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Digital Information System for the Polish Marine Areas – Modelling of Structures and Dynamics of Physical Processes in the Southern Baltic

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Abstract

Researching the dynamic environment of the Baltic Sea requires an interdisciplinary approach, with numerical models and computer simulations becoming essential tools. The 3D CEMBS-PolSEA ecosystem model, developed at the Institute of Oceanology of the Polish Academy of Sciences, aims to determine the basic hydrodynamic parameters of the southern Baltic Sea. The CSI-POM service (Digital Information System on the Environment of Polish Marine Areas) consists of new tools for studying the structures, dynamics, and variability of physical processes in the southern Baltic. The service includes tools for determining the thermocline, halocline, and pycnocline, conducting spatio-temporal analysis of water column structure, automatic detection of vortices, testing water mass inertia under forecasted wind forces, and automatic detection of upwelling currents. The novelty of this work lies in the development of tools for studying the dynamics of the structure and variability of physical processes in the southern Baltic Sea. These innovative techniques support scientists, the maritime community, and regulatory bodies by providing detailed insights into local phenomena such as vortex formation, water mixing. The tools are implemented on the project server and the Tryton+ supercomputer, enabling high temporal and spatial resolution results. The CSI-POM system's operational mode ensures access to the latest model results, with real-time and forecasted data. This enhances understanding and forecasting capabilities, informing about the current state of the environment and potential threats in the open sea.

Keywords

Numerical modelling; Baltic Sea; Polish Marine Areas; Ocean hydrodynamic

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1. Introduction

The study of internal sea systems holds a pivotal role in oceanographic research, especially concerning the World Ocean. The Baltic Sea, due to its complex functioning, is of particular interest not only for its scientific intrigue but also for its economic and political significance. The unique characteristics of the Baltic Sea stem from its salinity balance, influenced by significant freshwater inflows and a limited supply of saline water from the North Sea. This delicate balance positions the Baltic as one of the largest brackish water bodies globally.

The salinity distribution in the Baltic Sea is uneven, with dense, saline waters from the North Sea infiltrating the bottom layers, creating a pronounced halocline and significant salinity gradients. Salinity levels decrease from the Danish Straits along the transit zone, which serves as the axis for the deep basins where these inflows spread. River runoff further reduces the salinity of surface waters, while bottom waters exhibit increased salinity due to the North Sea inflows. Vertical mixing processes mitigate the salinity gradient, leading many researchers to classify the Baltic Sea as an estuary, characterized by such processes (Marmefelt and Omstedt, 1993; Stigebrandt, 1983).

Geographically, the Baltic Sea is relatively cold, situated in the northern temperate climate zone and influenced by eastern, continental air masses. The specific bathymetry, which isolates the Baltic from the warm waters of the North Atlantic Current, contributes to lower winter surface temperatures compared to the North Sea. Surface water temperatures range from 0 to over 20°C, and the average salinity of surface waters is significantly lower than that of the ocean, approximately 7.5 PSU (Leppäranta and Myrberg, 2009).

These environmental conditions have profound effects on the Baltic ecosystem, which is home to fauna adapted to low-salinity environments. Regular spring-summer algal blooms, now a major environmental and economic issue, are notable in this sea, with over thirty species of phytoplankton identified as harmful to human health (Öberg, 2017).

Researching the dynamic environment of the Baltic Sea presents substantial challenges, requiring an interdisciplinary approach. While new technological solutions aid scientists, they are not without limitations. Numerical models and computer simulations have become indispensable tools, surpassing traditional field studies using buoys, ships, or satellites in effectiveness. Such models are particularly vital for addressing interdisciplinary issues common in oceanographic research.

The numerical modelling of hydrodynamic and biochemical phenomena in the Baltic Sea is intricate, necessitating high-quality input data on river inflows, atmospheric conditions, and boundary conditions. The accuracy of these models, and their alignment with reality, hinges on the quality of this data. Given the dynamic nature of the environment, simultaneous environmental measurements and modelling studies are essential for providing a reliable depiction of the actual state of the studied area. High temporal and spatial resolution results offer detailed insights into local phenomena such as vortex formation, water mixing, and intrusions.

In the Marine Ecohydrodynamics Laboratory at the Institute of Oceanology of the Polish Academy of Sciences in Sopot, the 3D CEMBS ecosystem model was developed to determine the basic hydrodynamic and biochemical parameters of the Baltic Sea environment (Dzierzbicka-Głowacka et al., 2013a, 2013b). The accuracy of a numerical model is always a compromise between the model resolution and the available computing power and time required to perform the calculations. Continuous improvements and area-specific refinements are necessary for the model to become a reliable tool for assessing and forecasting the Baltic environment's state. In order to best represent the hydrodynamics of the southern Baltic Sea, we have developed the 3D CEMBS-PolSEA model (Dybowski et al., 2024b).

Presently, various scientific institutions across Europe, including those in Sweden, Denmark, Finland, and Poland, are engaged in modelling the Baltic Sea's hydrodynamic parameters, e.g., HIROMB, RCO, NEMO, SCOBI, DMI/ERGOM, HIRLAM, BALTSEM, CEMBS, M3D (Andrejev et al., 2011; Bossier et al., 2018; Dzierzbicka-Głowacka et al., 2013a, 2013b; Gröger et al., 2019; Gustafsson et al., 2014; Hordoir et al., 2019; Jedrasik et al., 2008; Lips et al., 2016; Neumann et al., 2002). However, none of the aforementioned solutions provide operational access to the type of data that we have developed within the CSI-POM service (Digital Information System for Polish Marine Areas). The novelty of the CSI-POM service lies in developing new tools for studying the structures, dynamics, and variability of physical processes in the southern Baltic: i) determining the thermocline, halocline, and pycnocline for the entire model domain, ii) spatio-temporal analysis of water column structure for parameters such as temperature, salinity, and currents, iii) automatic detection of vortices, iv) testing the inertia of water masses under forecasted wind forces, and v) automatic detection of upwelling currents.

The CSI-POM system is designed to serve a wide range of social and economic stakeholders. A key objective is to encourage collaboration between decision-makers in the maritime economy and the scientific community, leveraging scientific expertise for informed decision-making. The system is freely accessible via the website (www.csipom.pl/en/), providing comprehensive environmental data to various users, including scientists, students, tourists, maritime professionals, and local communities. Moreover, CSI-POM aims to enhance ecological awareness and foster a sense of responsibility toward environmental stewardship.

The insights gathered during consultations suggest that the CSI-POM system has the potential to find practical applications across various sectors, including information services, transport and logistics, fisheries, and offshore industries. It is anticipated that professionals such as captains and logistics managers will increasingly rely on the system. Their responsibilities are multifaceted, involving the coordination, execution, and oversight of diverse operations and information flows. These tasks demand the highest standards of quality, efficiency, and precision. The CSI-POM system is poised to become an indispensable tool, supporting these professionals in their routine operations.

This article presents the CSI-POM Digital Information System's first stage for modelling the structures and dynamics of physical processes in the South Baltic, aiming to enhance our understanding and forecasting capabilities in this complex marine environment.

2. Material and methods

The main goal of the project 'Digital Information System for Polish Marine Areas (CSI-POM)' was to develop an advanced numerical service that enables efficient monitoring and forecasting of hydrodynamic (CSI-POM Stage 1) and biochemical (CSI-POM Stage 2) conditions in the southern Baltic Sea. CSI-POM Stage 1 (Figure 1) aimed to provide a comprehensive solution that integrates numerical modelling with modern tools for analyzing physical processes to ensure more complete information about the state of the marine environment.

The model is based on the source code of the Parallel Ocean Program (POP) model. The ecosystem model of the Baltic Sea, 3D CEMBS, was also developed on the basis of this code.

The high-resolution 3D CEMBS-PolSEA model, developed as part of the project, has a horizontal resolution of approximately 575 m. In the vertical aspect, it is divided into 66 levels with surface layer thickness of 5 meters. The model also has a satellite data assimilation module for sea surface temperature (Janecki et al., 2021).

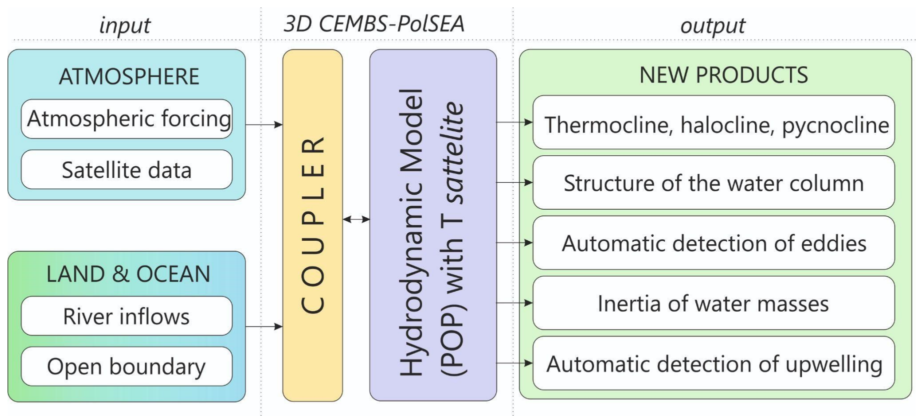

Figure 1. Structure of the Digital Information System for Polish Maritime Areas (CSI-POM Stage 1).

Data from the operational 3D CEMBS model (www.cembs.pl), is used to determine the boundary conditions at the water-water interface in the 3D CEMBS-PolSEA model.

Meteorological data (including, among others, rainfall and snowfall) are obtained from the atmospheric model UM (Unified Model) developed at the Interdisciplinary Modelling Center of the University of Warsaw. The 3D CEMBS-PolSEA model uses real-time information from the Institute of Meteorology and Water Management in Gdynia (Poland) about the freshwater inflow from rivers that have their outlets in the studied region (Dybowski et al., 2020, 2019).

