PROPAGATION OF THE VISTULA LAGOON OUTFLOW PLUME INTO THE BALTIC SEA: SATELLITE OBSERVATIONS, IN-SITU MEASUREMENTS AND NUMERICAL MODELING

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ABSTRACT

The influence of wind and hydrodynamic processes on spreading of turbid waters from the Vistula Lagoon into the Baltic Sea was studied. The research was based on joint analysis of remote sensing data, simultaneous subsatellite measurements and numerical modeling. The sharp difference in water optical properties of the Baltic Sea and the Vistula Lagoon, affected by intense summer bloom of cyanobacteria, made it possible to study the evolution and transformation of the outflow in July - early August 2014 using visible satellite data. Forced by coastal jet streams, the outflow spread throughout the Bay of Gdansk, dramatically affected by the circulation processes in the bay. A three-dimensional structure of the outflow was analyzed. In-situ measurements revealed the presence of the Vistula waters exclusively at the upper water layer. A numerical simulation of suspended matter spreading over the Bay of Gdansk was performed using a modified Princeton Ocean Model (POM).

Index Terms— the Baltic Sea, coastal remote sensing, in-situ measurements, numerical modeling

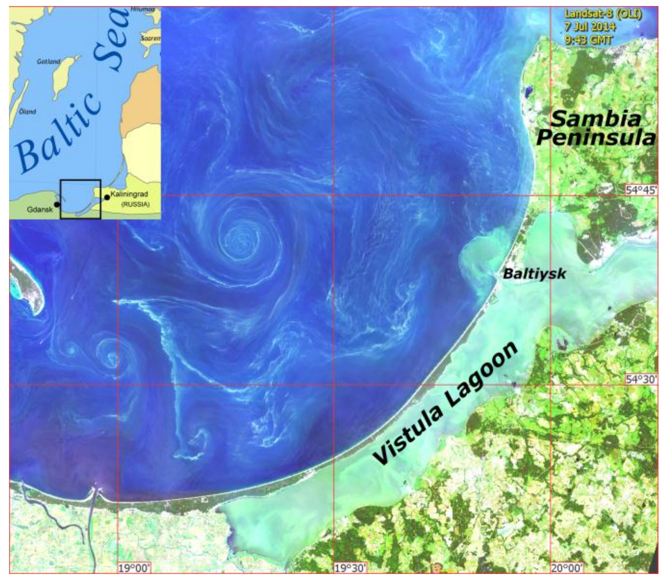

Figure 1. The map of the study area. True-color image of the southeastern part of the Baltic Sea acquired by OLI Landsat-8 on July 7, 2014, shows the Vistula Lagoon's outflow plume and eddies in the Bay of Gdansk. Credit: USGS.

1. INTRODUCTION

The ecological state of inland seas evokes serious concern among experts. There are multiple reasons, such as oil pollution increase due to the development of oil and gas industry and marine traffic, growth of concentration of suspended matter in water resulting in higher water turbidity and lower bioproductivity, anomalous algae bloom. The most important task of environmental monitoring consists not only in detecting anthropogenic and biogenic pollution of the seas but also in forecasting the spread of pollutants. Pollution forecast is feasible only based on a detailed knowledge of the whole variety of hydrodynamic processes typical of the region of interest. The tasks of pollution detection and investigation of dynamic processes in the marine environment are closely interconnected, since, once in the seawater, pollutants become part of the environment and evolve along the same laws. An acute problem of the Baltic Sea is eutrophication [1][2], that is multiplication of biogenic elements accompanied by an increase in biogenic productivity of the basins. The excess of nutrients results in sharp growth of the phytoplankton biomass, particularly rapid development of cyanobacteria [3].

The Gdansk basin, including the Vistula Lagoon, is among the most severely eutrophicated areas of the Baltic Sea [4]. Regular summer bloom of potentially toxic blue-green algae induces adverse changes in its water regime, worsens the oxygen status, causes fish mortality, etc.

In satellite visible data, the areas of enhanced bloom are clearly distinguished by bright green or green and brown colors. A sequence of satellite images of the same basin allows retrieving information on sea surface currents and the main hydrodynamic structures causing mesoscale current variability [5][6]. It is of high scientific and practical importance to investigate the impact of these eddy structures on the transport of various pollutants of the sea surface, including oil.

