a tidal cycle to a few
days). These point measurements usually show time series of SPM concentration in the vertical direction. They cannot provide horizontal information, which is especially important in high turbidity zones, where multiple sources of SPM may exist and where the SPM concentration can vary on a small spatial scale. The main source of SPM in the Belgian-Dutch coastal area is the import through the Strait of Dover. A minor source comes from the erosion of tertiary clay layers and Holocene mud deposits. The Westerschelde estuary is not an important source of mud. It may act as a sink as well as a source.

The use of optical remote sensing methods to produce SPM concentration maps benefits from the satellite capabilities to picture wide areas and provide synoptic views of SPM concentration distribution. The disadvantages are (1) they provide only data of the surface layer during cloud-free daytime, (2) the correction algorithms (section 2.1) tend to saturate at high SPM concentrations and reflectance levels, and (3) the time resolution is low (1-2 per day) (Van der Woerd et al., 2000). In the current study a method is presented in which in situ measurements and satellite images of SPM concentrations are combined to obtain information on the total cohesive sediment distribution at a long time (season) and large horizontal scale. The incorporation of the in situ measured tidal variation of SPM concentration is the innovative part in this process to obtain satellite based total SPM concentration maps.

The objective of the paper is to show the results of a study on SPM concentration distribution in the Belgian-Dutch coastal zone using Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite images and in situ measurements. The results can be seen as an important part in developing a sediment transport modelling system which can be used to evaluate the efficiency or the environmental impact of dumping operations.

2. SPM CONCENTRATION MAPPING FROM SEAWIFS IMAGES

2.1. Calculation of SPM concentration

In this study 370 SeaWiFS images were collected over the Belgian Coastal Zone (BCZ) from October 1997 to March 2004. Among these images, 172 scenes are entirely cloud-free over the BCZ. Most of the 370 images have been corrupted by less than 30% of clouds which were flagged during the processing of SPM concentration maps.

The SeaWiFS imagery used is the Top Of Atmosphere (TOA) radiance measured at the sensor level. Processing is needed to calculate the SPM concentration at the water surface. First the various atmospheric contributions to the TOA radiance, i.e., light scattering by air molecules and aerosols, absorption by oxygen and ozone and the sky
glint, have to be removed to produce the reflectance at the sea level $\rho_w$. This was carried out using the SeaDAS software algorithm extended to turbid waters. The description of this algorithm is beyond the scope of the present paper, but can be found in Ruddick et al. (2000).

Next, a hydro-optical model (Eq. 1, given by Nechad et al., 2003), designed for Belgian waters is used to convert $\rho_w$ into SPM surface concentrations $c_{surf}$:

$$c_{surf} = a_1 \frac{\rho_w}{0.187 - \rho_w} + a_2$$

where $a_1$ and $a_2$ are calibration parameters determined by a nonlinear regression analysis. The calibration of these parameters is carried out using 57 in situ reflectance spectra, measured by three Trios spectro-radiometers, and simultaneous in situ SPM concentration measurements. The calibration shows that the best results are obtained with the reflectance at band 670 nm $\rho_w^{670}$ and with $a_1$ and $a_2$ set equal to 102.3 and 3.85 mg/l respectively.

The relationship between $c_{surf}$ and $\rho_w^{670}$ has been further validated using 1021 in situ SPM concentration observations in the Southern North Sea from 1997 to 2003. The data were obtained from the Belgian Marine Data Centre (http://www.mumm.ac.be/datacentre). A grid with a horizontal resolution of 1.13 x 1.13 km², i.e., the resolution of the SeaWiFS image, is defined. In situ data are available in 38 cells of the grid. All data available in a single cell are used to compute a mean value for that cell. For the same cells, all data derived from the 370 SeaWiFS images are processed in the same way. This time-averaging is necessary since, due to the high temporal variability, the small time lag between the in situ data and the satellite-derived SPM concentration affects significantly the correlation. Comparison between both data sets indicates a high correlation of 81%.

