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Impact of cloud cover on local remote sensing – Piaśnica River case study

by

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Abstract

New satellite-based techniques open up new horizons to researchers and local communities. Concurrently, however, requirements and expectations with regard to satel-lite-based remote sensing products are increasingly higher. By relying on satellite-derived information, environmental observations can cover areas of a few to several metres resolution. Here we are dealing with free-of-charge and generally available sources of satellite-based information. The Piaśnica River mouth area was selected as an observation site representing a highly dynamic morphological transect. The paper compares products of cloud cover detection, supplied with data and available in the Copernicus database for a local area in the coastal zone of the Baltic Sea. The absolute difference did not exceed 5%, which confirms a high efficiency of the solutions offered. More than 96% of the clouded area determined for the Sentinel-2/MSI (Multispectral Instrument) was correctly identified when compared with supervised observations. The rate was lower (92%) for the Sentinel-3/OLCI (Ocean and Land Colour Instrument). It was eventually concluded that, at the local level, successful observations can be conducted using the cloud cover map supplied with the satellite data. At the same time, the analyses presented do not rule out further efforts to, e.g., increase the accuracy and speed of the analyses.

Key words: remote sensing, cloud, coastal morphology, Piaśnica, coastal zone satellite observations

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1. Introduction

Local, satellite-based sea surface monitoring has an increasingly expanding number of applications due to the growing requirements with respect to the accuracy of environmental assessments. Nevertheless, adequate atmospheric correction performed generally for cloud-free areas remains a challenge for satellite sensors, especially in optically complex coastal areas (Amin et al., 2014). In this article, we will evaluate the impact of cloud detection on the radiation budget (Zapadka et al., 2015) for Sentinel satellite data and validate the results with in situ data. Linkages between the radiation and the cloudiness on the local level may give new insights into the clouds' interactions with the environment (Lu et al., 2021). Although such interactions have been studied with radiation monitoring (Paszkuta et al., 2019), local and regional studies are regrettably few (Paszkuta et al., 2022, Paszkuta et al., 2021; Choi, 2022), mainly because of the inadequate quality of information, or its downright absence. The satellite radiometric scanning data from the Sentinel platform, obtained from the Copernicus data base (Table 1, Table 2) along with the associated ready-made cloudiness products were analysed to explore relationships between the appropriate cloud detection and the quality of research of the mouth of the Piaśnica River. To explore these interactions, a comparative analysis of information made by satellite radiometer was conducted; more specifically, environmental data were used in and compared with our own supervised and unsupervised, depending on the nature of data, observations. The human eye has the ability to efficiently delineate spectrally and spatially distinguished areas (such as clouds) from a satellite image. Unfortunately, precise attempts to automate this process (automatic-unsupervised procedures) are continually giving way to supervised procedures. However, due to the colossal amount of satellite information produced every day, the manual-supervised procedure must be limited to the validation regime only due to the length of time it requires. In the work, a skilled observer, using the visible and infrared channels (of the Sentinel-2/

Table 1

Spectral channels of Sentinel-2/MSI (Multispectral Instrument)

Band No.	S2A MSI		S2B MSI		Spatial resolution (m)
	Central wavelength (nm)	Bandwidth (nm)	Central wavelength (nm)	Bandwidth (nm)	
1	442.7	21	442.2	21	60
2	492.4	66	492.1	66	10
3	559.8	36	559.0	36	10
4	664.6	31	664.9	31	10
5	704.1	15	703.8	16	20
6	740.5	15	739.1	15	20
7	782.8	20	779.7	20	20
8	832.8	106	832.9	106	10
8a	864.7	21	864.0	22	20
9	945.1	20	943.2	21	60
10	1373.5	31	1376.9	30	60
11	1613.7	91	1610.4	94	20
12	2202.4	175	2185.7	185	20

Table 2

Spectral channels of Sentinel-3/OLCI

Channel No.	S3 OLCI	
	Central wavelength (nm)	Bandwidth (nm)
1	400	15
2	412.5	10
3	442.5	10
4	490	10
5	510	10
6	560	10
7	620	10
8	665	10
9	673.72	7.5
10	681.25	7.5
11	708.75	10
12	753.75	7.2
13	761.25	2.5
14	764.375	3.75
15	767.5	2.5
16	778.75	15
17	865	20
18	885	10
19	900	10
20	940	20
21	1020	40

MSI and Sentinel-3/OLCI) simultaneously delineated areas with clouds present. We consider such a mask to best represent the actual state of cloudiness in the atmosphere. An automatic-unsupervised procedure used to identify clouds is based on the reflectance threshold. The visible and infrared channels as well were used because clouds are characterised by high reflectance in these spectral regions. Additional criteria based on the reflectance are added to avoid confusing an ice cloud with snow. However, from an oceanographic point of view, this is not relevant (Gascon et al., 2016; EO 2020; Hollstein et al., 2016, Louis, 2022; Wevers et al., 2021).

This paper presents the relationships between the land surface satellite observations (their variability depending on the data quality) modulated mainly by the cloud cover, analysed from the standpoint of environmental observations of the mouth of the Piaśnica River.

2. Materials and methods

2.1. The potential of the present-day remote sensing

The constant improvement of satellite-based techniques which supply more and more information every day makes it possible to carry out environmental observations on a larger and larger scale. The local level information, on the order of a few to several metres, becomes available on-line to everybody and may, at present, be a basis for environmental studies on, e.g., river mouth morphology, its geomorphic dynamic, or river plumes in the sea. The Piaśnica River (Figure 1a-c) discharges in the southern part of the Baltic Sea (54°50'01"N 18°03'46"E; 54.833571 N 18.062685 E). The mouth has no permanent channel. A few days-long storm may be sufficient to alter the mouth channel very substantially. The changes may be very rapid and frequent up to several times a year. The temporal and spatial characteristics of those changes mirror the dynamic geomorphological alterations, ideal for satellite-based research, with the temporal and spatial resolution of the Sentinel-2/MSI satellite-borne MSI device (Table 1). The Piaśnica supplies water, e.g., of different characteristics to the Baltic Sea. The properties and intensity of the supply can be directly observed by the satellite. From the standpoint of the frequency of changes and the scope of the process, the OLCI radiometer carried by the Sentinel-3/OLCI satellite seems to be an ideal tool (Table 2). It can be argued that the measuring instruments carried by the Sentinel-2/MSI and Sentinel-3/OLCI are appropriate for local environment observations along the Baltic Sea coast. The largest difficulty here is an appropriate cloud detection that pertains to the cloud cover