3. Results

The validation of the model was done by comparing the results obtained from the model with in-situ and satellite data as well as data from other models to determine the level of agreement. A satisfying level of agreement was found and reported by Dybowski et al. (2024b) and is summarized in Table 1. Subsequently, decisions were made regarding the model's suitability for application.

Sea current values from the 3D CEMBS-PolSEA model were compared with data from the Copernicus Baltic Sea Physics Reanalysis (https://doi.org/10.48670/moi-00013), the characteristics of which were consistent (Dybowski et al., 2024b, accepted). Both the u and v components of the current speed had a statistical distribution of values consistent with the Baltic Sea Physics Reanalysis.

Figure 2 depicts exemplary results for basic hydrodynamic parameters from the 3D CEMBS-PolSEA model on April 7, 2023. The results presented in Figure 2 illustrate various oceanographic parameters across the southern Baltic Sea.

The four panels of Figure 2 provide the following information:

- Map of the surface temperature shows the spatial distribution of surface water temperature (°C).
- Map of the surface salinity in Practical Salinity Units (PSU). It shows a gradient of salinity, with the highest salinities around 9–10 PSU near the open sea, and lower values near the coast, particularly around river inflows or freshwater sources.
- Map of the sea surface height displays sea surface height variations (in cm) relative to the mean sea level. The red areas indicate positive sea level anomalies, while the blue areas represent negative anomalies. This pattern reflects the influence of atmospheric pressure systems, or wind forcing.
- The last panel depicts surface current velocities (in cm/s) along with vectors indicating the direction of the currents. The background shading represents current strength, with darker regions indicating stronger flows. The vectors reveal a circulation pattern, possibly influenced by wind forcing or coastal dynamics.

Together, these panels provide a comprehensive overview of the modelled physical conditions in the study area, including temperature, salinity, sea level anomalies, and surface currents.

Table 1. Summary of 3D CEMBS-PolSEA model validation for n = 11029 measurements.

	ICES		CEMBS-PolSEA		ICES vs. CEMBS-PolSEA		
	Mean	STD	Mean	STD	cRMS	Pearson's r	Mean Error
Temperature [°C]	7.29	3.54	7.25	3.35	1.14	0.95	0.04
Salinity [–]	9.05	2.58	9.17	1.79	1.29	0.89	−0.12

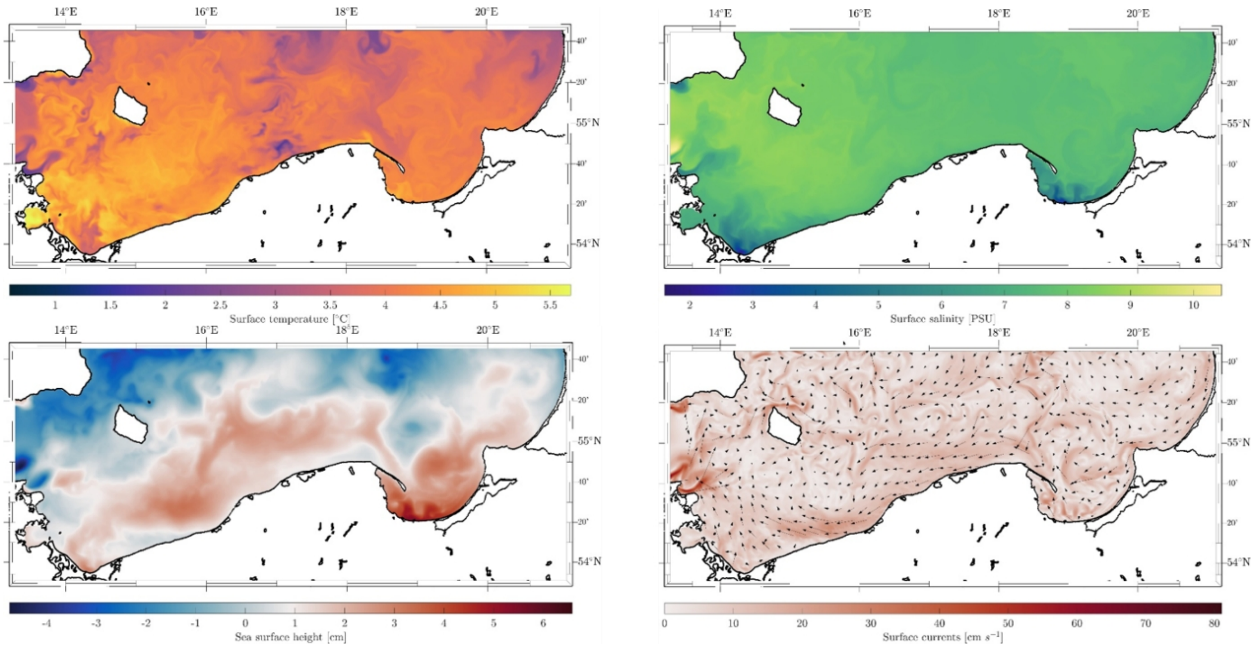

Figure 2. Presentation of exemplary results from the 3D CEMBS-PolSEA model of the Southern Baltic Sea for basic hydrodynamic parameters (temperature, salinity, sea surface height, and currents) on April 7, 2023.

3.1 Tools for determining the structure, dynamics, and variability of physical processes in the Southern Baltic Sea

As part of the work, new research tools/numerical modules were developed to determine the structure, dynamics, and variability of physical processes in the Southern Baltic Sea:

1. Analysis of spatio-temporal structures of physical parameters in the Southern Baltic Sea.
2. Determination of key parameters (top, bottom, thickness) for thermocline, halocline, and pycnocline.
3. Automatic detection of marine eddies.
4. Study of inertial mass movements under forecasted wind forcing.
5. Automatic detection of upwelling currents.

These innovative techniques will be invaluable support for scientists, the maritime community, and regulatory bodies. The scope of work included the creation of source codes (functions, scripts) in various programming languages (Matlab, Python, etc.) for individual tools and their implementation (and integration with the project website) on the project server and the Tryton+ supercomputer in 2024.

3.1.1 Tools for analysis of spatio-temporal structures of physical parameters in the Southern Baltic Sea

One of the tools developed is for creating a spatio-temporal analysis of water column structure for investigated hydrodynamic parameters in the 3D CEMBS-PolSEA model. This product allows drawing profiles on the map and then, for a selected day and profile, generates an image of the cross-sectional profile variability for the selected parameter.

The first step was to create the getProfileCoords.m function, which performs linear interpolation between points (P1, P2,..., Pn) to obtain evenly spaced coordinates on the profile. As a result of the function's operation, all intermediate locations on the lines connecting these points are determined.

Another function used in creating spatio-temporal profiles is the getProfileData.m function, which is used to retrieve data from netCDF files (from the 3D CEMBS-PolSEA model) at specified points on the profile.

The final product is the source code profile.m, which creates a visualization of data on the cross-sectional profile for the selected date. The described functions are placed on the backend server of the CSI-POM system and integrated with an interactive portal for the user.

An example of water temperature for July 10, 2024, on a user-selected profile (Figure 3A) is shown below (Figure 3B).

In addition to the ability to present vertical cross-sections along a specified path, the service also allows for the presentation of 3D CEMBS-PolSEA model results as a time series for a specific (selected on the map) point, as well as for a given time interval and selected depth. This form of presentation is available for four basic physical variables, namely temperature, salinity, ocean currents, and sea surface height (Figure 4).

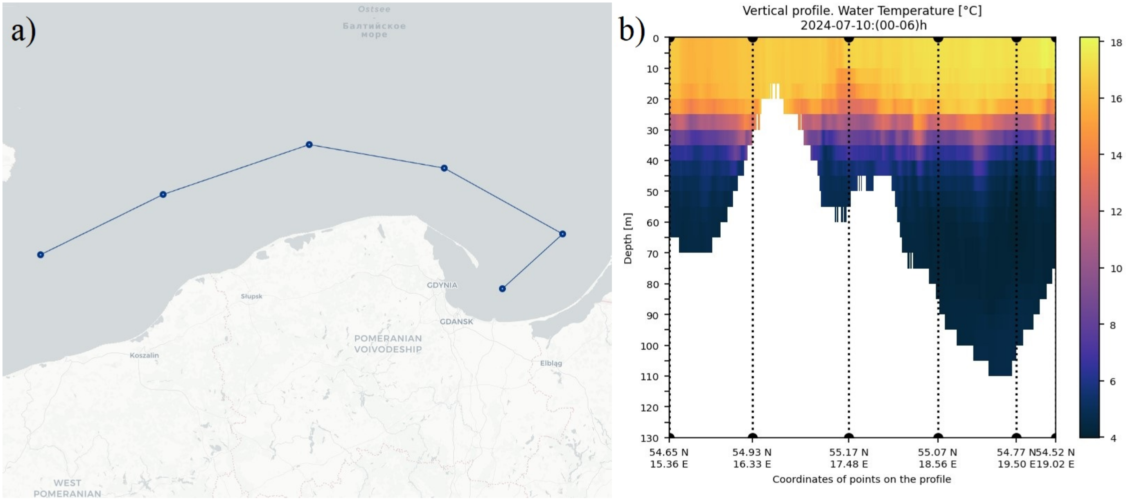

Figure 3. a) User-selected trace on the map for which the CSI-POM system will generate a cross-sectional profile, and b) cross-section profile of water temperature on July 10, 2024, along the path passing through 6 points selected by the user.