Finally the Environment for Vizualizing Images (ENVI) software is used to georeference the $\rho_w$ images. All satellite images were projected to the defined grid of 1.13 x 1.13 km².

### 2.2. SeaWiFS derived surface SPM maps

All SeaWiFS data are then used to derive SPM concentration maps (Fig. 2). The SPM average concentration map in Fig. 2a shows concentrations from 20 to 100 mg/l in the narrow 20 km band along the Belgian coast. These average concentrations do not exceed 60 mg/l except in the small area located to the south west of Zeebrugge (ZB) towards Oostende (OS). In this area, the SPM median concentration value ranges from
Fig 2. SeaWiFS derived surface SPM concentration maps from October 1997 to March 2004. (a) average of 370 images, (b) the median surface SPM concentrations, (c) the standard deviation of the surface SPM concentrations and (d) the maximum surface SPM concentrations.
40 to 100 mg/l (Fig. 2b) and high SPM concentration standard deviations are noted (Fig. 2c) close to the coast which indicates that this is a turbid area with high temporal variations.

The area located near the mouth of the Westerschelde estuary has average values of SPM concentrations between 20 to 60 mg/l; the median values do not exceed 40 mg/l and the standard deviation ranges from 20 to 30 mg/l. This indicates that these waters are less turbid than in the area between Zeebrugge and Oostende and that it has less temporal variation.

The most homogeneous area with the lowest spatial and time variations in SPM concentration is located offshore with an average SPM concentration less than 20 mg/l and a very low standard deviation.

The area located to the south of Oostende has a median value less than 20 mg/l, which means that this area is very often a relatively clear water area. Nevertheless very high values (from 110 to 140 mg/l) occasionally occur yielding average SPM concentrations from 20 to 40 mg/l, higher than in the offshore area. We note that high SPM concentrations occur even 20 km offshore (about 80 mg/l) as shown in the maximum SPM map (Fig. 2d).

2.3. Classification of SPM concentration maps

To further characterise the dynamics of SPM in the area of interest, the spatial correlation of the SPM concentration time-series was calculated to identify separate areas with similar SPM dynamics. The SeaWiFS images have been processed as explained below.

For each grid cell as defined above, further called a reference grid cell, the following procedure was followed:

- all valid surface SPM concentrations for the reference grid cell, not disturbed due to clouds or to atmospheric correction failure, were selected.
- for another grid cell, the valid surface SPM concentrations are selected from the SeaWiFS images as well.
- if at least 100 corresponding valid SPM concentration pairs are found, the correlation between the SPM concentrations at these two grid cells is calculated. A value of 100 pairs is taken to insure that the results are based on a large number of SeaWiFS images.
- this selection of valid surface SPM concentrations and calculation of the correlation if 100 corresponding valid SPM concentration pairs are found is repeated for all grid cells.
• when all correlations between the SPM concentrations at the reference grid cell and the SPM concentrations at the other grid cells are calculated, a map can be prepared of the area with correlations higher than 70%. This area is defined as the High Correlation Area (HCA) for that reference grid cell.

After calculating for each cell the HCA, the HCA with the largest surface is selected. This largest High Correlation Area (HCA-1) (see Fig. 3a) includes 2774 cells, which represents around 3500 km². As expected from the previous section, this HCA-1 is located offshore.

A second high correlation area was selected after masking out the HCA-1 area, by applying the same procedure as described above. For all remaining grid cells, the correlation with the other grid cells was calculated and the areas for which the correlation was higher than 70% were constructed. Amongst all the HCA's, the most extended HCA was selected again. This yields the HCA-2 area, which is located in the north east, near the mouth of the Westerschelde estuary (Fig. 3b). The area represents about 1100 km². In the west of the area, an overlap exists between the HCA-1 and HCA-2 areas. The area without the HCA-1 and HCA-2 is very narrow.