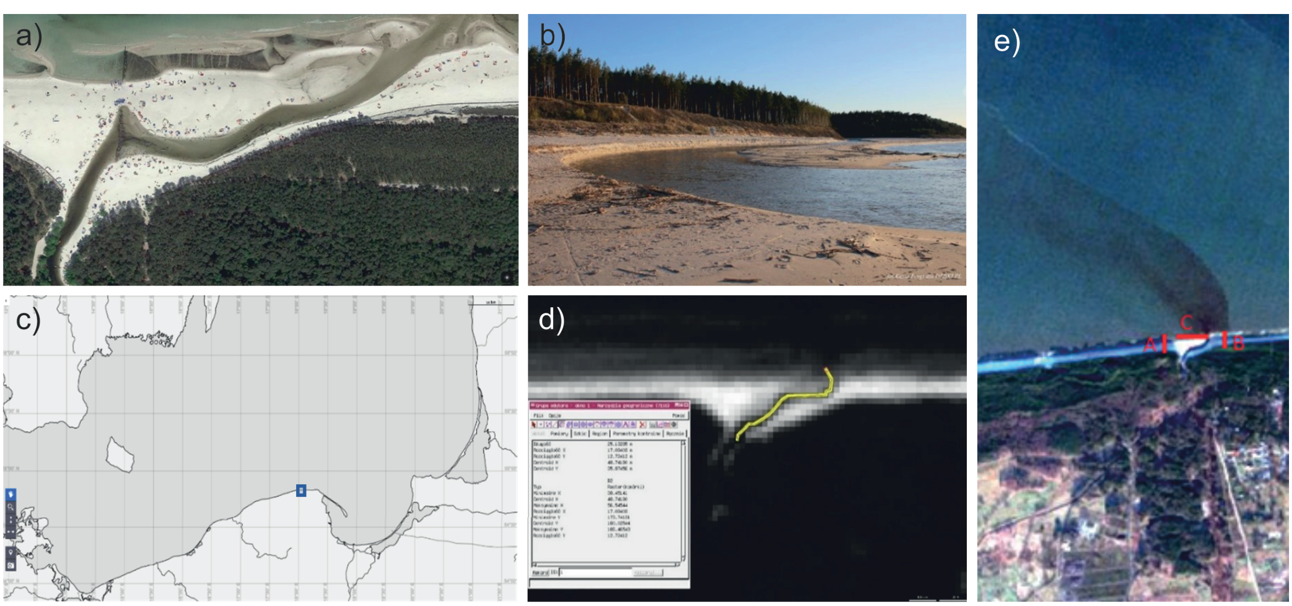

Figure 1

The River Piaśnica mouth: (a) Satellite view (source: googlemaps - Copernicus). (b) At the beach level (http://www.debki.pl). (c) Situation map of the area presented (blue square). (d) Mouth length with Sentinel-2/MSI data. (e) Distribution of the mouth lengths analysed, for environmental comparisons.

range in particular. The study site covered an about 3 km^2 area around the mouth of the Piaśnica (Figure 1c-d), a part of the coastal zone including both the offshore and inland portions. The information used in the study were supplied by the Sentinel platforms and downloaded from the Copernicus portal. The major devices of the mission include the Sentinel-1 consisting of two satellites moving along a polar orbit and equipped with a Synthetic Aperture Radar (SAR). The MSI device carried by the Sentinel-2/MSI satellites was constructed in response to the need for a high geometric and spectral measurement efficiency. The MSI nadir spatial resolution ranges within 10–60 m. The MSI measures the Earth radiation in 13 spectral bands, from the visible and the near-infrared (VNIR) to the shortwave infrared (SWIR) (Table 1). Sentinel-3/OLCI is the successor to the Medium Resolution Imaging Spectrometer/Environmental Satellite (MERIS/ENVISAT) with an increased number of spectral channels, improved radiometer settings and simplified processing. It has three instruments: Ocean and Land Colour Instrument (OLCI) – with spatial resolution up to 300 m (Table 2), Sea and Land Surface Temperature Radiometer (SLSTR) and Synthetic Aperture Radar Altimeter (SRAL). The environmental information used in this paper was supplied by the SatBaltic system. The data are a hybrid of operational modelling (sea parameter forecasting, e.g. SST) and sea parameter estimation for the Meteosat Second Generation (MSG) instrument at 1 km resolution. While correction is important in the regional scale assessments (e.g., by determining effects of the sea-based factors on the atmosphere), the cloud detection is a very important information constraint in local observations and decisive for the frequently long-term gaps in the data (e.g., cloud cover over the Polish coast in winter; [Paszkuta et al. ,2019]). It is therefore clear that environmental assessments at regional and local scales require particular care in estimating the extent of cloud cover, especially when it relates to the area of convective cloud formation. The Copernicus processing system is an Earth observation programme that provides up-to-date and easily accessible information on: cloud mask, cloud altitude and amount for visible and infrared range, the occurrence of fog, low stratus or thin cirrus. There are separate solutions for threshold, multi-channel and spatial convergence tests, broken down to cloud cover with water or ice characteristics (product level 2 of the Sentinel-3/OLCI and Sentinel-2/MSI). The methods, mostly based on traditional detection techniques (dynamic thresholding, surface tests, multi-channel relations) are global in scope. How then do they behave at the local and regional level at the Baltic Sea latitudes? This is the question that will be answered in the last part of the paper, drawing upon examples from geomorphological and oceanographic research. The Sentinel-3/OLCI image of 5 January 2020 (9:24 UTC) shown in (Figure 2a) is a typical example of a simultaneous presence of different types of clouds. The scene combines both distinct formations (cumulus, clear sea with land) and thin cirrus-type clouds. The Sentinel-3/OLCI example shows the cloud cover product (Figure 2b) supplied with satellite data over the convection zone to be very good. An experienced observer can detect small uncertainties (marked in Figure 2a) which do not alter the accuracy of the global-level detection. On the local level, the product is good as well, although there could be some reservations regarding overestimation of areas at high solar incidence angles, the lack of estimation of cloud edges and semi-transparent formations as well as some difficulties with identification of cloud shadows over lower-lying layers. However, it should be remembered that the characteristics refers to

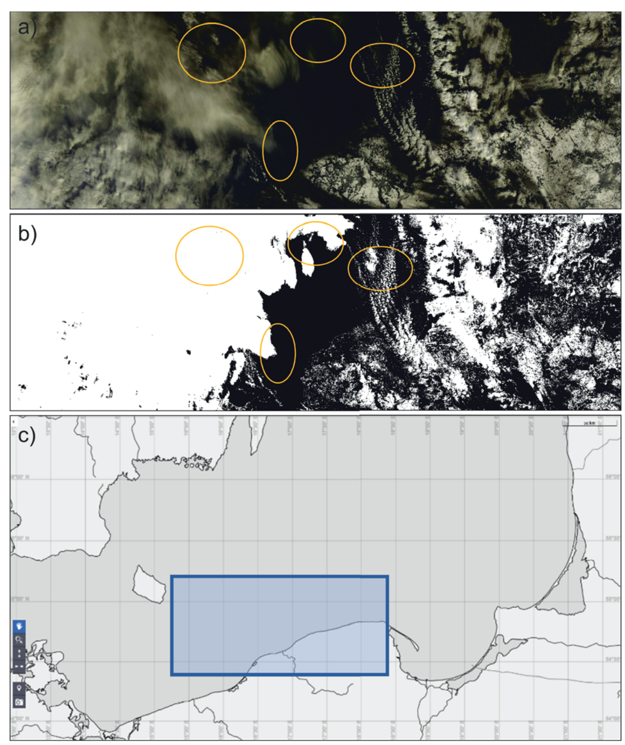

Figure 2

An example of data supplied by the Sentinel-3/OLCI of 2020.01.05 9:24 UTC for the southern Baltic Sea: (a) RGB - Composites True Color (for Sentinel-3/OLCI channels: 4 blue, 6 green, 8 red – see Table 2). (b) a systemic cloud cover mask supplied with data (S3B_OL_2_LFR/OTCI/LQSF_CLOUD); (c) Situation map of the area presented.