As part of a complex study of coastal waters of the southeastern part of the Baltic Sea, our scientific expedition took place in late July – early August 2014. The investigation of the influence various hydrodynamic and meteorological processes

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have on the spread and structure of turbid waters carried out of the Vistula Lagoon via the Kaliningrad Sea Canal (the Strait of Baltiysk) into the sea was among its main tasks. The task was solved based on joint analysis of satellite images and data of simultaneous subsatellite measurements.

2. STUDY AREA

Field studies were performed in the 20-mile zone in the southeastern part of the Baltic Sea on the Strait of Baltiysk beam and near the Sambia Peninsula (Fig. 1). The outstanding feature of the Sambia Peninsula is the Vistula Spit separating shallow waters of the Vistula Lagoon from the sea. Water exchange occurs through the narrow Strait of Baltiysk; its width reaches 400 m, length 2 km, average depth 8.8 m. The Vistula Lagoon is a bay – almost enclosed water body, into which many rivers disembogue their waters. The hydrological regime of the Vistula Lagoon is affected by fluctuations of the Baltic Sea level and river discharges. Water salinity at the entrance to the Strait of Baltiysk amounts to 2-6 PSU (practical salinity units), whereas surface waters salinity in the coastal area is nearly 7.3 PSU [7].

The strength and direction of prevailing winds determine the pattern of the currents in the bay. The north and northwestern winds pile up water into the lagoon where it moves along the sea shore counterclockwise. On the contrary, the southeastern and south winds result in clockwise water circulation, water mass flows out of the lagoon through the Strait of Baltiysk. Statistical average data on the regime of incoming currents (sea water inflows) and outflows (lagoon water carry-over) shows: unidirectional inflows and outflows make up 74.9%; 11.7% is accounted for by two-layer exchange flows (inflow occurs in bottom waters, outflow – in near-surface layer) and 13.4% - bidirectional flows – back-and-forth [7]. During the period preceded the field studies, under the influence of eastern winds a water plume developed out of the Vistula Lagoon, which is distinctly manifested in satellite images (Fig. 1; 2).

2. SATELLITE OBSERVATIONS

A significant difference in optical properties of the Baltic seawater and the Vistula Lagoon water in the period of intense phytoplankton bloom make it possible to observe the spread and evolution of the Lagoon’s outflow plume based on satellite visible data. In late July – early August 2014, data from Terra/Aqua MODIS, Landsat-8 OLI/TIRS, Landsat-7 ETM+ sensors were obtained in cloudless or low-cloud conditions. In total, 29 satellite images were processed and analyzed.

The MODIS data were used to derive the true-color images, water leaving radiance at 0,551 µm, chlorophyll-a concentration and sea surface temperature products. Most clearly the plume can be distinguished in the true color images, where it appears like light-green stream, and on the maps of water leaving radiance. In the images obtained by OLI and TIRS Landsat-8, characterized by significantly higher spatial resolution, the plume structure can be clearly seen not only in true-color images (30-m resolution), but in infrared range as well (100-m resolution).

The true-color images obtained from 22.07.14 to 09.08.14 from Aqua MODIS and Landsat-8 OLI data are shown in Figure 2. Subsatellite measurements started on 29 July. Nevertheless, it is important to consider the whole series of 12 satellite images in

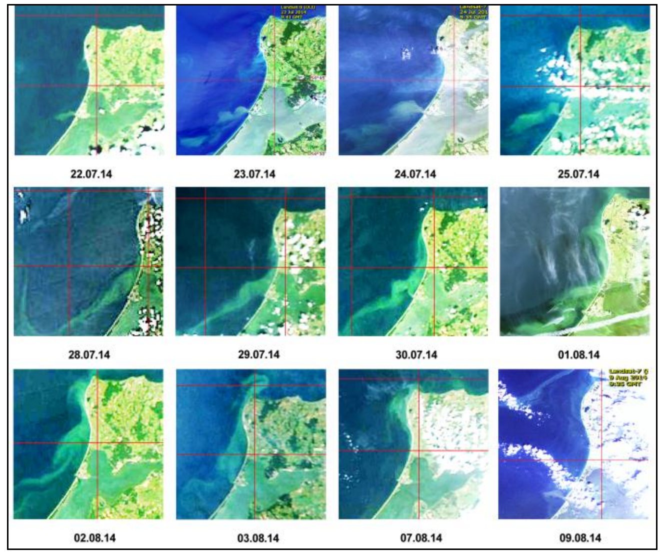

Figure 2. Fragments of true-color images obtained from 22.07.14 to 09.08.14 from Aqua MODIS and Landsat-8 OLI data show Vistula Lagoon’s outflow evolution and transformation.