This area is actually uncorrelated with either HCA-1 or HCA-2. The standard deviation of SPM concentrations here reaches 50 mg/l (the highest throughout the BCZ). The third HCA (HCA-3) covers partly this area and was found in the 20 km band along the coast (Fig. 3c). Also for this HCA-3 area overlaps exist with the two other HCA's.

Since there are overlaps between the three HCA's and that some grid cells do not belong to any of the HCA's, an additional processing was executed to allocate each of the grid cells to one of the three defined areas. To do this for each of the grid cells, the correlation with the three reference grid cells for the HCA's are calculated. The grid cell is then appointed to that area for which it has the highest correlation with its reference grid cell. The resulting division of the BCZ in three separate areas is presented in Fig. 3d.

The SPM concentration in these three areas is characterised as follows:

• Offshore area, where SPM concentrations remain generally low (<10 mg/l).
• Zeebrugge area, which extends from about Zeebrugge to the mouth of the Westerschelde estuary. In 60% of the images, the SPM concentration is lower than 50 mg/l, while 40% of the images show a high SPM concentration in this area.
• Oostende area, which has high SPM concentrations more often than in the Zeebrugge area (70% of the images show high SPM concentrations in this area).
Fig. 3. (a) 1st High Correlation Area (HCA-1); (b) 2nd High Correlation area (HCA-2); (c) 3rd High Correlation Area; (d) division of the BCZ in the offshore area (light), Zeebrugge area (middle) and Oostende area (dark).
The difference between the offshore area and the coastal areas is due to the fact that (1) the transport of SPM is mainly concentrated in the coastal area and (2) the differences in bathymetry. For the apparently different SPM dynamics in the two neighbouring Zeebrugge and Oostende areas on the other hand, a convincing explanation has not yet been established. Some striking differences between both areas can however offer explanations:

- 95% of the dredging and dumping occurs in the Zeebrugge area. Comparison between the natural input of SPM and the quantities dredged and dumped at sea showed that an important part of the SPM is involved in the dredging/dumping cycle (Fettweis and Van den Eynde, 2003).
- The bottom in the Zeebrugge area consists of Holocene mud near the coast, which is difficult to erode, and shallow sand plates offshore, where the hydrodynamic conditions prevent mud from being permanently deposited (Fettweis and Van den Eynde, 2003). In the Oostende area, soft mud which has been deposited during slack water can be found (Van Lancker et al., 2003). This could mean that in the Zeebrugge area the mud stays in suspension during most of the tidal cycle and that mud is only permanently deposited in the man-made environments of navigation channels and harbours. In the Oostende area on the other hand, the hydrodynamics allow SPM to be deposited and only severe storms will bring the fine material back into suspension.
- The Westerschelde estuary also has an influence, even if it is limited, on the SPM dynamics of the Zeebrugge area. Although the ratio of fluvial to marine SPM is almost constant at the mouth of the estuary (Verlaan et al., 1998), the SPM concentration varies significantly as a function of river discharge.

### 3. SPM CONCENTRATION FROM IN SITU MEASUREMENTS

Knowledge of resuspension, transport and deposition of fine grained sediment is important to understand the variations in SPM concentration observed in satellite images. This knowledge is provided from in situ measurements. The results of ten measurements are discussed below; they have been carried out with the R/V “Belgica” from 1999 to 2002. The different measurement surveys are presented in Table 1 and Fig. 4.
Table 1. *In-situ* measurements of SPM concentration. (1) Name of campaign; (2) Starting time of the measurement; (3) Duration of the measurements; (4) Time of maximum SPM concentration related to high (HW) or low water (LW); (5) Duration of SPM concentration peak; (6) Ratio between surface and vertical averaged SPM concentration; (7) Ratio between surface and bottom SPM concentration (±3 m); (8) area in which measurement is situated.