the global level. This cannot rule out efforts for local refinement of the dedicated characteristics, e.g., by applying morphological and oceanographic data. A location map of the area of the presented example is shown in Figure 2c. Another example, illustrated by Figure 3a, refers to the Sentinel-2/MSI scene of 1 January 2020 (at 10:03 UTC). Compared to the Sentinel-3/OLCI data, the Sentinel-2/MSI spatial resolution is an order of magnitude higher. Like in the previous example, a full spectrum of objects with which to illustrate cloud cover detection is visible: the thick and low cumulus clouds, the thin cirrus ones, and cloudless surfaces of the sea. Figure 3b and Figure 3c illustrate results of a systemic detection algorithm for clouds. As in the previous example, the system works well globally. Analysis of the supervised observations reveals some uncertainties in the local interpretation, marked by white ellipses in (Figure 3a). The analyses illustrate small overestimates of the cloud cover extent and reflect difficulties with resolving single and high formations against the backdrop of the coastal zone e.g., those marked in (Figure 3a). Those uncertainties do not affect the quality of detection on the global level, but leave room for local detection improvements. A location map of the area of the presented example is shown in Figure 3d. The temporal and spatial characteristics of devices and products supplied by the Copernicus system record

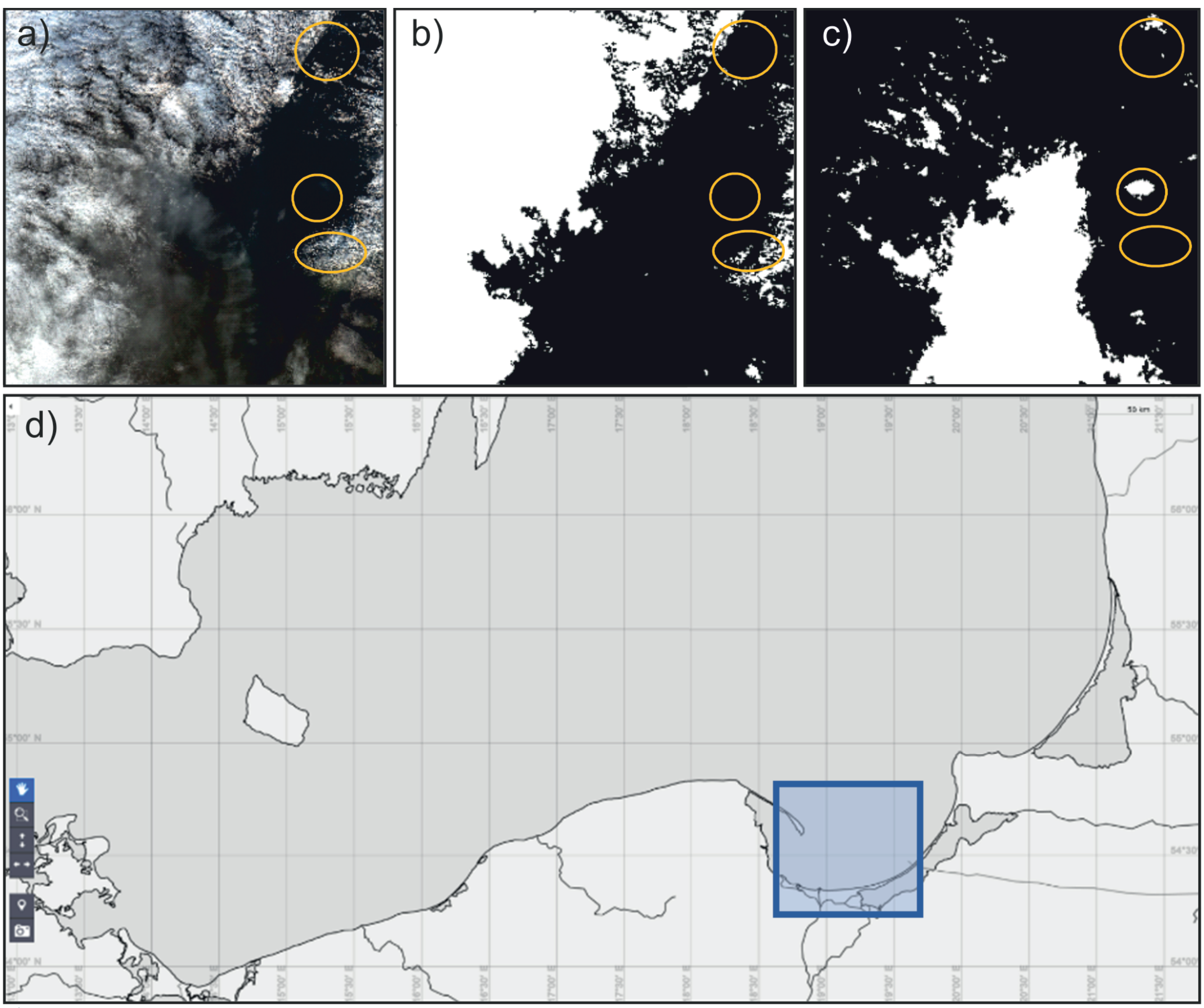

Figure 3

A Sentinel-2/MSI image of the Gulf of Gdańsk of 2020.01.01 10:03 UTC: (a) RGB - Composites True Color (for Sentinel-2/MSI channels: 2 blue, 3 green ,4 red – see Table 1). (b) Opaque cloud cover mask. (c) Cirrus cloud cover mask; supplied with the systemic data. (d) Situation map of the area presented.

dynamic oceanographic and geomorphological changes occurring locally in the coastal zone. Therefore, it may be contended that it is possible to monitor changes in the mouth of the Piaśnica with the Sentinel data, with due consideration to temporal and spatial data series.

2.2. Detection methods

First, the 2017 data supplied by the Sentinel-2/MSI were analysed. The original cloud flags included in the L2A products were used for direct mapping of Sentinel-2/MSI data; optionally, it is possible to run the L1C products through Sen2cor's SNAP software processor calculations. It should be noted that the Sentinel-3/OLCI cloud detection algorithm has been improved in 2021, although the archive data has not been updated. Using the free access to the Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/#/home), image series to be downloaded were identified. The images were unpacked and resampled to the test site at the mouth of the Piaśnica, as in (Figure 1d-e), using the SNAP software. The free SNAP software processes the bottom-up radiation directly recorded by the MSI radiometer (Table 1). Processing of the radiation includes angular correction, one of the main sources of uncertainty in instantaneous radiation data. The work involved a comparison between the automatic-unsupervised detection procedure of Sentinel-2/MSI and Sentinel-3/OLCI (generated at Copernicus) and 'eye-ball verification' of clouded areas. In the manual-supervised procedure, a skilled observer, using the visible and infrared channels (respectively Sentinel-2/MSI and Sentinel-3/OLCI) delineated areas with clouds present – map by map. In this way, a mask was determined which was subjected to further comparison. The percentage of the study area flagged as cloudy was analysed mask by mask. Data for the analysis were taken at an average frequency of once a week (Table 3, Figure 4), which produced about 48 representative examples. The number of examples to be analysed was mainly influenced by the cloud detection and the source of data.

Therefore, for obvious reasons, it was difficult to select representative scenes in the winter season, hence the higher irregularity of sampling. The cloud cover extent was determined for each map in a supervised manner. The results were compared with products supplied by the system (Figure 4a). Figure 4a

Table 3

The data base used for comparisons. The cloud cover estimates for supervised (Sup) and systemic (Sys) observations in % of test site surface area.