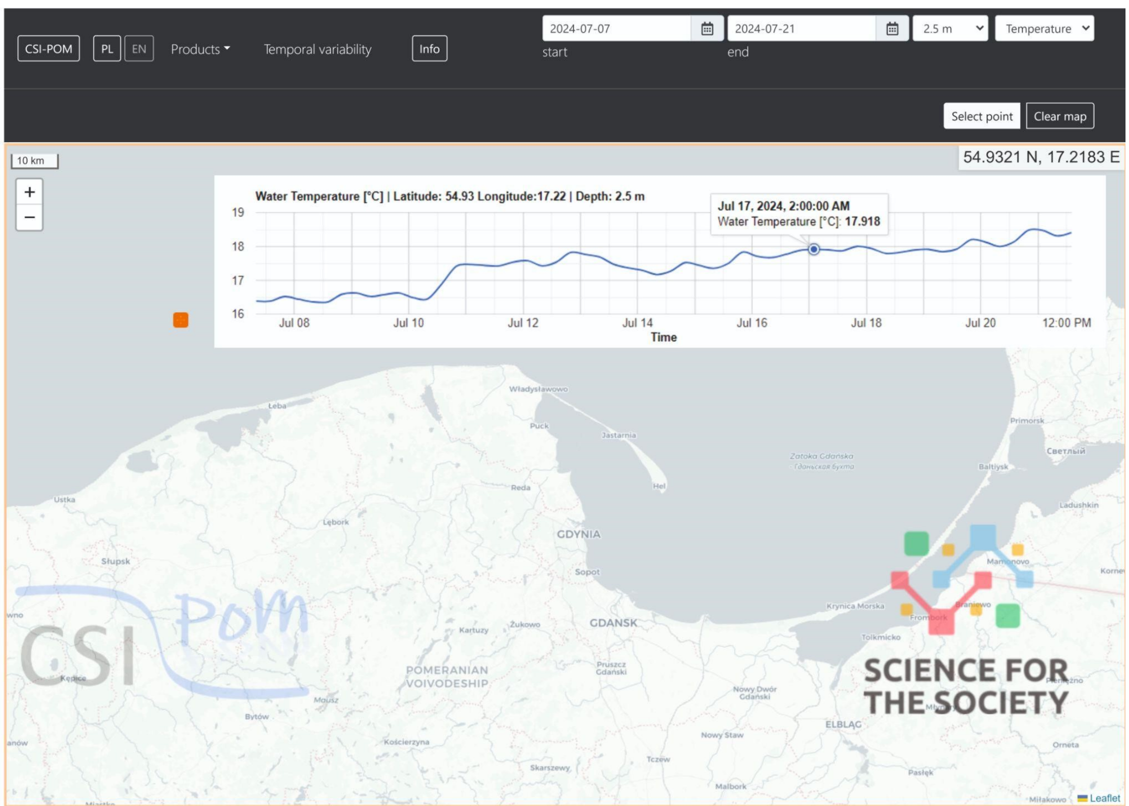

Figure 4. Temporal variability for selected points on the map with a user-defined time window. Four variables can be displayed, i.e., temperature, salinity, currents, and sea level.

3.1.2 Tools for determining the key parameters (top, bottom, thickness) of thermocline, halocline, and pycnocline

This product provides information on the current and forecasted depth of the thermocline, halocline, and pycnocline in the analyzed area. Both the top and the bottom depths of the thermo/halo/pycnocline, as well as their thickness, are determined.

The computations behind this tool are as follows. The vertical profile of the analyzed variable (temperature, salinity, or density) is being processed. If the data resolution in the profile is too coarse, interpolation is performed. The accuracy with which the algorithm, adjusted/expanded within the CSI-POM project, MovSTD (Janecki et al., 2022), can determine the desired depth is closely related to the data resolution in the profile.

Then, a condition is checked for the standard deviation throughout the entire profile. If it is less than MINSTD (which is the threshold value for the standard deviation of the values in the entire profile), the algorithm returns a Not A Number (NaN) value, signalling that the profile is homogeneous (isothermal, isohaline, isopycnal) and, according to our methodology, is completely mixed, or there is no thermocline/halocline/pycnocline present. Attempting to use the MovSTD algorithm to determine it may result in providing an erroneous value, related to a local change in temperature/salinity/density rather than the existence of an isocline in the analyzed profile. If the above condition is met (when the STD profile is greater than MINSTD), we proceed to smooth the profile using a moving average, with a step determined by the FRAME parameter (which is the number of consecutive values in the profile taken to determine moving averages). On this smoothed vertical profile, we calculate the moving standard deviation (MSTD), which is the most important operation in the presented method. The result of

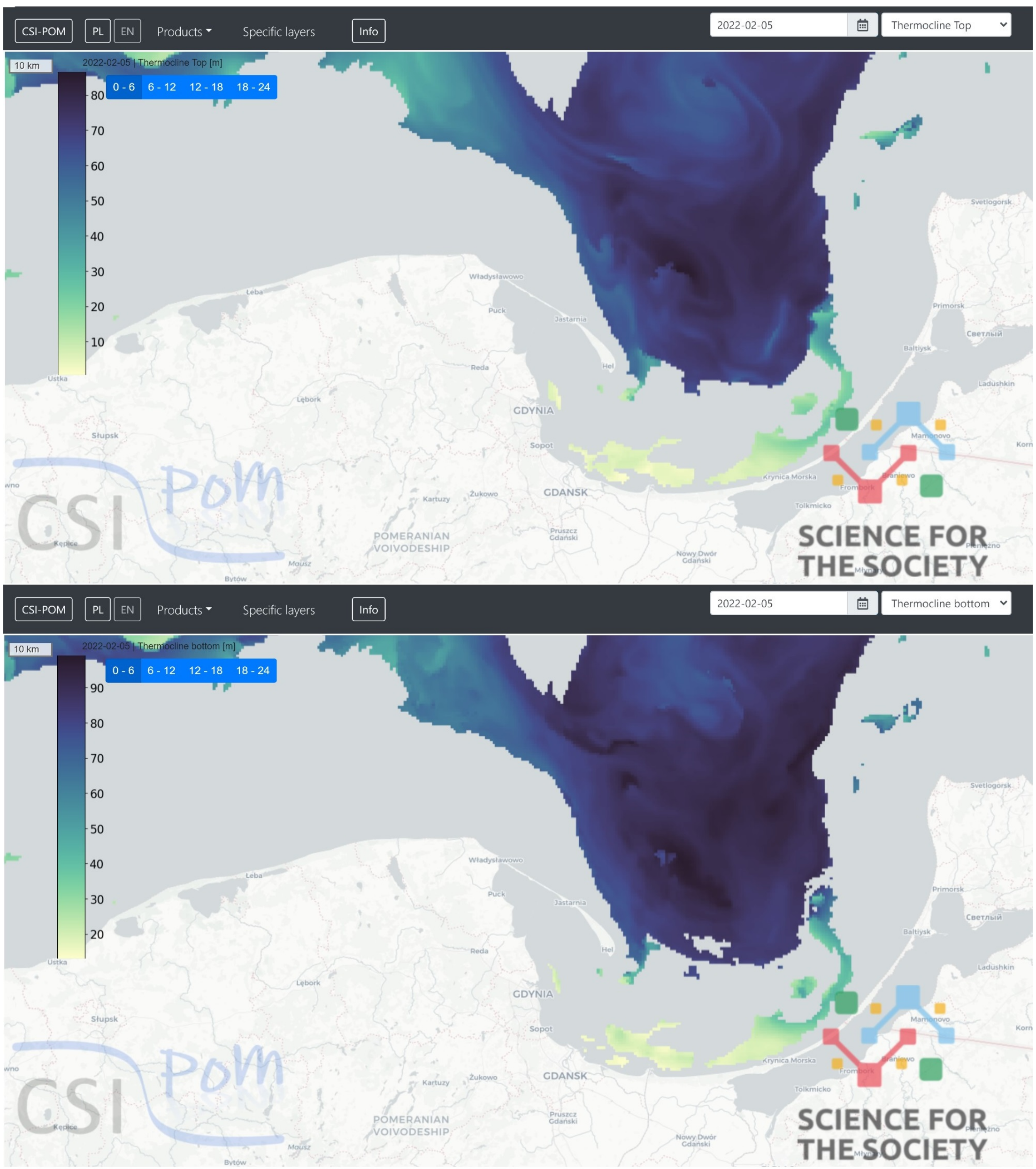

Figure 5. Top and bottom depths of the thermocline for February 5, 2022.

this operation is used to determine the location where the greatest changes in value occur in the analyzed profile.

In the next step, we find the maximum of MSTD and its corresponding index, idxmax. The number of this index is used as the starting point for searching the MSTD curve. At this stage, the algorithm starts checking the cut-off condition in the direction towards decreasing indices (for the top of the thermocline/halocline/pycnocline — TTD/THD/TPD) or increasing indices (for the bottom of the thermocline/halocline/pycnocline — BTD/BHD/BPD). For each subsequent index, it is checked whether the value of MSTD for the next index has dropped below the value of the maximum MSTD, $MSTD(idxmax) = mk$, multiplied by the threshold parameter THRES according to the formula below:

$$MSTD(idx) < THRES \times mk \quad (1)$$

The first index found in the loop satisfying the above relationship (Equation 1) indicates the layer number in the vertical profile where the top or bottom of the thermocline, halocline, or pycnocline is located. After referring this index to the associated depth vector DEPTH in the profile, we obtain the desired depth value.