order to analyze the influence of different factors on the spread of the outflow. The data permitted to track the outflow plume evolution starting from its appearance on 22 July, over to its maximal spread in the Gdansk Bay by 30 July and subsequent drift to northeast along the Sambia Peninsular coast accompanied by an eddy formation on 9 August near Cape Taran (northwestern part of the Sambia Peninsula).

3. DATA AND METHODS OF THE FIELD EXPERIMENTS

The dynamic conditions in the area of the subsatellite experiment were investigated using the acoustic Doppler current profiler TRDI Workhorse Sentinel 300 kHz (ADCP) mounted on board a research catamaran. Also, water probing was performed on the route using YSI CastAway CTD and YSI 6600V2 multiparametric probe equipped with water turbidity and dissolved oxygen sensors. In addition to catamaran measurements, water hydrological structure was investigated near the town of Baltiysk and in the Baltiysk Strait from a small motor boat.

In the course of the expedition, six on-route ADCP cross-sections to distances of up to 20 miles off the coast were performed in combination with CTD-probing, water sampling and continual monitoring of meteorological parameters. Coastal boat activities included hydrological measurements in the Vistula Lagoon, Strait of Baltiysk and near the open sea coast.

4. RESULTS

4.1. The influence of wind conditions on outflow spreading

Water circulation in this region of the Baltic Sea develops under the influence of the wind field in contrast, for example, to the Black Sea, where water flow is largely conditioned by the permanent Rim Current. In the period from 22 to 29 of July 2014, the winds of eastern (northeastern, southeastern) direction prevailed, which contributed not only to outflow intensity of the plume, but to initiation of currents under the upwelling conditions as well. Along the shore, the streamline of currents was anticyclonic. The plume extended in the same direction, to the south-west. Starting 28 July, the wind slackened, its direction changed, first to southern and then to western (01.08.2014). In this period, the plume stream proliferated over the Bay of Gdansk and reached its maximum length by 30 July. After that, till the end of observations the wind remained low and constantly changed its direction. Distinct southern and western components of wind vector lead to reduced water flow from the lagoon and the plume starts to proliferate in the northern direction along the Sambia Peninsula, accompanied by formation of a cyclonic eddy near Cape Taran. So, the joint analysis of satellite data and wind conditions in the study area revealed that the main extension direction of a turbid water plume from the Vistula Lagoon derived from satellite data is similar to the one of wind-initiated currents.

4.2. Comparison of results of in-situ measurements and satellite observations

The aim was to assess the accuracy of plume characteristics retrieval from satellite data and determine its 3D structure. Subsatellite measurements of current and parameters of hydrological structure in the region of the plume were undertaken. The results were compared with satellite data. Let us consider results obtained 30 July 2014. Figure 3 presents the general outline of the experiment and surface current measurements by means of ADCP. The black arrows show current vectors along the ADCP transect. CTD stations in the coastal area are depicted by points, each corresponding to three stations. The main directions of surface currents revealed from ADCP data are shown by blue arrows.

As was demonstrated by ADCP measurements at the exit from the Strait, the current at 4 m depth was characterized by low magnitude and on average reached 5-7 m/s with the predominant north-eastern direction. The plume contour, detected with the use of MODIS Aqua data, also moved to the northeast along the shore. At 4.5 km distance off the shore, the surface currents changed the direction to the south-west. Besides, gradual growth of the current velocity up to 10-15 cm/s was observed. The plume of Vistula waters also shifted to the south-west. At 7-8 km from the shore, the speed of currents increased to 20-30 cm/s, and the direction turned to the south-southwest, which resulted in the plume contour moving closer to the shore. The current change was registered down to a depth of 10 m. No direction changes occurred further downward, where water mass flowed at velocities of up to 10 cm/s in the northeastern direction.