No.	Date	Sup	Sys	No.	Date	Sup	Sys
1	2017-01-01T10:04:12	77	85	25	2017-07-23 T10:10:31	39	56
2	2017-01-11T10:03:51	5.2	7.7	26	2017-08-02 T10:10:31	19	25
3	2017-01-24T10:13:11	35	59	27	2017-08-09 T10:00:31	23	29
4	2017-01-31T10:02:31	3.1	5.7	28	2017-08-17 T10:10:19	2.1	1.2
5	2017-02-10T10:01:31	12	15	29	2017-08-24 T10:00:19	0.1	4.6
6	2017-02-03T10:12:21	80	90	30	2017-09-01 T10:10:21	23	46
7	2017-02-23T10:10:21	72	79	31	2017-09-08 T10:00:31	36	56
8	2017-03-12T10:00:21	40	49	32	2017-09-16 T10:10:19	17	17
9	2017-03-15T10:10:21	5.1	9.7	33	2017-09-26 T10:10:09	37	44
10	2017-03-22T10:00:21	0	0	34	2017-10-01 T10:10:21	0	0
11	2017-04-01T10:00:21	4.8	6.6	35	2017-10-08 T10:00:31	18	16
12	2017-04-11T10:00:31	32	44	36	2017-10-16 T10:10:09	1	1.7
13	2017-04-14T10:10:21	12	22	37	2017-10-18 T10:00:31	49	42
14	2017-05-01T10:00:31	0	0.5	38	2017-10-23 T10:00:39	74	92
15	2017-05-11T10:00:31	29	47	39	2017-10-31 T10:11:41	67	87
16	2017-05-14T10:10:31	23	35	40	2017-11-05 T10:11:59	1.5	4.6
17	2017-05-21T10:00:31	35	37	41	2017-11-07 T10:02:21	2.5	3.4
18	2017-05-24T10:10:31	8.4	11	42	2017-11-15 T10:12:49	19	17
19	2017-06-03T10:10:31	11	10	43	2017-11-17 T10:03:01	61	86
20	2017-06-13T10:10:31	51	65	44	2017-12-02 T10:03:49	1.5	2.7
21	2017-06-20T10:00:31	15	35	45	2017-12-10 T10:14:11	10	12
22	2017-07-03T10:10:21	39	48	46	2017-12-17 T10:04:11	31	34
23	2017-07-10T10:00:31	20	26	47	2017-12-22 T10:04:19	58	60
24	2017-07-15T10:00:29	0.5	1.6	48	2017-12-30 T10:14:21	0	0

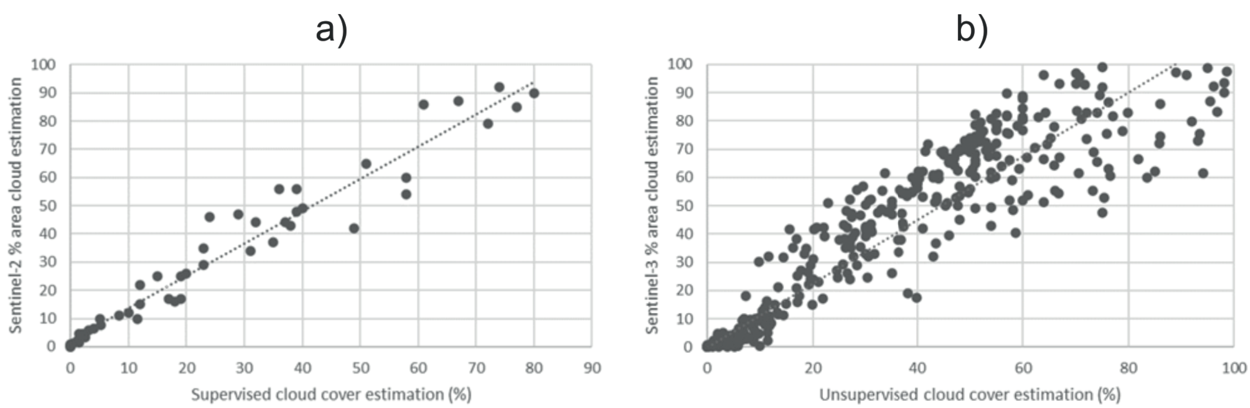

Figure 4

A relationship between Copernicus data- based cloud cover over the Piaśnica site: (a) Cloud cover estimated in a supervised manner (by a trained observer) with Sentinel-2/MSI data. (b) Unsupervised estimation (Paszkuta 2019) with Sentinel-3/OLCI data.

shows a relationship between the study site coverage (%) in 2017 as estimated in the supervised manner by an experienced observer and as determined by the Sentinel-2/MSI system for the Copernicus data (Table 3). A fairly good linear relationship is visible: the uncertainty increases with cloudiness. Cloud coverage of 0% is a cloudless situation at which the cloud cover should basically have no influence on information from the Earth, recorded by the radiometer.

The 13 channels of the MSI radiometer have been tuned to the so-called atmospheric windows, where gas absorption is relatively weak or to the absorption bands (e.g., channels 9, 10, and to an extent 12 – see Table 1) necessary for atmospheric correction. This formed a basis for analysing reflected radiation to derive the parameters characterising the river mouth, i.e., length, width, extent of opaqueness, etc. In the following section, the relationship between the reflected radiation from the Earth, calculated from MSI data, and parameters related to sea state is presented. The analyses involved a situation described as cloudless or amenable to see the site at the mouth of the Piaśnica . Such fields were identified in a supervised manner by an experienced observer, for 10-m resolution map, as in (Table 1) (channels 2, 3, 4, 8). An attempt was made to compare the MSI-based radiation values and the environmental parameters supplied by the SatBaltic system (Woźniak et al., 2011a,b) for the Piaśnica study site (Figure 5) and the instantaneously correlated time, with a maximum deviation of approx. 1 h, and averaged. Such a comparison should answer the question

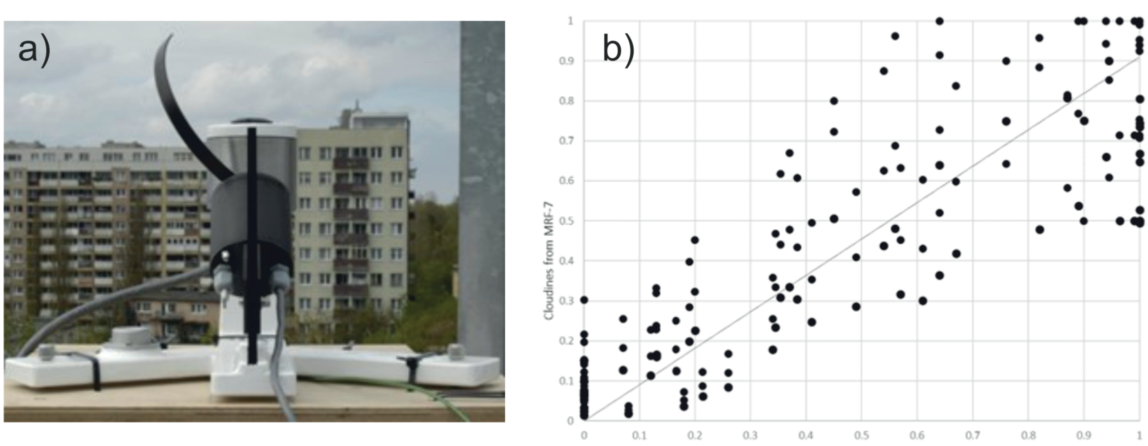

Figure 5

Field research: (a) MFR-7 radiometer for measurements including atmospheric state. (b) Comparison of results with satellite estimates.