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3.1. Processing of the data

The turbidity in the water column was measured with an Optical Back Scattering (OBS) sensor, mounted on a Rosette water sampling - SBE9 SCDT system. Data were acquired every half second. Every hour a vertical profile was measured. Furthermore every 20 minutes, a water sample was collected at about 3 m above the bottom using the 10 litre Niskin bottles of the Rosette water sampling system. These water samples were used for gravimetrical determination of the SPM concentration.

The values of SPM concentration, determined by filtration, and the simultaneously measured OBS values are used to set up a relationship between the OBS readings and the actual SPM concentration. A linear relation between SPM concentration and OBS is assumed and calculated using a least squares method. Since the relationship depends on
the characteristics of the sediments in suspension as well as on the hydrodynamic conditions and the time of the measurements, the relationship is calculated for each survey period separately. Only for three surveys, with very low concentrations (8-25 mg/l), the correlation coefficient is less than 50%. The average correlation coefficient for the other surveys is 86%. The slope of the regression line between SPM concentration and OBS output for the other surveys varies between 1.11 FTU/mg/l and 2.08 FTU/mg/l.

Vertical profiles are measured every hour. The profiles cover the water column from about 3 m above the bottom to about 1 m below the sea surface. In order to take into account the entire profile, including the lowest layer in which the highest concentrations are expected, an extrapolation is made using a theoretical profile. This extrapolation is important to calculate an accurate depth-average SPM concentration.

The following profile was assumed (van Rijn, 1993):

\[
c(z) = c_a \left( \frac{h - z}{z} \frac{a}{h - a} \right)^{\frac{w_c}{\beta \kappa}} \quad \text{for} \quad \frac{z}{h} < 0.5
\]
\[
c(z) = c_a \left( \frac{a}{h - a} \right)^{\frac{w_c}{\beta \kappa}} e^{-\frac{w_c}{\beta \kappa} \left( \frac{z}{h} - 0.5 \right)} \quad \text{for} \quad \frac{z}{h} \geq 0.5
\]

Fig. 4. Survey stations in the Belgian coastal waters. Dots are wave station Bol van Heist and wind station Wandelaar; the SPM survey stations are indicated with triangles.
where \( c(z) \) is the concentration at a height \( z \) above the bottom, \( h \) is the total water depth, \( c_a \) is a reference concentration at a reference height \( a \) above the bottom, \( w_s \) is the fall velocity, \( \beta \) is a factor describing the difference between the diffusion of a liquid particle and a discrete sediment particle, \( \kappa \) is the von Karman constant, equal to 0.4, and \( u_* \) is the shear velocity. The parameter \( Z = w_s / \beta \kappa u_* \) is the Rouse parameter, which is a measure for the SPM concentration vertical gradient. Van Rijn (1993) argues that this profile gives the best agreement with observations and that it has the advantage that the concentration at the surface does not have to be zero as is the case in the well-known Rouse profile. Since the reference height and the reference concentration at the bottom are only used as fitting parameters for the concentration profile, the exact value of the reference height is not important. Here a fixed value above the bottom is used (\( a = 0.10 \) m). This value is of the same order of magnitude as the minimum value for \( a \) proposed by van Rijn (1984), which was 0.01\( h \).

For each profile the reference concentration \( c_a \) and the Rouse parameter \( Z \) are determined using a nonlinear least squares method. The van Rijn (1993) profile gives a good fitting of the measured profiles. Assuming a standard deviation of the measuring error of 10% of the maximum concentration, the Goodness-of-Fit is better than 0.5 (0.9) in 92% (75%) of the profiles.