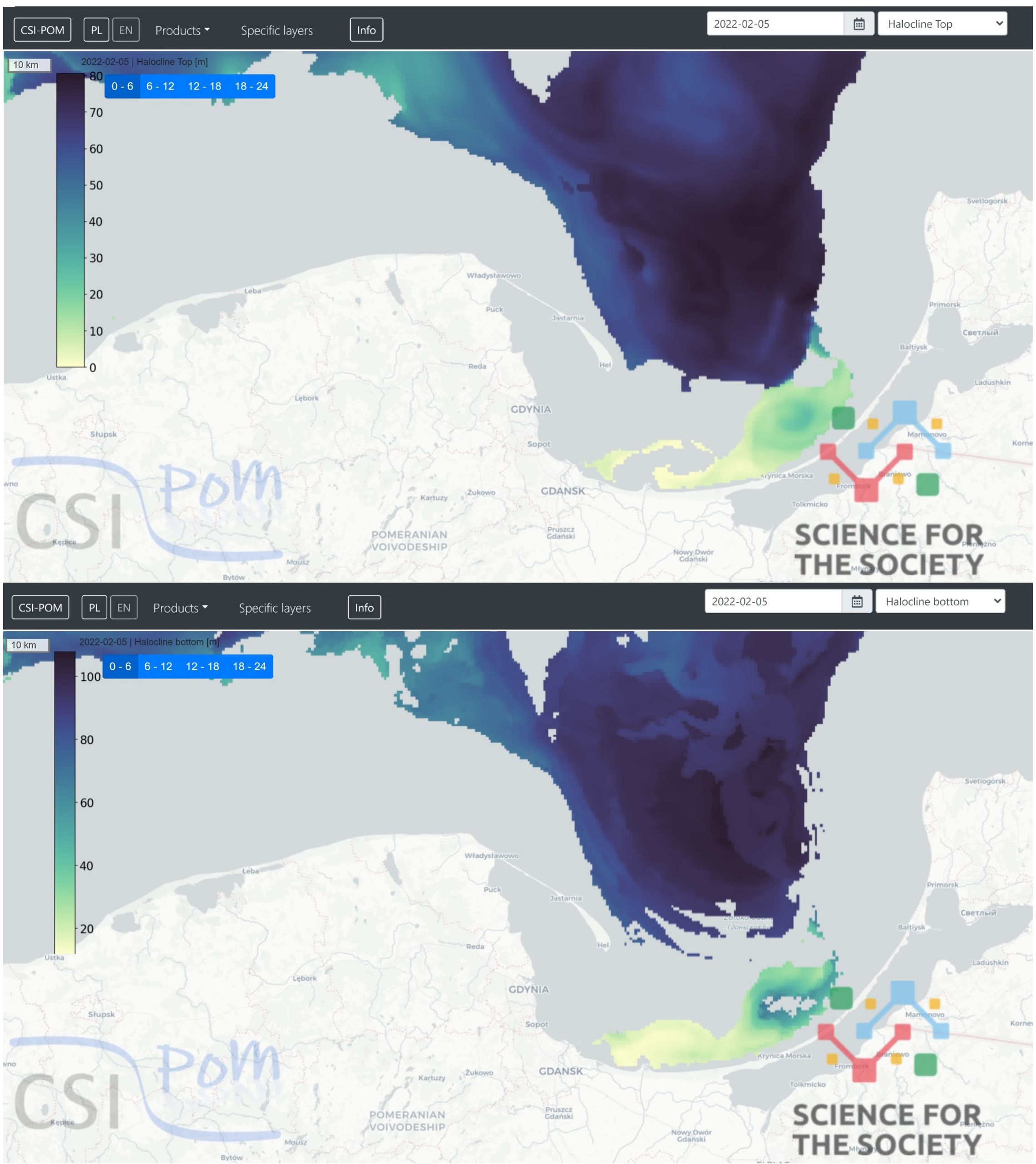

Figure 6. Top and bottom depths of the halocline for February 5, 2022.

During the calibration of the method, the following values of input parameters were established:

- FRAME = 30 (equivalent to 6 meters);
- MINSTD = 0.2 °C for the thermocline, 0.2 for the halocline and 0.0003 g/cm^3 for pycnocline;
- THRES = 0.3 for the thermocline and 0.2 for the halocline and pycnocline.

Below are the presented results for the top and bottom depths of the thermocline (Figure 5), halocline (Figure 6), and pycnocline (Figure 7) for February 5, 2022.

The white areas on the maps in the above figures indicate profiles where the MovSTD Algorithm was unable to determine the top/bottom depths of the thermocline/halocline/pycnocline or where the water column was sufficiently mixed or shallow that the thermocline/halocline/pycnocline did not form. Knowing the top and bottom depths of the thermocline/halocline/pycnocline allows for the determination of their thickness by subtracting the depth of the top from the depth of the bottom (Figures 8–10).

3.1.3 Automatic detection of marine eddies

This is a product that provides both qualitative and quantitative characteristics of swirling water masses. Using numerical forecast, the predicted location of the vortex and its size are determined.

From a netCDF file containing the model's output data, the script retrieves the necessary data to calculate the Γ1

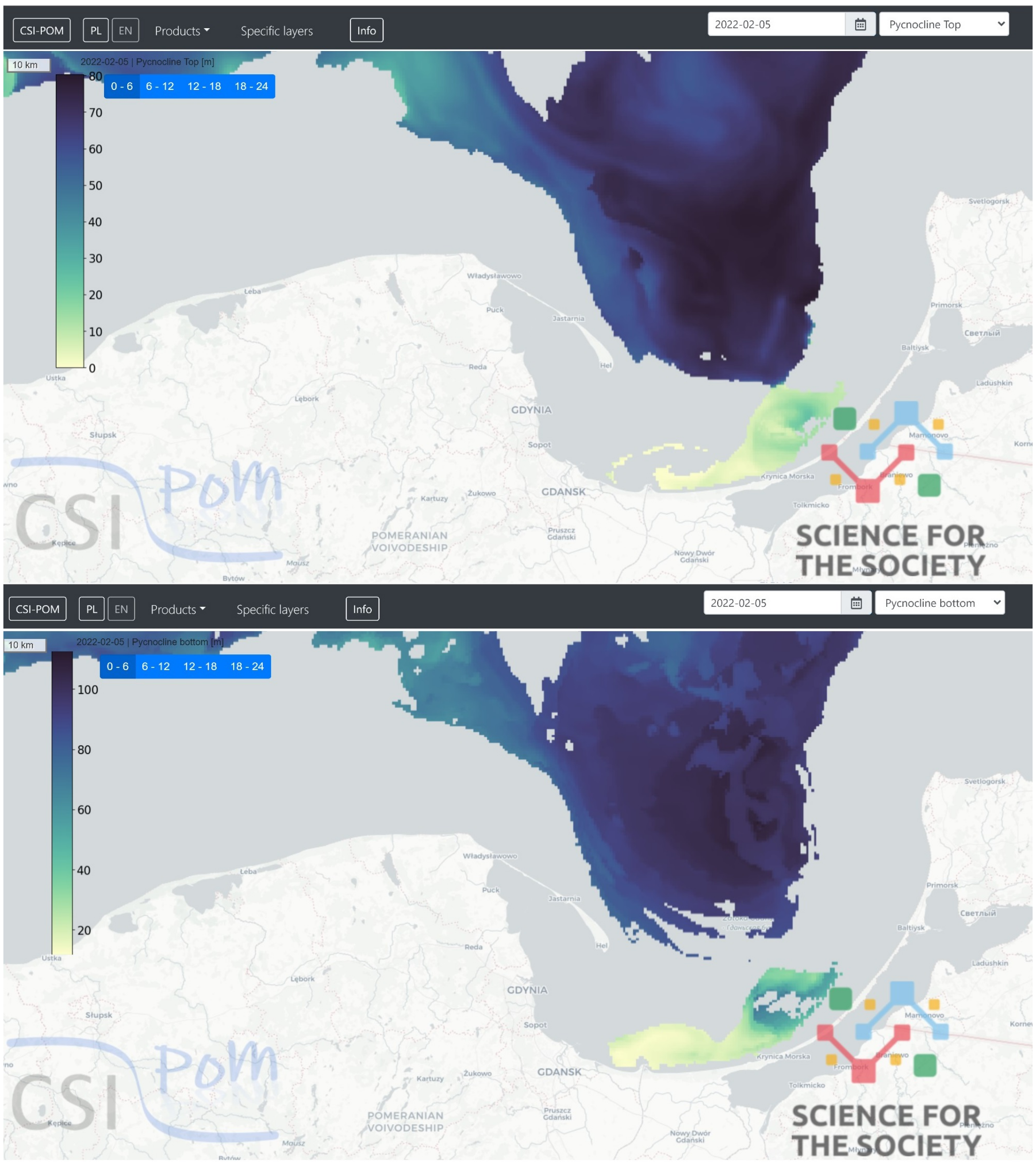

Figure 7. Top and bottom depths of the pycnocline for February 5, 2022.