whether satellite-based studies would be possible on a local level. At this stage, it was most important to correctly eliminate the uncertainties brought about by inappropriate detection of cloud cover extent. Therefore, it was a priori decided to rely on an observer who, based on their knowledge and expertise, would efficiently classify the images. This is obviously a time-consuming effort, restricted to small series of examples compared to the amount of satellite data supplied daily. Therefore, the scope of the work was limited to a single scene a week, although it was not always possible to identify clear skies with such a short time interval. The choice of the interval was also dictated by the period of geomorphological changes; geomorphology needs more or less a week to respond to forcing. The data in support of the argument are discussed more thoroughly in next section. Our supervised observations demonstrated that satellite-based techniques are appropriate to collect observations on changes in geomorphology produced by environmental transformations on a local level. As the emerging associations were identified and the detection proved feasible, processing the amount of information supplied daily would benefit from the process being automated. To this end, an attempt was made to carry out unsupervised observations (adjusted to the Sentinel-3/OLCI radiometer, as in (Paszkuta et al., 2019)). Since supervised estimation is limited to short series only, the following section illustrates the difficulties that arise when automating coastal zone classification at the local scale. For map segregation or classification, the gist of unsupervised detection is for the analysis to be automatic, without observer involvement. This was possible to accomplish with the on-line access to the database, with the operator's role consisting only of controlling the continuity of the analytical process. Considering the nature of the study as well as information on the cloud cover, it was decided to select another set of information from the Copernicus Sentinel-3/OLCI database (Table 2). The procedure involved comparisons of radiation data, appropriately coupled with physical properties of the atmosphere, supplied with the Sentinel-3/OLCI information (Figure 2). The results were simulated using the technique developed by the author (Paszkuta et al., 2019). The correlated models M3D (Kowalewski, 1997) and Solrad (Krężel et al., 2008), developed for the spectral channels of the Sentinel-3/OLCI, were used to determine radiation transfer through the cloudless atmosphere. The radiation model is an integer form, so they can be freely adapted to different instruments (MSG, Sentinel, ect.) depending on the channel range. Atmospheric profiles of temperature, humidity and ozone were obtained by interpolation of atmospheric model standards for the Baltic Sea latitude. The interpolation was in agreement with the differences between the locally observed and modelled sea surface temperatures. The aerosol optical density was taken from satellite-based observations for the assumed optical density of 0.1. Results of comparisons of unsupervised estimations are shown in (Figure 4b). The analysis was based on about 500 maps developed during the year 2017, which averaged to more than 1 measurement a day.

The results of the study were collected using different manners:

- unsupervised-automatic manner: very simple clouds assessment by the amount of reflected or emitted radiance reaching the satellite was apply (Paszkuta et al. 2019). The radiation models are in integer form, so they can be freely adapted to different instruments (Meteosat/ Spinning Enhanced Visible and InfraRed Imager (SEVIRI), Sentinel-2/MSI, Sentinel-3/OLCI, ect.) depending on the channel range. Systemic data used in this research were taken from the website https://scihub.copernicus.eu/ (accessed on 02 april 2022), as satellite cloud masks obtained from the Sentinel-2/MSI and Sentinel-3/OLCI. As well as in this group, cloud masks developed specifically for the Baltic Sea were analysed from http://www.satbaltyk.pl (accessed 02.04.2022) (Woźniak et al. 2011a, 2011b). The originally formed grid was normalized using the nearest neighbor method at a spatial resolution of 1 km. For the daytime, the split-window operation on pairs of adjacent channels 4 and 8 was used (see Table 1) and channels 8 and 18 was used (see Table 2). After transformation and normalization, the pixel intensities of the maps belong to the range [0, 1]. All the algorithm details of the estimation of cloudiness and uncertainty arising from the cell size were presented in (Paszkuta et al. 2019) .On the satellite image, the atmospheric transmission function *h(x, y)* summarizes, a priori, the emission of radiation from the sea and the clouds. Its modeled equivalent relates only to radiation from the sea in cloudless weather. *h* may be a normalized function that determines the path of radiation reaching the satellite. It can be adapted for further research with short-wave band data as follows:

$$h_1 = \frac{L_2 - L_2^M}{\dfrac{L_1^M L_2 - L_2^M L_1}{L_2 - L_1^M - L_1 + L_2^M} - L_2^M} \qquad (1)$$

where h_1 is a dimensionless parameter that determines the cloudiness coefficient based on the short-wave range; L_1 and L_2 are radiances in the neighboring channels; and L_1^M and L_2^M are radiances from the sea in a cloudless atmosphere modeled for L_1 and L_2, respectively. The radiation that reaches the satellite in a cloudless atmosphere was determined using the SolRad model (Krężel et al. 2008) in relation to the Solar Zenith Angle (SZA). A comprehensive analysis of the method was presented in references [Krężel & Paszkuta 2011, Paszkuta et al. 2019]. The long wavelength part is described as [Paszkuta et al. 2021]:

$$h_2 = \frac{T_2 - T_2^M}{\dfrac{T_1^M T_2 - T_2^M T_1}{T_2 - T_1^M - T_1 + T_2^M} - T_2^M} \tag{2}$$

where h_2 is a dimensionless parameter that determines the cloudiness coefficient from the long-wave radiation information; T_1 and T_2 are the temperatures in Kelvins (K); T_1^M and T_2^M are the cloudless atmosphere values in K as determined from the model. The solution evaluates the brightness temperature, according to the M3D model (Kowalewski 1997). Finally, we chose h as maximum pixel value of rasters [h_1 or h_2], where h_1 and h_2 are dimensionless and normalized from 0 to 1. The higher value is used to generate the final cloud map. A more detailed description of the algorithm can be found in (Paszkuta et al. 2019).

- supervised-manual manner: it is a popular method (Arino et al. 2007, Chen et al. 2015, Inglada et al. 2017) although controversial because it depends on the subjective nature of the observer, who has an individual predisposition. Recently, it has been used very often in training of modern techniques, by the author it was successfully used and described in earlier publications (Paszkuta et al. 2019, Paszkuta et al. 2022). The experienced observer classifies image by image (Setinel-2/MSI: channel 2-4, 8, 10-12 and Sentinel-3/OLCI: channel 2-8) determining individual masks or cloud maps. Thus, their product will show the image mask or, in more complex combinations, the cloud map. Many authors consider supervised classification to be superior to unsupervised approaches (Foody et al. 2006, Stehman 2009). Its main disadvantage is the need for training data. This is often criticised and seen as a barrier to implementing operational systems on a global scale.

- in-situ manner: relating the obtained results of the satellite estimation of cloudiness to the results of field surveys is never easy. The main difficulty is the large uncertainty, reaching over 30% (Mieslinger et al., 2022). Many factors contribute to this uncertainty, but the primary problem is the validation of satellite data at the local level with point and instantaneous ground-based information. One of the most important challenges is the correlation in time as well as space between satellite projections and ground-based measurements (Paszkuta et al. 2019). A completely different problem is the lack of data to validate the coastal zone and the sea, where, by nature, the amount of data to be compared is smaller than for land, and the variability of meteorological conditions – due to the extent of the convective zone – is very high. An example of such measurements are the results collected at the Marine Station of the University of Gdansk in Hel using the Solar Radiation – Multifilter Rotating Shadowband Radiometer (MRF-7) with a moving shadowband (Figure 5a). The MFR-7 is a commercial product manufactured and calibrated by Yankee Environmental Systems (YES). It incorporates a broadband silicon pyranometer that takes measurements taking into account the state of the atmosphere because clouds are the most important factor affecting radiation values in the atmosphere. From a tactical point of view, the Hel Peninsula is the only place of its kind in Poland to conduct land-based marine measurements. The geographical positioning of the device was: (54.36N 18.48E; 54.60666 E 18.80088 N) (the area on the coastline was shifted towards the Gulf of Gdansk 18.78908, 54.6095267 in order to standardise the marine data). Surrounded by the sea, the training ground can partially reflect the nature of the marine work without losing the continuity corresponding to land-based surveys. In Figure 5b we see some results of the dependence of the cloud cover measurement of the SatBaltic database vs. the MRF-7 ground-based measurements. Despite the high uncertainty factor, the proportional character of the phenomenon is maintained. Uncertainty increases as the amount of cloud cover increases.