### 3.2. Tidal variations

The measurements show that the SPM concentration in the coastal zone varies with tide with minima between 20-70 mg/l and maxima between 100-600 mg/l. Low values have been measured during three surveys (8-25 mg/l). Two of these surveys were situated in the offshore area, which explains these low values. The third one (survey 00/31) is situated in the high turbidity area, i.e., in the Zeebrugge area. High SPM concentrations had been measured in the vicinity six weeks before (survey 00/26) and after (survey 01/01). The low SPM concentration can be explained by a combination of differences in tidal amplitude (neap versus spring tide) together with a meteorologically induced offshore drift of the suspended matter. An almost continuous wind from S-SSW (towards offshore) (see Fig. 5c), from the beginning of November 2000 till the 7th of December 2000, the start of the 00/31 measurements, might have contributed to this drift. Thus the SPM entering through the Strait of Dover into the North Sea was blown towards the North, away from the Belgian-Dutch coastal zone.

The measurements illustrate that the peaks in SPM concentration are coupled to the peaks in current velocity and occur after the maxima in current velocity (Fettweis et al., 2002). The occurrence of a time lag in suspended sediment transport is well known.
Seasonal variability of suspended particulate matter

Fig. 5. Hydrodynamic and meteorological information during several of the survey periods: (a) Predicted tidal amplitude at Oostende, (b) measured wave height at 'Bol van Heist' and (c) wind speed and direction at 'Wandelaar.' The time of three SeaWiFS images (17 and 19/10/2000, 16/01/2001) and of three through tide measurements (00/26; 00/31; 01/01) are indicated.

(Basset et al., 2002; Dyer, 1995; Hoitink et al., 2003) and is related to the fact that the re-suspended mud needs a certain time to be distributed over the water column. Van Parys and Pieters (2001) observed this process near Zeebrugge, where the mud bed starts to be re-suspended when the tidal current increases to 0.15 m/s, but only at a later time, when the current velocity is greater than 0.5 m/s, was an increase of SPM concentration measured near the surface.
3.3. Vertical variation

The measured vertical profiles reveal that the SPM concentration is usually about 50 mg/l in the coastal area and can reach up to 600 mg/l (Fig. 6). The surface SPM concentration as well as the stratification is high only for about 2 hours during ebb and flood, i.e., about 1/3 of the tidal cycle. Strong vertical gradients were observed during surveys 00/14, 01/01, 01/06a and 01/6b, when SPM concentration was high (Table 1 and Fig. 6). During the rest of the tide, which corresponds to about 2/3 of the tidal cycle, the measured SPM concentration and stratification are much lower and corre-

Fig. 6. Vertical distribution of SPM concentration during a tidal cycle in the Belgian coastal zone (a) at station 00/08, (b) at station 00/26, (c) at station 01/01 and (d) at station 01/06b.
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respond to a background value, which is high (50 mg/l) in the high turbidity zone (Oostende and Zeebrugge area). It is still not clear what the reason is for the occurrence of strong vertical gradients during some surveys while during others only small gradients are observed, although situated in the same area.

To make an accurate estimation of the ratio between the surface and the depth-averaged SPM concentrations during the tidal cycle, for each of the profiles, Eq. 2 was used to fit the survey data for finding the best reference concentration at the bottom $c_a$ and Rouse parameter $Z$. The time variation over these two parameters for survey 01/01 is given in Fig. 7 as an example, together with the total water depth. The figure shows that the vertical gradient and the reference concentration reach a maximum some hours before high and low water, i.e., during periods of tidal acceleration (Maa and Kim, 2002). Furthermore it is clear that the SPM concentration gradients increase together with the reference bottom concentrations. This is observed in almost all measured profiles.

For all the profiles the depth-averaged and the surface SPM concentration were calculated, together with their ratio. For the three different areas, defined in section 2.3, the mean evolution of this ratio is calculated over the tidal cycle (Fig. 8). In the near-shore Zeebrugge and Oostende area (Fig. 3d), a clear cycle can be observed: 1 hour

![Fig. 7. Variation over time of the bottom reference concentration $c_a$ and the Rouse parameter $Z$ for survey 01/01.](image-url)
before high water and around low water, the ratio between the depth-averaged and the surface SPM concentration increases to about 2 and about 1.5 respectively. In the Oostende area the ratio around low water increases to almost 2.2. In the offshore area, on the other hand, the ratio between the depth-averaged and the surface SPM concentration stays constant over the entire tidal cycle and is limited to values below 1.1. Only one hour after high water, the ratio increases to about 1.25.