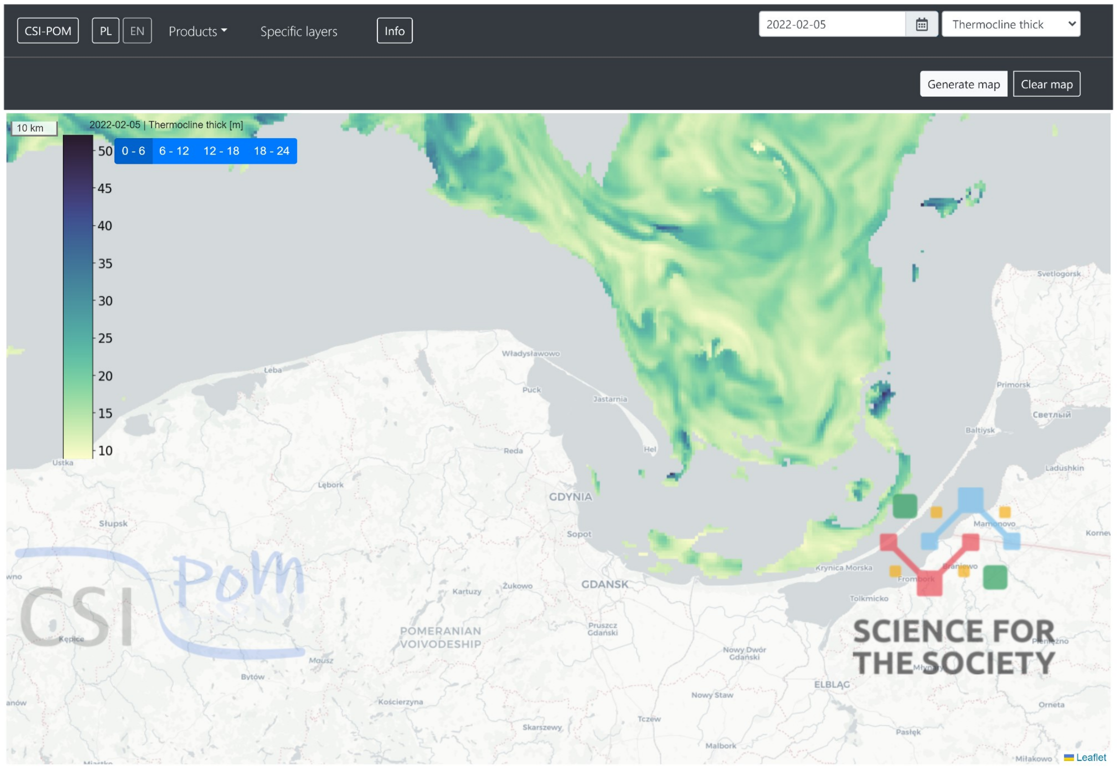

Figure 8. Thickness of the thermocline – February 5, 2022.

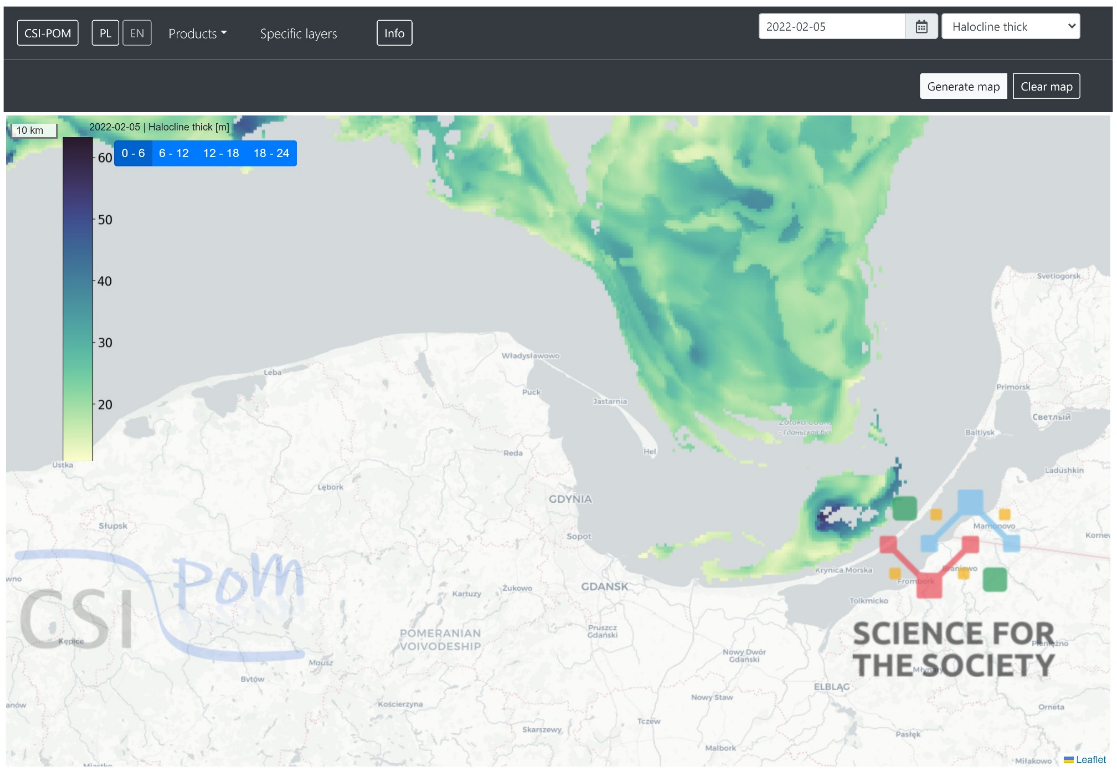

Figure 9. Thickness of the halocline – February 5, 2022.

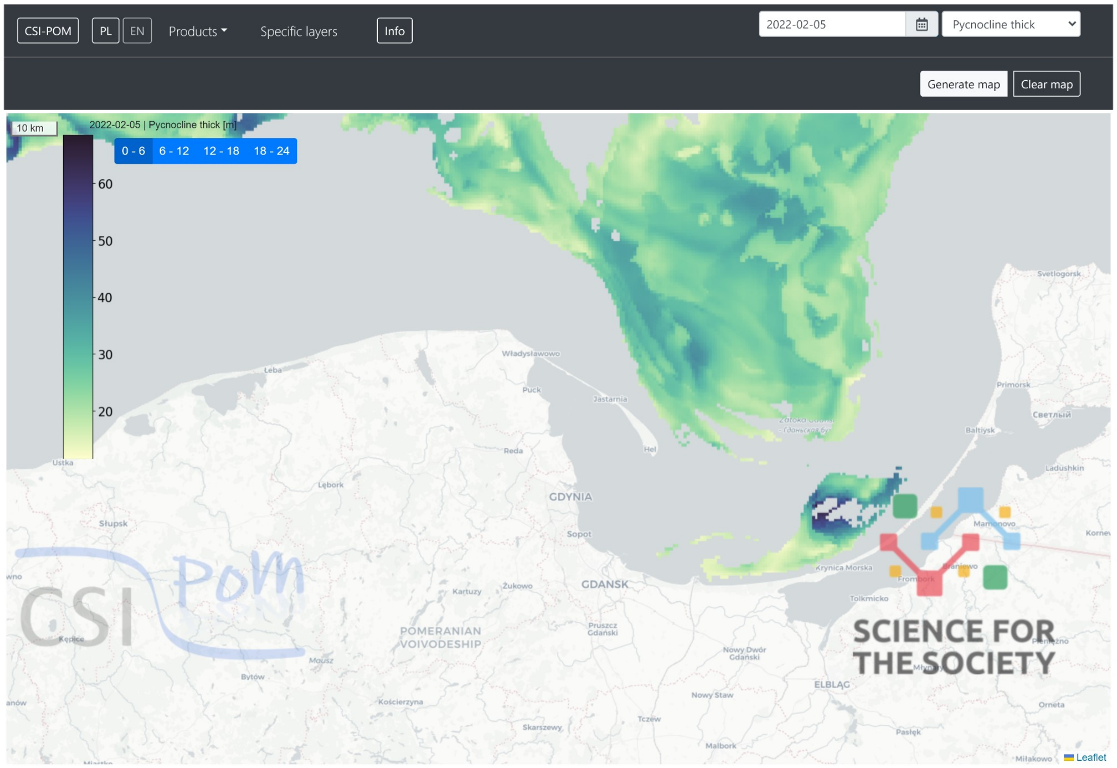

Figure 10. Thickness of the pycnocline – February 5, 2022.

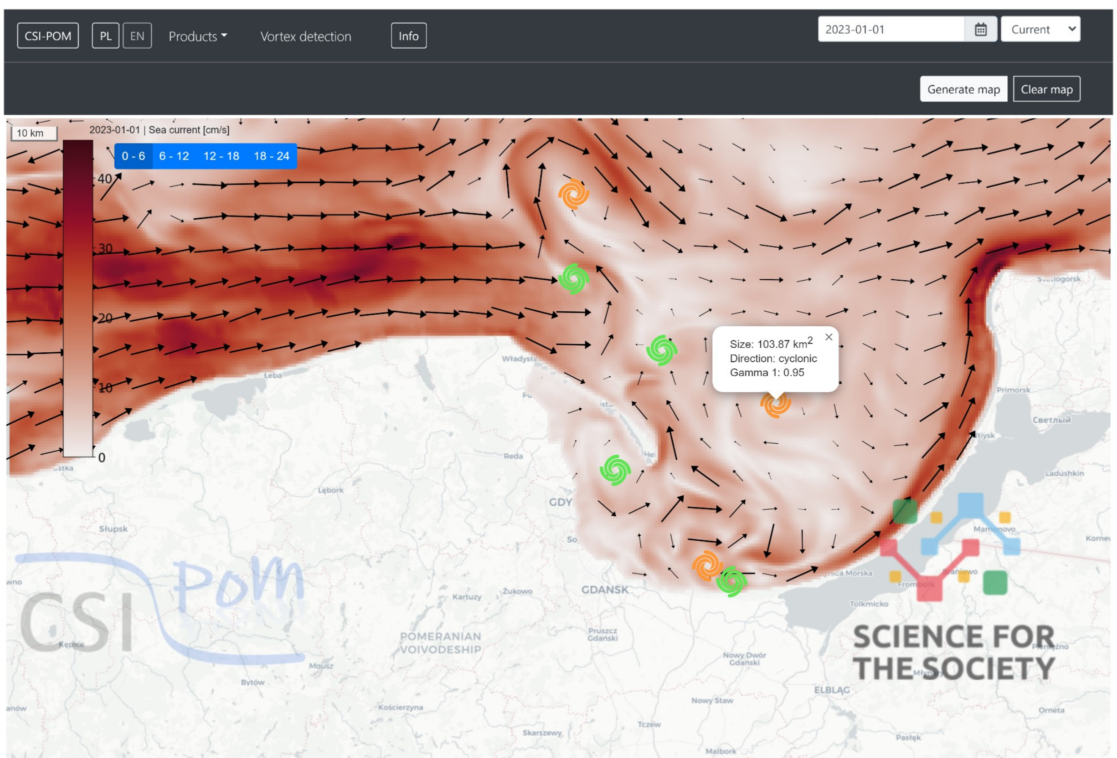

Figure 11. Marine eddies identification using the automatic detection algorithm. Schematic vortex icons marked on the map are interactive – after clicking on the icon, information about the size of the eddy, cyclonality and the value of the Γ1 function appears.