One of the core tasks of the research was to verify remote sensing data that were used for detection of the plume area. Earlier it was noted that the plume area in true-color satellite images was identified as a field of more turbid waters. ADCP acoustic backscatter data make it possible to determine areas of raised suspended matter concentration at a high degree of accuracy and, thus, identify an outflow of turbid Vistula Lagoon waters. Figure 4a shows backscatter distribution along the ADCP transect. Notice that the current reversal point falls in the area of low backscatter, in the absence of water from Vistula Lagoon.

The satellite images obtained at the time of the measurements confirm the absence of Lagoon waters in this area. At a distance of 4-6 km from the coast, we see higher backscatter values in agreement with satellite data. At a distance of 8 km, the backscatter diminishes to the levels of open seawater of the Baltic Sea.

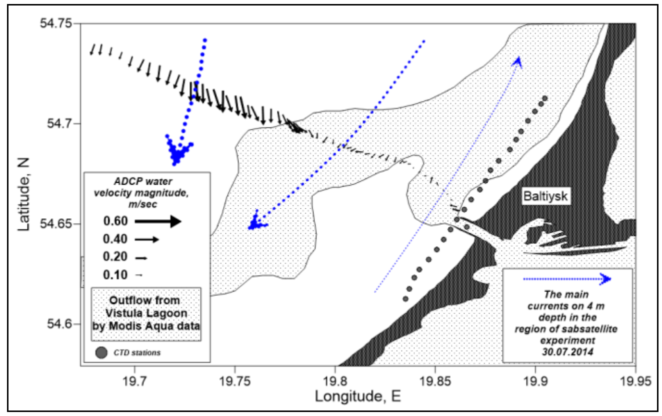

Figure 3. The general scheme of in-situ measurements during the field study on 30 July 2014; and results of surface currents measurements by means of ADCP.

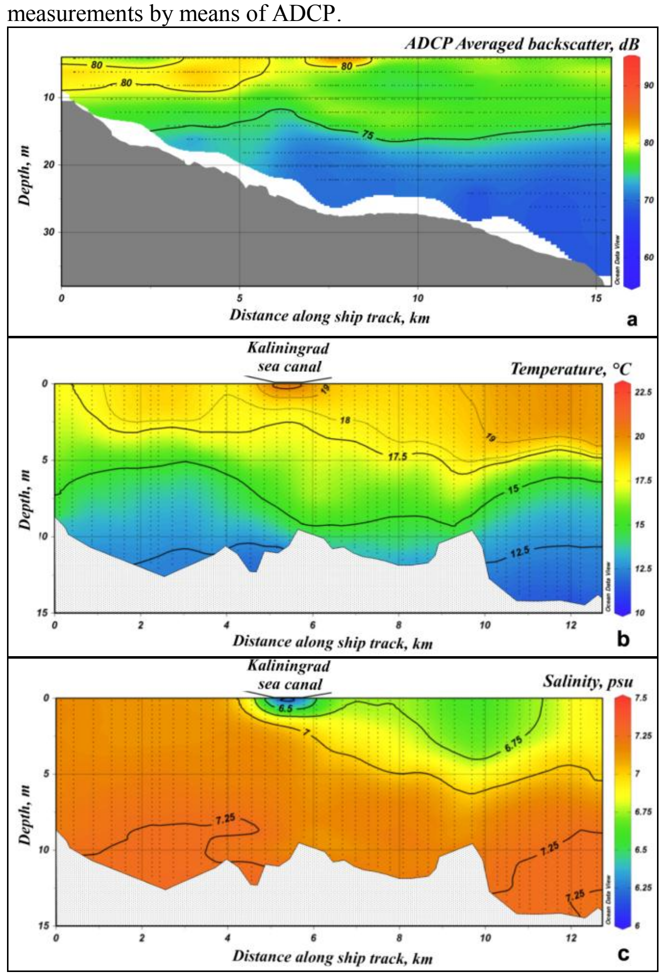

Figure 4. Manifestation of outflow waters in ADCP average backscatter chart (*a*); temperature map (*b*) and salinity field (*c*) of 30.07.2014.