4. SEASONAL DEPTH-AVERAGED SPM CONCENTRATION MAPS

In order to obtain depth-averaged SPM concentrations from satellite measured surface SPM concentration maps, corrections have to be applied. As is shown in Fig. 8, the ratio between the surface SPM concentration and the depth-averaged SPM concentration varies during the tidal cycle. During the background period, the ratio between the surface SPM concentration and the depth-averaged SPM concentration is almost equal to one and the surface SPM concentration, derived from the satellite images, will represent well the averaged SPM concentration. During the periods with higher stratifi-
cation, however, this ratio can be higher than 2.2 and the satellite images underestimate the depth-averaged SPM concentration. Furthermore, this correction factor varies over the BCZ. Therefore different correction functions are setup for the three sub-regions identified in section 2.

The following procedure is followed:

- for each grid cell, the surface SPM concentration is calculated (section 2.1).
- the HCA-1, HCA-2 or HCA-3 (section 2.3) in which the grid cell is lying, is identified;
- the time in the tidal cycle corresponding to that of the satellite image is determined with the help of a hydrodynamic model (Luyten et al., 1999);
- the correction factor from Fig. 8 is applied to calculate the depth-averaged SPM concentration.

The corrected satellite images are then used to calculate a season-averaged SPM concentration in the domain. Results are presented in Fig. 9. The influence of season is clearly visible: the SPM concentration is lower during spring and summer and higher during autumn and winter.

These seasonal maps have been used to construct boundary conditions for a cohesive sediment transport model of the area. Using a two-dimensional numerical model for hydrodynamics and sediment transport, Fettweis and Van den Eynde (2003) showed that the processes responsible for the formation of a high turbidity zone at the Belgian-Dutch coastal area (offshore of Zeebrugge) are the currents and the import of SPM through the Strait of Dover. Mainly because of the decreasing magnitude of residual transport and the shallowness of the area, the SPM is concentrated in the Belgian-Dutch coastal waters and forms a turbidity maximum near to Zeebrugge.

5. CONCLUSIONS

In the Belgian-Dutch coastal zone, SPM concentration is high. The main source of SPM in the southern North Sea is the Dover Strait. In the current study a method is presented to incorporate in situ measurements and satellite imagery for a better estimation of depth-averaged SPM concentration, which should help to define more realistic initial and boundary conditions for a local area cohesive sediment transport model.

A spatial analysis of the satellite derived surface SPM concentrations shows that three separate sub-regions can be identified: an offshore area with generally low SPM concentrations and two nearshore highly turbid areas.
Fig. 9. Depth and seasonal averaged SPM concentration (mg/l) in the southern North Sea derived from 370 SeaWiFS maps (1997-2004) and corrected using 10 through tide measurements. (a) winter; (b) spring; (c) summer; and (d) autumn.
Seasonal variability of suspended particulate matter

In situ measurements during a tidal cycle further allowed to distinguish between the SPM dynamics offshore and in the high turbidity areas. In the latter, the SPM concentration is generally high and a pronounced vertical gradient is observed during 1/3 of the tide. During such a period, the depth-averaged SPM concentration is about 50% to 100% higher than the surface SPM concentration derived from satellite images. This important variation of SPM concentration during a tidal cycle has to be taken into account when correcting satellite imagery to obtain total SPM concentration maps.

In the present paper, a procedure is proposed to derive depth-averaged SPM concentration maps from SeaWiFS satellite images. It is clear that the proposed procedure is only a first result, because all in situ measurements of SPM concentration profiles were used for setting up the correction factor and thus no estimation could be made on the improvement obtained.

Finally, seasonal depth-averaged SPM concentration maps were prepared and presented.

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