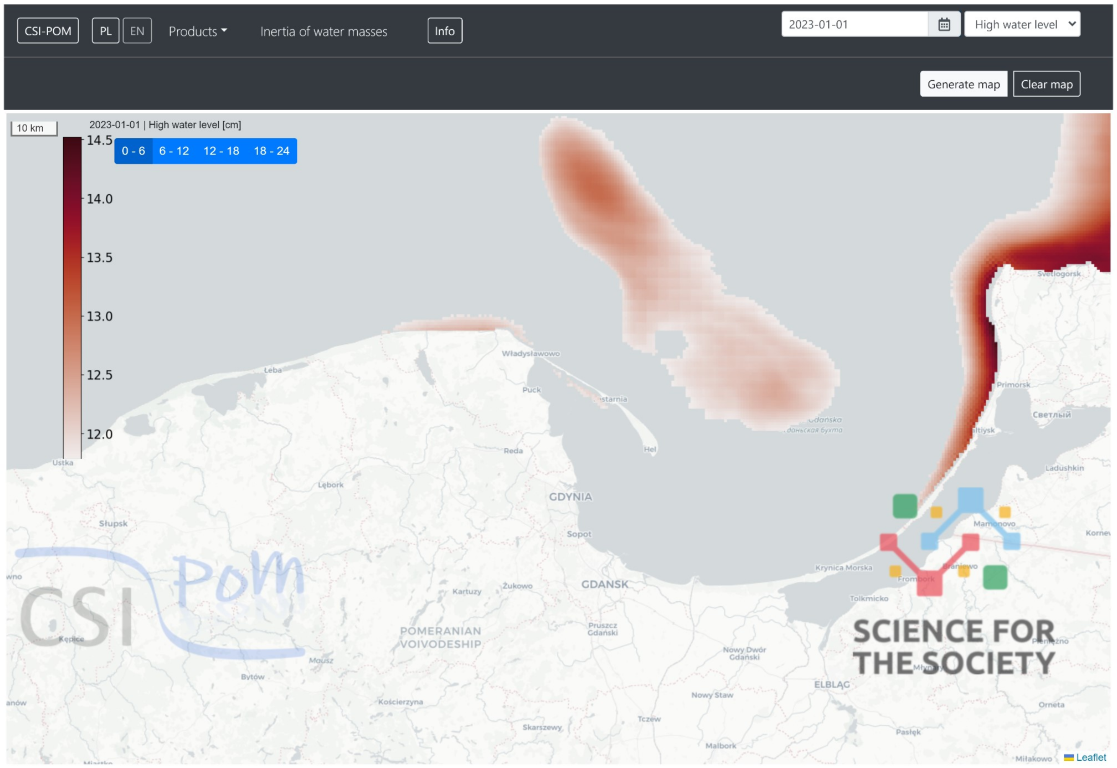

Figure 12. An example of the algorithm detecting water level rises.

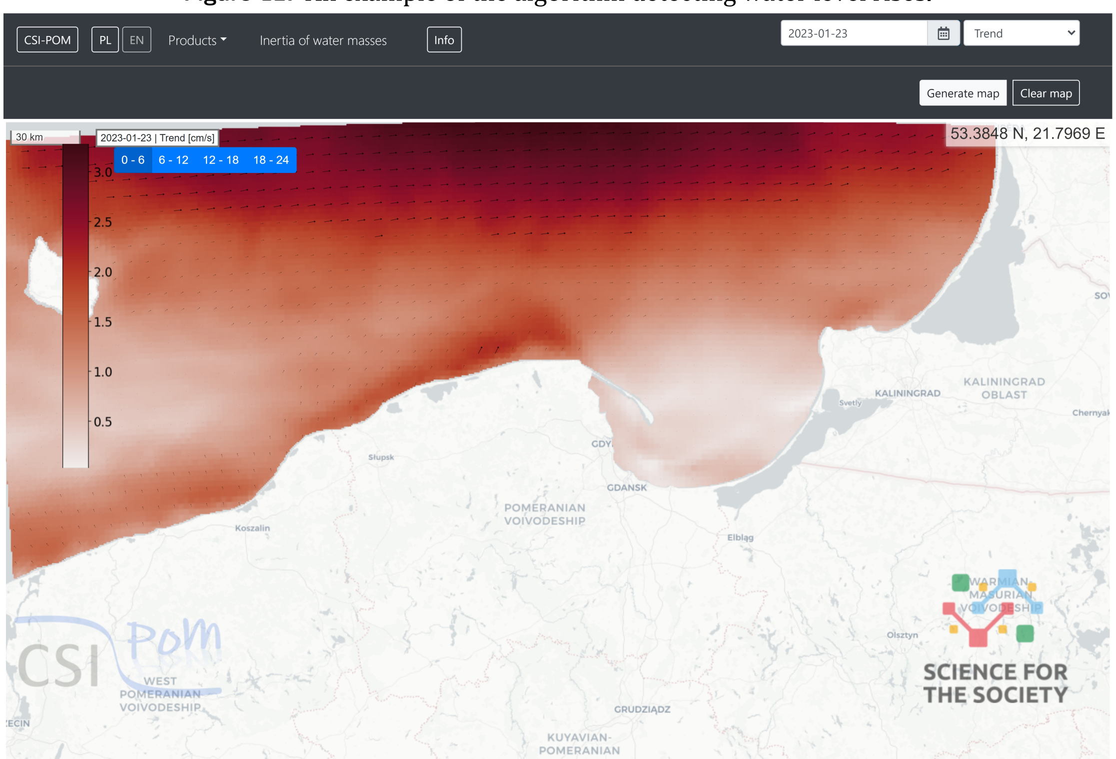

Figure 13. Wind trend for a sample 72-hour time window.

function (Graftieaux et al., 2001), and then assigns areas with sufficiently high values of the Γ1 function to clusters. The algorithm's operation is described in the article by Dybowski et al. (2024a) (submitted to Weather and Forecasting).

A graphical representation of the automatic vortex de-

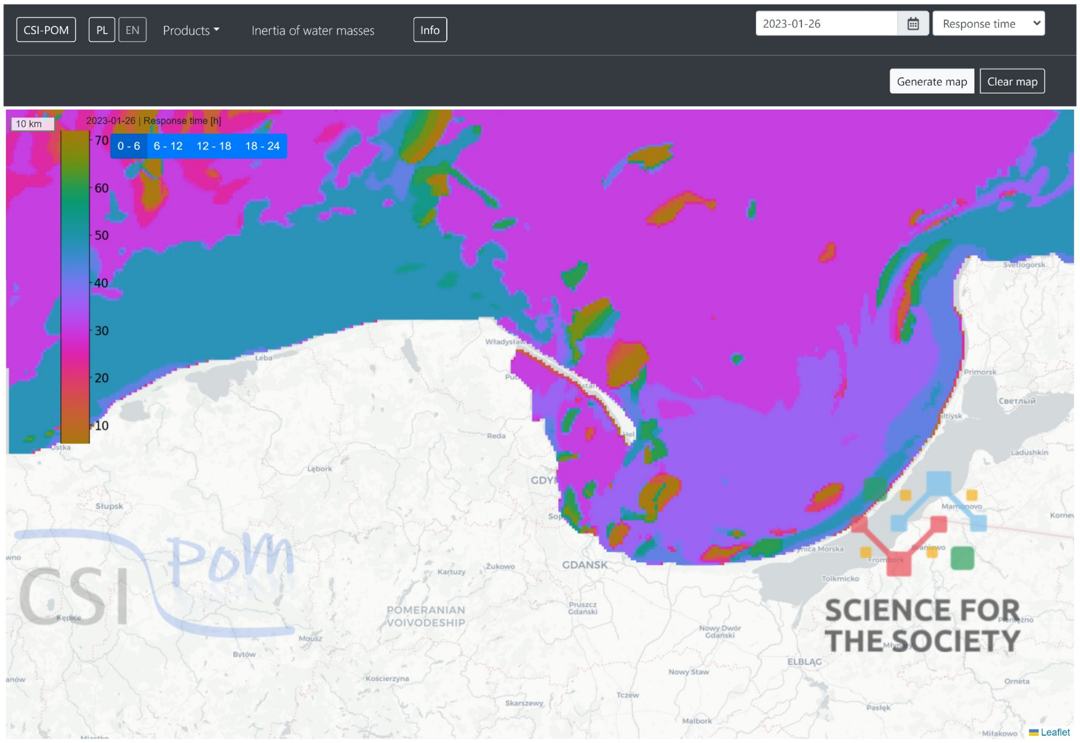

Figure 14. An example of the algorithm calculating response time.