3. Results

This paragraph will answer the question posed earlier: to what extent can the quality of geomorphological and oceanographic observations in the coastal zone be influenced at the local level? To answer the question, the largest source of uncertainty – the cloud cover – was analysed. The efficiency of two-cloud estimation procedures was compared: supervised and unsupervised (routinely provided by the Copernicus satellite system for Sentinel data). This choice was dictated by the intention to objectively perceive the actual state of the atmosphere above the study site (supervised estimations at the possibly highest resolution) and available possibilities of process automation (regional-scale operational data). An accurate elimination of clouded areas enhances the efficiency of using available information (upward radiation reaching the satellite) for environmental assessment purposes.

3.1. Cloud cover

The compared detection procedures generated similar binary cloud masks. Within the delineated coastal study area, cloudless and clouded areas were identified as representing class 0 and 1, respectively. Only water cloud-free areas (class 0), expressed as a percentage of the study area, were included in the subsequent environmental analysis (land areas were not included in the analyses, technically = null). From the point of view of oceanography and coastal geomorphology, clouded areas do not carry any sea/water information. The multiclass cloudiness information provided by the unattended satellite system was reclassified into a binary scheme. The results of comparing the two processes are shown in (Figure 4), results of the estimation being summarised in (Table 3). Figure 4 shows the relationship between the results of estimating the amount of cloud cover expressed as a percentage of the surface coverage of the surveyed area (0% – cloudless and 100% – clouded) determined in a supervised manner by a qualified operator and automatically by the system, respectively for Sentinel-2/MSI data Figure 4a and Sentinel-3/OLCI data (Figure 4b). Both procedures performed very well and confirmed the feasibility of conducting similar studies, i.e., the high-resolution supervised analysis provides improved results and illustrates the merits of running local-scale automated analyses. The differences were most frequently visible as underestimation of the systemic maps, i.e., the authors' own estimation revealed more clouded areas. Fog-covered areas and thin cirrus clouds, so important in the regional analysis but less so globally, were correctly classified as clouded. As a result, the approach to estimating the differences between the two procedures results from the reliability of the comparison or the statistical sufficiency of data (the more data, the lower uncertainty). To illustrate the problem, the results of the comparison will be described as: areas correctly classified as clouded; areas correctly classified as clear; areas overestimated by the systemic data; and underestimated areas. The comparisons were performed for both series of data (Sentinel-2/MSI and Sentinel-3/OLCI) (Table 4). Results for the representative 48 (Sentinel-2/MSI) and 409 (Sentinel-3/OLCI) scenes of 2017 are summarised in (Table 4). Table 4 and Figure 4 show also a comparison of cloud masks supplied by the two methods with the systemic masks provided by Copernicus. In unsupervised estimations for the Sentinel-3/OLCI data, the initial cloud mask was extended by a 100-m buffer. Such a treatment, although effective, is not ideal as, e.g., the extension closes small gaps between cloud formations which eventually are poorly reliable in geomorphological analyses anyway. The results showed a generally good fit for averages, at the levels of 96 and 92% for the Sentinel-2/MSI vs. supervised estimation and for Sentinel vs. unsupervised estimations, respectively. However, when analysing the comparison, it should be remembered that the map has a lower resolution so the amount of information generated is incomparably lower. Owing to the amount of information supplied and the objective of this study, the analysis of unsupervised estimation results when the cloud cover is automatically masked seems more interesting. Obviously, it is possible to compare both series of measurements, and qualitatively, the Sentinel-2/MSI is more advantageous owing to, e.g., the sampling frequency sufficient for the purposes of geomorphology. As a result, the data shown in (Table 3 , Figure 4a) compare temporally correlated data series. The statistical metrics are summarised in (Table 4). The average mask accuracies were 95.6 and 92.1%, respectively. This means that, on the average, 4.4 and 7.9% of pixels were differently classified (clear-clouded as 1-0 and clouded-clear as 0-1). The amount of uncertainty was lower in the Sentinel-2/MSI estimation. This was a result of the unsupervised nature of observations compared and the generally poorer resolution of the Sentinel-3/OLCI. However, depending on the scene, a high variability of results is evident, which most probably means that an improvement may be expected as a result of combining the two methods, for example supervised estimations for Sentinel-3/OLCI with a simultaneous reduction of time intervals. As a result, the Sentinel-3/OLCI data fitting technique performed well in the high cloud conditions, with slightly worse results for scenes with semi-transparent clouds and fog close to the surface. The method tended to overestimate the cloud cover above high-radiation targets. The presence of underestimated areas against the backdrop of cloud cover was observed; such false targets are generated by shadows cast by higher-located formations. The problem obviously disappears with

Table 4

Results of comparison cloud cover estimation, simplified to binary information, with data supplied by the Copernicus Sentinel-2/MSI and Sentinel-3/OLCI.

	Agreement (%)	Disagreement (%)
Copernicus Sentinel-2/MSI	96	4
Copernicus Sentinel-3/OLCI	92	8

the manual estimation, but it cannot be ruled out that the extended range maps do not generate other, indeterminate uncertainties. The accuracy of the system masks is good, unfortunately these masks do not take into account most fogs. Moreover, systemic masks usually ignore small clouds. Of the two methods, the results provided by the Sentinel-3/OLCI are more homogenous.

A detailed discussion of the relationship between cloud cover and radiation reaching the satellite sensor was described in a previous publication (Krężel et al. 2008). In Table 3, we have information that the system solution determines the cloud cover field to a greater extent in the realised sets. The described cases (Figure 2 and Figure 3) in agreement with Table 3 confirm that the automatic detection does not recognise many clouds that could be detected manually (fog, small clouds, clouds in higher cloud shadows, etc.), given the strong overestimation of the system solutions at the local level - which may explain the fact of the higher values of the system solutions in Table 3.

The difference between the data in Table 3 may therefore be due to an overestimation of the systematic global detection algorithms, as an experienced observer is able to determine cloud boundaries more accurately especially at the local level (confirmed by many authors Arino et al. 2007, Chen et al. 2015, Inglada et al. 2017). However, supervised estimation is rarely unbiased and it is indeed difficult to draw the described conclusions from Table 3 alone. In general, the correlations in Figure 4 do not show 'above-normal' differences (a good indicator of comparable sets), but a closer analysis reveals, for overcast situations (< 20), an over-interpretation of the system solution (especially in Figure 4b).

This is an academic dispute, as the supervised method is subjective; in the author's opinion, currently numerical algorithms cannot overcome the skilled eye of the observer - at least qualitatively. The human advantage has been demonstrated in many previous publications (Foody et al. 2006, Stehman 2009,). For the purposes of this paper, it was decided to accept it as capable of looking at clouds locally - without hiding its weaknesses. However, the claim that an unattended view is better is bold and revolutionary - though not impossible. This is evidenced by the accounts and examples given, which show an overestimation of systemic solutions to local sensing.