In order to identify the distributed character of the water plume flowing from the Vistula Lagoon, CTD-profiling was performed along the shore (42 stations), the profile line cut across the plume. The distribution of temperature and salinity of the seawater along the coast line is given in Figures 4*b,c*. In these pictures, the profile lines are oriented from the south-west to the north-east. The plume on the surface at nearly 300 m distance from the shore is characterized by water salinity of 6.25 PSU and temperature of 20.5°C. Further to south-west, the thermohaline structure acquires more pronounced marine character with water temperature not exceeding 18°C on the sea surface and salinity of 7.2 PSU, typical of the open Baltic Sea water in the studied region. It is notable that the salinity field is almost homogeneous in both vertical and horizontal directions to the south-west of the Canal. However, when the north-eastern region was examined the decrease in salinity and growth of temperature were observed to the depth of ~5 m.

It is characteristic that the plume waters were not detected at the 7-9 km distance along the CTD-profile. The decreased salinity area proliferates to the depth of 1-2 m. At the same time, at 10-12 km from the profile line, a region with temperature >19°C and salinity <6.75 PSU that propagates to 4-5 m depth was revealed.

5. NUMERICAL MODELING OF SUSPENDED MATTER DRIFT

A numerical modeling of suspended matter drift was implemented with the aim to estimate the impact of hydrodynamic processes and wind conditions on the spread of the outflow plume from the Vistula Lagoon. The simulation experiment was performed on the basis of Princeton Ocean Model [8]. The modeling area encompassed the southeastern Baltic Sea with horizontal resolution of ~ 1 km. The radiation condition [8] was used on the partly opened lateral boundaries of the modeling area. We used output data from a version of HIRLAM applied at the Estonian Meteorological and Hydrological Institute providing meteorological parameters on approximately 10 km horizontal grid with 3 h time step was used. The computing period was from 20.07 to 10.08.2014. The initial stratifications of temperature and salinity were assumed horizontally uniform, they were set using data on typical thermohaline structure of the southeastern Baltic waters in summer. The initial distribution of a passive tracer was close to the one identified on 24.07.2014 in satellite images.

Figure 5 presents modeling results for 30.07 marked by a maximal length of the outflow plume over the time of observation (left) and for 08.08, when an eddy near Cape Taran began to form (right).

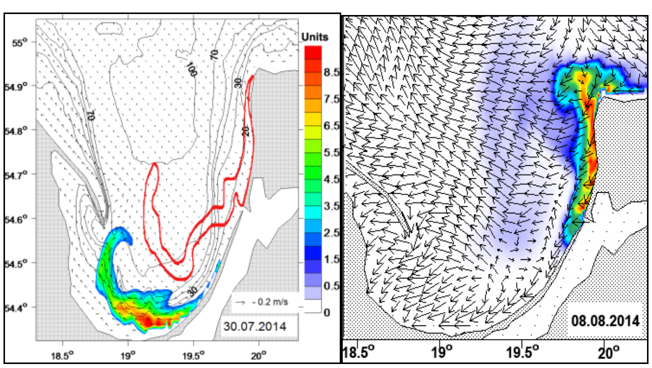

Figure 5. Numerical modeling result of suspended matter drift: left - for 30 July 2014, when the outflow was of maximal length. Red line corresponds to the outflow plume position derived from MODIS Aqua data; right – for 08 August 2014, during eddy formation near Cape Taran.

Although the model does not take into account some important parameters, such as constant inflow of suspended matter and the effect of circulation processes, the modeled suspended matter transfer agrees well with the outflow plume observed in satellite data.

6. CONCLUSION

Almost cloudless weather conditions persisting for more than two weeks in late July – early August 2014 made it possible to observe the spread of an outflow plume from the Vistula Lagoon over the southeastern Baltic Sea. Simultaneous in-situ measurements showed that the outflow, whose plume was identified in satellite images, affects the fields of temperature and salinity, as well as scattered acoustic signal that can be associated with water turbidity. The water from the Lagoon practically did not spread deeper than 5 m. A joint analysis of satellite data and subsatellite measurements demonstrated that satellite visible data allow detecting rather correctly the spread of the outflow from the Vistula Lagoon, which is confirmed by ADCP acoustic scattering data.

The joint analysis of satellite data and numerical modeling results permitted estimating the impact of wind on the spread of the outflow plume. The impact was shown to be the most significant, responsible for shaping the field of main currents in the area. Nevertheless, modeling results can differ dramatically from satellite observations if water circulation is excluded from consideration. This should be kept on mind when forecasting the spread of pollutants, first of all oil, in the coastal zone in case of pollution danger for the coast.

7. REFERENCES

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