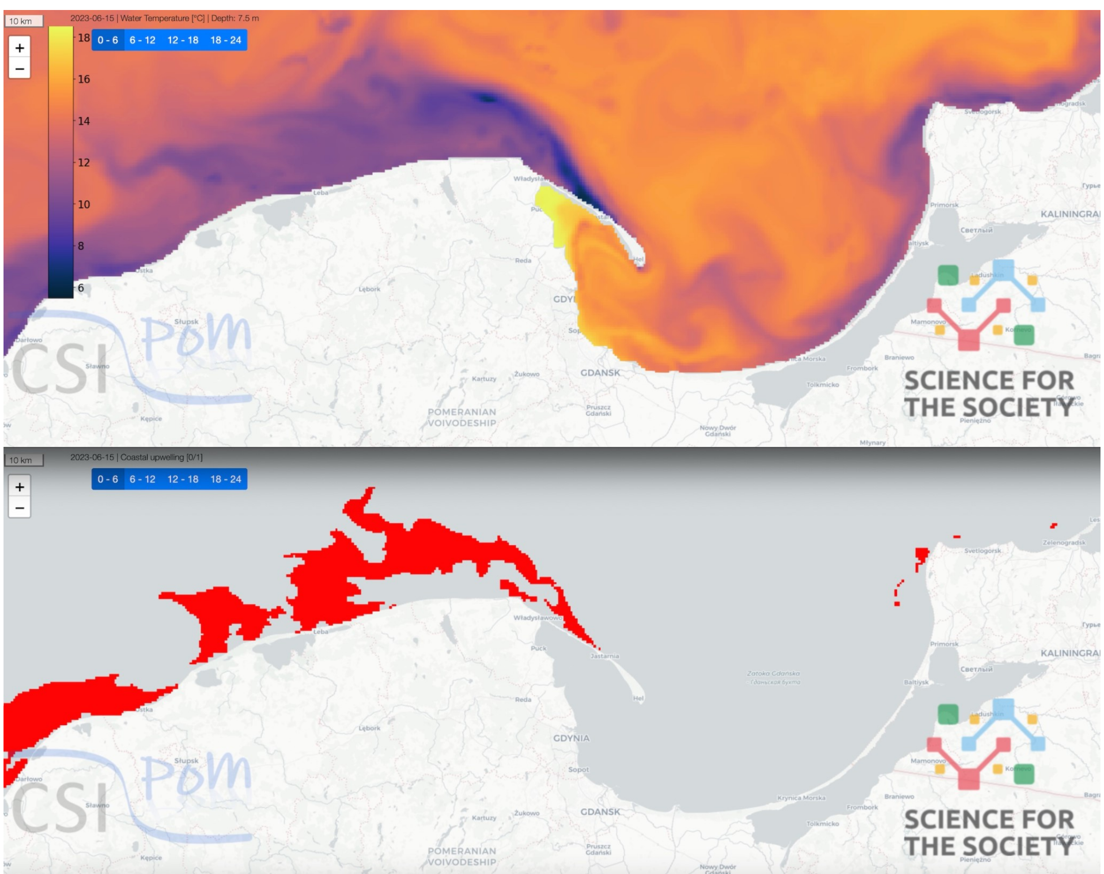

Figure 15. Sample result of upwelling detected by the system on the 15th of June 2023.

tection algorithm is presented in Figure 11, where the vortex icons indicate the centroids for the determined clusters, indicating potential vortex existence in the respective locations.

3.1.4 Tools for studying the inertia of water masses under forecasted wind forcing

The tool for investigating the inertia of water masses under forecasted wind forcing provides insights into the expected trends, response times of water masses to persistent weather conditions, and predictions of water mass accumulations.

Developed as a research tool, it enables the analysis of water mass inertia concerning forecasted wind forcing. This tool supports the understanding of water mass reactions to persistent weather conditions and facilitates the prediction of potential water mass accumulations. Based on model results, the tool detects forecasted potential water mass accumulations in specific areas (Figure 12), which is crucial for risk management related to extreme weather conditions. For each time-averaged model output, we calculate the mean sea level. The elevated sea level, for the purposes of this service, is defined as a sea level height exceeding the mean by more than one standard deviation.

The tool monitors meteorological forecasts and allows the analysis of the impact of forecasted winds on water movements. The system can identify potential trends (Figure 13) and determine the response time of water masses to changing atmospheric conditions (Figure 14). In the current implementation of the service, the wind trend is defined as a 72-hour average of wind-forcing. The purpose of calculating the trend is to identify periods during the year when a consistent wind-forcing direction persists over a significant portion of the domain. For such a defined wind forcing trend, we then calculate the cross-correlation between the wind forcing trend and the forecasted direction of ocean currents. The time lag at which the cross-correlation function reaches its maximum provides information on the time required to overcome the inertia of the water and transmit the wind-forcing direction to the aver-

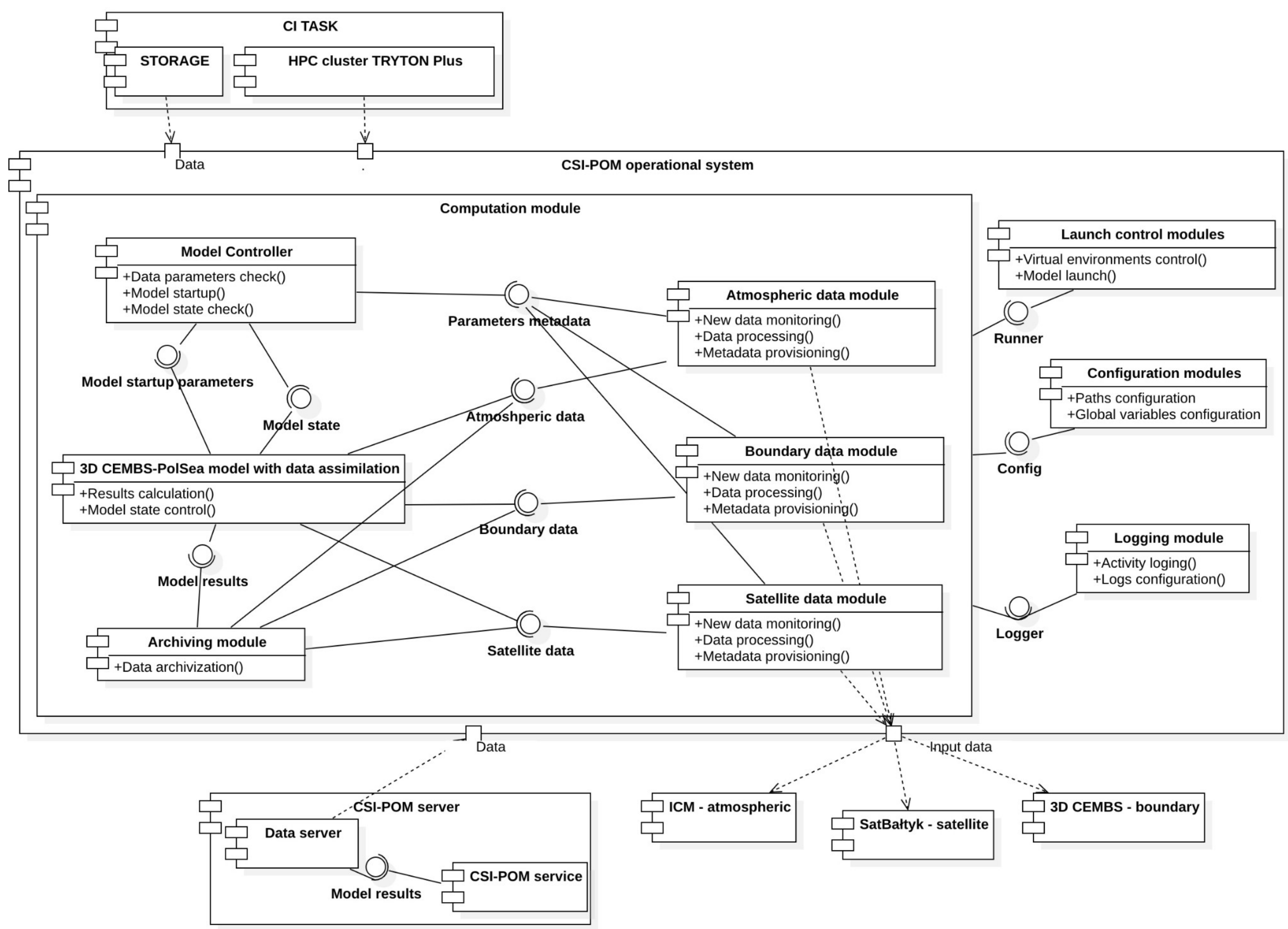

Figure 16. Component diagram of the CSI-POM system.

aged water flow. This enables the rapid identification and prediction of how water masses will respond to specific changes in wind speed and direction.

The developed research tool enhances understanding and forecasting of water mass movements concerning forecasted weather conditions. Its implementation improves overall knowledge of water dynamics under various weather conditions.

3.1.5 The tool for automated detection of the coastal upwelling events

This tool provides information on the spatial distribution of coastal upwelling, an event that due to wind forcing causes deep sea water to rise to the surface, usually from depths below the thermocline. The upwelling detection module is based on the results of the 3D CEMBS-PolSEA model. It uses certain characteristics of the Baltic Sea. Because the Baltic Sea extends at latitudes from approximately 54°N to 66°N, a north-south SST gradient can be observed. Moreover, between May and September, a strong vertical thermal stratification prevails. During upwelling events, a significant drop in surface temperature can usually be observed due to the uplift of cold water masses from deeper layers. Horizontal gradients of surface temperature can be observed, reaching up to 5°C per kilometre. By partitioning the southern Baltic Sea area covered by the 3D CEMBS-PolSEA model into longitudinal zones and computing average surface temperatures for each zone, areas with upwelling presence can be detected where temperature drop from the calculated mean is greater than a predefined threshold value. Through empirical refinement, this threshold was set at 2.5°C. As already mentioned, to detect upwelling, a substantial drop in temperature is necessary, which results from the uplift of cold water masses from the layers below the thermocline. Therefore, this method (Nowicki et al., 2015) remains effective only during the period of strong thermal stratification in the Baltic Sea, specifically between May and September.