3.2. Environmental estimations

The basic parameter used for morphological characterisation is the length of the river along a fixed beach section (Figure 6). According to (Figure 1d), the

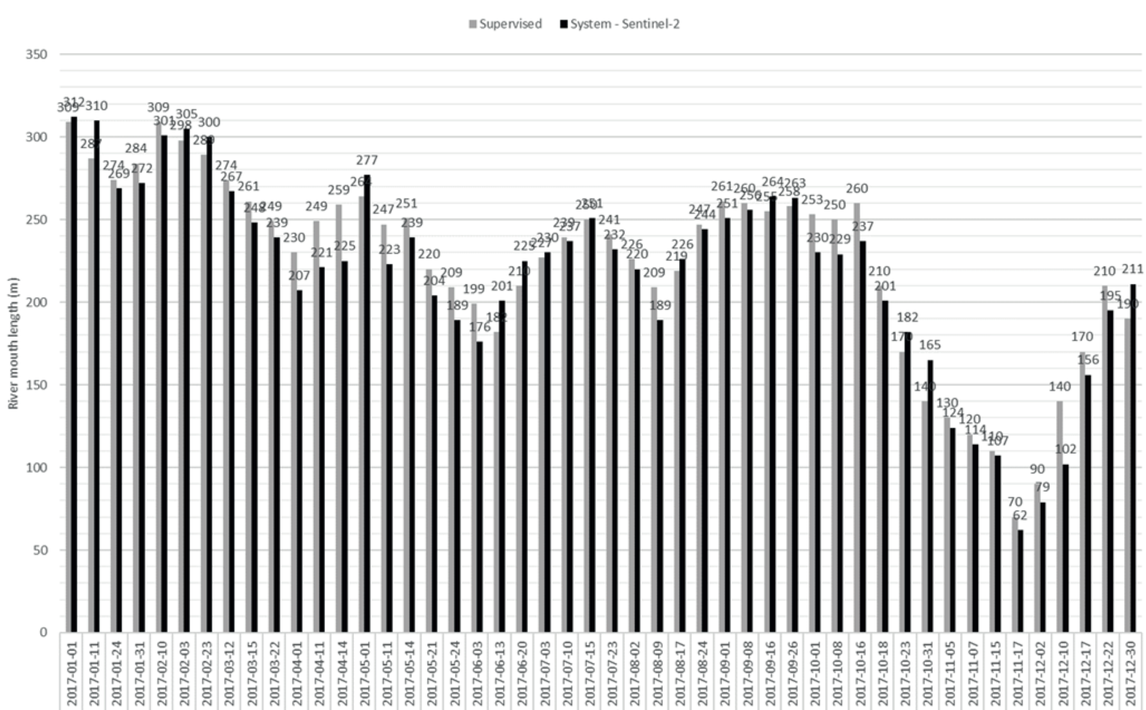

Figure 6

Variability in the Piaśnica mouth length at the fixed beach section in 2017, resulting from supervised and systemic cloud cover estimation.

river length measurements began at a fixed point at which the river channel was distinctly visible (from satellite) in an open area at the so-called starting point of the sandy beach or dune unvegetated in every season of the measurement period (section C in Figure 1e). The starting point was identical for all the maps analysed, as it was not changed in that part of the river mouth. The river mouth terminus was determined each time at a site of the river-sea contact. The auxiliary parameters included distance A and distance B (Figure 1e) understood as the length of the dry beach and the width of the shore in the section undergoing changes. The parameters were determined with the TNTMips Microimage software using the available techniques of image classification and vector analysis (Figure 1d). The measurements were taken by extending a straight line, along geographic directions, from the fixed initial point to the shoreline. The distance between the line and the actual river mouth was measured.

As seen in (Figure 6), the changes analysed proved to be of a low dynamics, which confirms that the time interval had been correctly set. Differences in the estimation produced by the different cloud cover assessment techniques used are not pronounced; they increase at fast passages and distinct leaps, suggesting an instantaneous nature of changes in the cloud cover. For this reason, further estimation will use the systemic masks only. The state of the sea is known to be of a key importance for the river mouth shape. The comparisons involved different environmental parameters drawn from the SatBaltic database that can be used to characterise the state of the coastal zone. The values were determined in the same way for the constant and averaged grid mesh corresponding to the site of the river discharge to the sea. (Figure 7a, Figure 7b) show two parameters, most important for the coastal zone, described in the SatBaltic system. The sea level is inversely correlated with the river mouth length: the higher the level, the shorter the cross-beach river section. Such a relationship is evident from the comparison of satellite data in (Figure 7a). On the other hand, the dry beach width is directly correlated with the river mouth length described by the Sentinel-2/MSI (Figure 7b). Finally, the relationship shown in Figure 7c, where the width of the dry beach increases as the sea level decreases, is not surprising. The three characteristics illustrate the correctness of data selection and method choice. Compared to earlier results, the general accuracy for the two parameters shown in (Figure 8a) is observed to have decreased. The substantial decrease is a result of the nature of the data that are

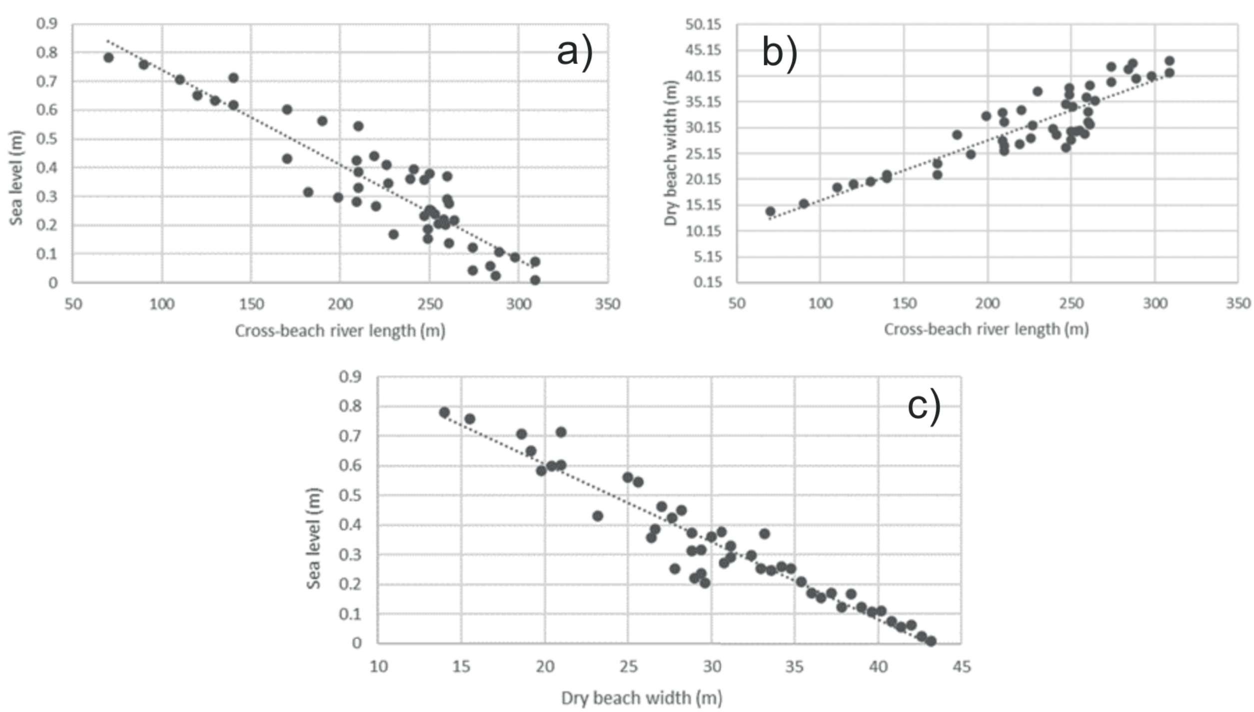

Figure 7

Annual changes of the Piaśnica mouth length in relation to: (a) The sea level. (b) Dry beach parameter (data source: SatBaltic). (c) The relation of sea level to the dry beach width.