Figure 15 shows a sample result of the upwelling event detected by the system. The upper part displays a surface temperature map with clearly visible areas of lower surface temperature. The lower part depicts areas where the algorithm successfully identified upwelling areas.

The entire module was written in Python programming language and is a part of the operational system. It checks periodically if new results from the 3D CEMBS-PolSEA model are available and prepares upwelling maps based on the algorithm mentioned above. This enables the provisioning of current results, which are then accessible from the project's website (www.csipom.pl/en/).

3.2 Operational Digital Environmental Information System for Polish Marine Areas (CSI-POM)

To ensure access to the latest model results, an operational system was necessary to manage the operation of all modules responsible for processing the aforementioned input data as well as the operation of the model itself.

The coordinating module for the operational mode of the 3D CEMBS-PolSEA model consists of several components. Each component is responsible for launching and controlling one of the modules used in the subsequent stages of data processing from various sources, and one component is responsible for launching and controlling the 3D CEMBS-PolSEA model itself. Additionally, the operational system as well as all data processing modules use a common component responsible for logging, enabling the administrator to monitor the system's operation. An exception here is the 3D CEMBS-PolSEA model itself, which has its built-in logging system.

Figure 16 presents a diagram of the components comprising the 3D CEMBS-PolSEA system, along with the most

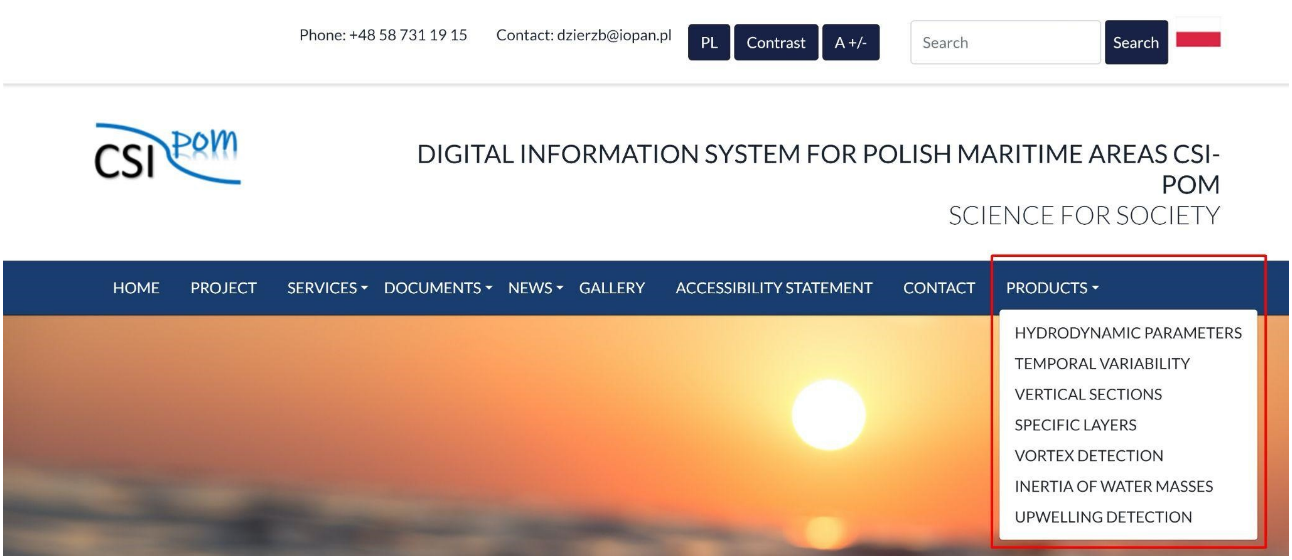

Figure 17. Website of the CSI-POM service (www.csipom.pl/en/) with products tab marked in red frame.

important external systems it communicates with.

Almost every parameter or group of parameters from different sources requires slightly different transformations to prepare them for use in the model.

An integral part of the Digital Information System for Polish Marine Areas is the visualization and sharing of results with the public. The developed CSI-POM system allows for the creation of maps and spatial, temporal, and point-based characteristics for the studied parameters and physical processes. These results are presented on the website in real-time and in the form of forecasts for the next two days, informing about the current state of the environment and potential threats in the open sea and coastal zone of Poland.

Access to all services is provided through the website located at the domain www.csipom.pl/en/ under the PRODUCTS tab (Figure 17):

A. HYDRODYNAMIC PARAMETERS

B. TEMPORAL VARIABILITY

C. VERTICAL PROFILES

D. SPECIFIC LAYERS

E. VORTEX DETECTION

F. INERTIA OF WATER MASSES

G. UPWELLING DETECTION

The portal has been created in line with the latest trends, e.g., separating the data presentation mechanisms (front-end) from the data processing layer (back-end). This solution allows for easy expansion of the portal with new features and provides scalability to add additional hardware resources in case of heavy portal traffic. Data from the model and tools are processed directly from netCDF output files.

4. Discussion

The CSI-POM service is a response to the identified problem in the marine economy, which is the need for a reliable and accurate tool for observing changes occurring in the marine environment, including planning and evaluating optimal physical conditions for conducted activities, making optimal decisions during planning activities in various sectors of the marine economy, and planning for increased safety and efficiency of work. Conscious investment management will help avoid unnecessary losses and schedule changes.

The application of the CSI-POM system is expected to increase the efficiency of work at sea by various entities in the marine economy. Hydrometeorological conditions affect all areas of maritime operations. Therefore, it is essential to have a reliable and accurate tool for forecasting them. We assume that the solutions presented within the CSI-POM service will attract a broad audience. The potential interest among various social and economic groups is outlined in Table 2.

The CSI-POM service aligns with the primary objectives of the Pomorskie Smart Specializations (PSS), approved by The Board of the Pomeranian Voivodeship, in the offshore and port-logistics technology sector, contributing to the acceleration of growth in maritime companies within the Pomeranian and West Pomeranian regions through research and development, and the creation of innovative tools for the safe exploration and exploitation of marine resources.

Through the implementation of the CSI-POM service, the following specific objectives of the PSS were achieved:

- The development and implementation of innovative technical, technological, and organizational solutions enabling the forecasting of conditions in Polish Marine Areas;
- The establishment of sustainable and efficient mechanisms for cooperation between entrepreneurs and the scientific research community in the maritime economy (facilitating the use of the system's results by both businesses and researchers, fostering an ongoing exchange of knowledge and methodologies);
- Increasing public awareness of the importance of the Baltic Sea and its potential for Poland's economic de-

Table 2. The potential application of individual CSI-POM service tools across various economic sectors and social groups.

Target group/ tool	Sea level	Currents	Vortex detection	Water column structure	Water mass inertia	Thermocline and pycnocline	Coastal upwelling
Offshore, transport, and logistics companies	✓	✓	✓	✓	✓	✓	
Fishing companies	✓		✓	✓		✓	✓
Coastal and marine angling	✓	✓	✓	✓		✓	✓
Sports and tourism entities	✓	✓	✓			✓	
Maritime services	✓	✓	✓	✓	✓	✓	✓
Academic scientific units	✓	✓	✓	✓	✓	✓	✓
Schools (educational tool)	✓	✓	✓	✓	✓	✓	✓

velopment, as well as the responsibility for marine ecosystem protection through informational activities (including continuous publication of system results on the website, participation in conferences to disseminate findings, publications in industry journals, and a social survey to assess demand for the CSI-POM digital system).

The CSI-POM system has been developed using an innovative approach to the issue by building a three-dimensional hydrodynamic numerical model with high resolution for Polish Marine Areas (named 3D CEMBS-PolSEA) with a module assimilating satellite data. The model incorporates tools for studying the strongly layered structure of the Southern Baltic waters, generating comprehensive forecasts of the physical conditions of the studied water body. To the best of our knowledge, these solutions are currently not being developed in the Baltic Sea area.

Model data for the CSI-POM system are processed four times a day regardless of cloud cover for the entire model area and are widely available in the form of maps through the website, to reach users as quickly as possible.

Environmental protection policy must be integrated with economic policy. To this end, appropriate management programs based on the idea of sustainable development should be created, aimed at the economic development of the sector while maintaining environmental conditions. It is also necessary to promote knowledge about the functioning of water systems and the effects of economic activities on the natural environment in order to minimize the impact of the economy on the environment in the future.

5. Summary and conclusions

The CSI-POM system is a digital information system designed to monitor and forecast hydrodynamic conditions in Polish Marine Areas. The developed CSI-POM system, when assessing hydrometeorological conditions in Polish Marine Areas, enables:

a) In offshore areas, transport and logistics, marine energy:

i) Identification of hydrodynamic windows, minimizing losses, and ensuring safety for workers during daily work at sea.

ii) Making optimal decisions based on hydrodynamic conditions for operations at sea, including the coastal zone and port areas.

iii) Planning downtime related to adverse sea conditions to avoid unnecessary changes in work schedules.

b) In the field of sports and tourism:

i) Planning, organizing, or rescheduling events/recreational activities based on current hydrodynamic information.

ii) Making optimal decisions based on reliable information during events organized on water bodies.

There is a lack of such a comprehensive solution in the market, with elements/tools focusing on the research of the strongly layered, vertical structure of the Baltic Sea. Consultations were carried out with entities from the maritime economy sector, such as the Sea Fishermen's Association in Władysławowo and the Port of Gdynia, to examine the impact of the research being conducted.

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Conflict of interest

None declared.

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