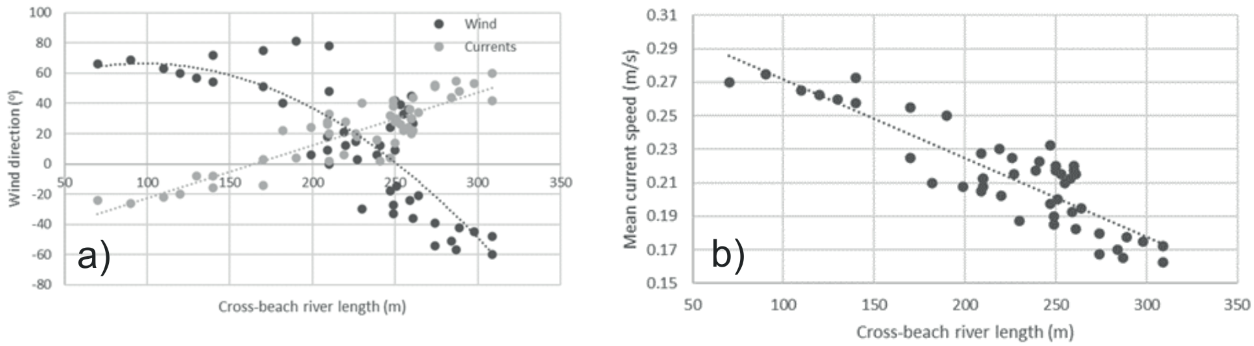

Figure 8

Annual changes in the Piaśnica mouth length in relation to: (a) Wind direction. (b) Current speed (data source: SatBaltic).

much more variable. The relationships calculated for the averaged parameters showed a much higher accuracy of the results (Figure 8b). Generally, changes in the current direction and wind speed do affect the length of the mouth of the Piaśnica. The higher the mean current speed (not the instantaneous speed!), the shorter the mouth (Figure 8a). Importantly, the eastern direction is of a key importance with respect to both the wind and currents. It can be also noticed that the direction ceases to be important above a certain wind and current speed. A change in map accuracy may be a source of uncertainty; the solution is to analyse more data. At the second stage, the cloud cover above the study site was analysed at a 100-m resolution. After the Sentinel-3/OLCI map accuracy was adjusted, the reference values had to decrease: the importance of small objects was momentarily diminished, but their statistical significance increased. A comparison of the reference maps, with respect to the SatBaltic grid, requires that the coastal area, including the entire part of the sea adjacent to the

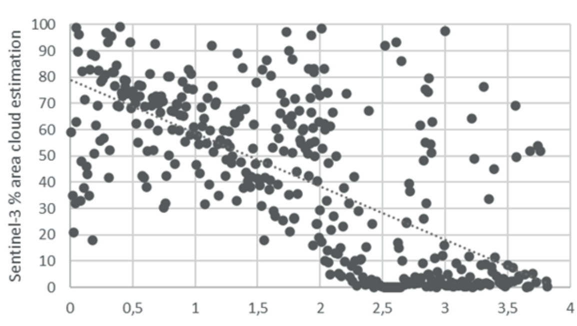

Figure 9

Annual changes in cloud cover on selected maps of the study site in the Piaśnica mouth area in relation to water turbidity index.

river mouth (a 1-km^2 pixel), be defined. (Figure 9) illustrates a relationship between the cloud cover and the turbidity index (Dogliotti et al., 2015; Nechad et al., 2010). Basically, the function is linear and declines to zero. This may result from the nature of the turbidity index which has been determined from radiation, at least partly reflected from the clouds, rather than directly from the sea. Thus, it is revealed how an incorrect cloud cover estimation may affect environmental information. The environmental data referred to allow to draw some general conclusions. Firstly, analysis of geophysical data should be based on data averaged over a longer period of time, e.g., adjusted to the course of geomorphological processes (i.e., two consecutive measurements should be taken at an appropriate time interval or a larger amount of data should be averaged). The week-long interval between consecutive measurements, adopted in this study, proved sufficient to record morphological processes at the mouth of the Piaśnica. Secondly, the effects of accurate cloud detection may play a minor role only during supervised analyses (qualitative). With respect to unsupervised analyses (quantitative), the uncertainty introduced by the cloud detection should not be ignored and has to be treated with utmost care. The results suggest unequivocally that the satellite data presented are amenable to be used in geophysical (geomorphological and oceanographic) research in the coastal zone, and uphold the hypothesis posed at the beginning. Several-metres objects can be successfully analysed at this stage.

4. Discussion

Relationships between cloud cover and cloud-reflected radiation lie in the heart of processes, recorded at the satellite level, that take place in the atmosphere of the coastal zone. Satellite data from the Copernicus system Sentinel-2/MSI and Sentinel-3/OLCI (Baetens et al.,2019) as well as environmental data made it possible to follow the effects of cloud cover on the correct interpretation of Earth-surface morphological characterisation. Inferences regarding the cloud cover extent emerged from comparisons between products supervised by an experienced observer and products of unsupervised systems which supply results together with satellite data; in addition, the author's own solution adjusted to the local characteristics of the Baltic Sea was taken into account. The study described was focussed on a clearly convection-affected coastal area, the could cover above which has a local tendency to be higher for optically thinner clouds and lower for optically distinct clouds, compared to the systemic solutions. The absolute difference is below 5%, which confirms the surprisingly high efficiency of the global systems and, at the same time, opens up a possibility of conducting focussed research on a local level to, e.g., increase the accuracy and speed of the work. The magnitude of discrepancies may result from input parameters of the systemic solutions which are mainly aimed at providing global estimation, and from the different nature of data sets used in comparisons. It has been assumed that an experienced observer working in a supervised manner is able to assess the state of the atmosphere. With respect to the data used in this study, more than 96% of clouded areas in the Sentinel-2/MSI were identified correctly. Although the percentage for the Sentinel-3/OLCI was lower (92%), it was a very good result and may be explained by a higher information quality and the supervised data used in the comparisons.

5. Conclusions

This study presents information on the derivation of comprehensive and much-needed data in oceanography on the transformation of the marine coastal zone. A method supervised by a subjective observer provided an alternative to compare system solutions of source elimination limiting remote sensing of the Earth's surface. Several representative samples and diverse sources were used, including in-situ. Supervised estimation was included as a priority, as proper assessment of cloud status in an automated manner is difficult.

The study compiled different seasons and series lengths over the southern Baltic, the Gulf of Gdansk and the coastal zone of the sea. In the designated region, more than 96% of the cloud areas in the Sentinel-2/MSI were identified correctly. Although the percentage for Sentinel-3/OLCI was lower (92%), it was still a very good result and can be explained by the higher quality of the information. Although the accuracy of the system solutions is high, at the same time it confirms the need for focus studies at the local level in order to, for example, increase accuracy and speed. This study shows that the automated elimination of clouded areas is at a good level, but the information management plans should take into account the revealed differences in order to make recommendations for accurate local estimates. The methodological process presented in this study shows the importance of using multiple methods and sources to estimate cloud parameters, as this reduces uncertainty in, e.g., morphological studies. Although the results obtained using the river length analysis based on the radiation map in a cloudless atmosphere proved to be successful, caution should be exercised when implementing automatic methods especially with regard to the ever-increasing quality of satellite data. It is possible to obtain erroneous results, as was the case in situations of overestimation by automated systems revealed in this study. It is also suggested that in the future, automated methods will be necessary to determine cloud parameters due to the constantly increasing amount of information. In order to control the reliability of quality parameters, random supervised assessments may be necessary. Given the systematic increase in the quality and quantity of satellite data and its importance for society and the environment, automated methods must be recognised as a priority source for coastal zone studies at the local level as well.

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