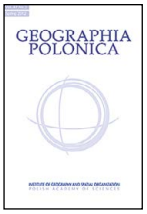

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THERMAL REGIME OF THE VISTULA RIVER MOUTH AND THE GDAŃSK BAY

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Abstract

Surface water temperature characteristics of the Vistula River mouth and the Gdańsk Bay were determined on the basis of available observations, remote sensing and hydrodynamic models. The water temperature in the Vistula River and the Gdańsk Bay was found to be much higher than the air temperature. In recent decades, the water temperature in the Vistula River mouth and the Gdańsk Bay has increased significantly. It has been determined that water temperature in the bay is affected not only by air temperature, but also by water discharge of the Vistula River and wind.

Key words

water temperature • air temperature • remote sensing • coastal zone • the Baltic Sea

Introduction

Monitoring of surface water temperature (SWT) is carried out in relation to inland and sea waters, including open and coastal waters. Relevant research makes it possible to find out the changes over the last decades. SWT is also a key parameter for analyzing the impact of climate change on aquatic ecosystems (Czernecki & Ptak, 2018; De Santis et al., 2022). The study of thermals of inland and sea waters allows us to reveal space-time relationships between various natural factors. Significant assistance in such researches provides remote sensing. First of all, it helps to identify the spatial features of water temperature.

Many models that serve to assess long-term trend and water temperature forecasts use information provided by satellites Landsat, ATSR and AVHRR series (Sharma et al., 2015) and MODIS (Pareeth et al., 2017). Compilation of data from different sources is useful for studying the complex relationships between

the temperature of sea waters and waters of rivers flowing into the sea (often a bay or a lagoon) and also the air temperature.

The Vistula River mouth and the Gdańsk Bay are interesting objects of research regarding the peculiarities of the thermal regime of waters. It is no coincidence that this region and the processes in it are the object of many studies (Chubarenko & Margoński, 2008; Girjatowicz, 2014; Szaniawska, 2018; Zhelezova et al., 2018). In particular, there are studies devoted to the thermal regime of the Vistula River. It has been identified that water temperature in the river has increased significantly in recent decades as the result of climate change (Graf & Wrzesiński, 2020; Ptak et al., 2020; Ptak et al., 2022). The same results were obtained for many European rivers and lakes (Webb et al, 2007; Adrian et al., 2009; Marszelewski & Pius, 2016; Ptak et al., 2016; Woolway et al., 2017; Lieberherr et al., 2018; Vyshnevskyi & Shevchuk, 2021; Wrzesiński & Graf, 2022; Vyshnevskyi & Shevchuk, 2023). Corresponding studies of sea water temperature, in particular European seas, are being conducted (Vyshnevskyi et al., 2023). Thus, in 1915-2021, the mean annual water temperature in the northwestern part of the Black Sea increased by 2.0°C. Almost all of this growth has occurred over the past three decades. The increase in sea water temperature causes certain consequences, for example, for sea grass, fish resources, water quality, etc. (Mooij et al., 2008; Marba & Duarte, 2010).

In fact, even careful processing of routine monitoring data does not make it possible to determine the thermal regime features of such complicated objects as the Vistula River and the Gdańsk Bay. The thermal regime of these water bodies differs significantly in different seasons. In addition to air temperature, the depth of water bodies, the water discharge of the Vistula River and some other factors play an important role. This is one of the reasons for the use of remote sensing. There are quite a few papers devoted to the use of remote sensing to study the thermal regime of lakes, reservoirs and seas (Alcântara et al., 2010; Barsi et al., 2014; Lieberherr & Wunderle, 2018; Schaeffer et al., 2018; Sharaf et al., 2019; Virdis et al., 2020; Vyshnevskyi & Shevchuk, 2021 Dyba et al., 2022). Recently, this technology has been used, in particular, to study thermal regime of the northwestrn part of the Black Sea (Vyshnevskyi et al., 2023) and the Danube Delta (Vyshnevskyi & Shevchuk, 2023). The same approach was used to study the SWT of water bodies in Poland (Dyba et al., 2022). In the latter and in other cases, some attention was paid to the measurement accuracy, based on remote sensing. The difference between the temperature measured in situ and the temperature calculated from band 10 of Landsat 8 satellite is typically less than 1°C.

A number of modern solutions (models, applications) are used in the study of the sea waters of the Baltic Sea. An outline history of Polish research forming the basis of the remote sensing of the Baltic Sea was presented by Woźniak et al. (2011). The thermal features of the Gdańsk Bay including the Vistula Lagoon was the subject of ecohydrodynamic modeling which was desctibed in papers (Konik et al., 2019; Kowalewska-Kalkowska & Kowalewski, 2019). In order to identify the water temperature distribution in the southern part of the Baltic (waters of the Polish Baltic coast), an ecohydrodynamic model (http://model.ocean.univ.gda.pl/) was developed, which allows making a 48-hour forecast of hydrological and hydrodynamic conditions for the southern part of the Baltic Sea, the Gdańsk Bay with the Vistula Lagoon, the Pomeranian Bay and the Szczecin Lagoon. Forecasts include the fields of surface currents, temperature and salinity of seawater. The newer version of the ecohydrodynamic model on the SatBałtyk platform (http: //satbaltyk.iopan.gda.pl) differs from the initial version of the hydrodynamic model by higher resolution and larger accuracy in relation to temperature. The SatBałtyk platform allows analyzing sea surface temperature observed by satellite and supplemented by the results of the ecohydrodynamic model. Another example is the «Maritime Spectator» application (Copernicus 2022), which is used

in the study of sea waters. The application is constantly powered by images obtained by sensors placed on satellites Sentinel family. Data recorded by Sentinel-3 are of particular importance to monitor sea temperature, water surface height, wind speed or ice sheet thickness. The images recorded by the satellite allow for the analysis of the state of the sea surface with a unique spatial and temporal resolution, which is not possible with traditional methods.

The main aim of this study is to determine the features of thermal regime of water in the zone of the Polish Baltic coast, including the mouth of the Vistula River, the Gdańsk Bay and the Vistula Lagoon using the data of regular monitoring, satellite images and the ecohydrodynamic models.

Materials and methods

Study objects

The research subjects included the lower reaches of the Vistula River, Gdańsk Bay of the Baltic Sea and the Vistula Lagoon (Fig. 1)

The Vistula River is the largest Polish river which flows into the Gdańsk Bay of the Baltic Sea. The length of the river is 1047 km, the cachment area is 199,813 km^2 (Łajczak et al., 2006). There are some other data about hydrographic parametes of the river, but the difference is not significunt. The closest hydrological station to the Vistula River mouth, where the observation over the water runoff is carried out, is Tczew. This station is located at 908.6 kilometer of the Vistula River. The cachment area at this station is 193,806 km^2, the mean annual discharge for 1951-2010 is 1,048 m^3 s^{-1} (Kubiak-Wójcicka, 2018).

The human impact on the Vistula River mouth is described in details in papers (Lajczak et al., 2006; Wróblewski et al., 2015). In 1895 a canal connecting the river and the Gdańsk Bay was constructed bypassing the natural channel near Gdańsk city (Wróblewski et al., 2015). It means that nowadays the Vistula River in its mouth flows in the artifical channel, which inflowes to the sea in a different place than it was in the natural conditions. In addition, there is an artificial channel that connects the river with the Vistula Lagoon.

The Gdańsk Bay is the southern part of the Baltic Sea. The area of bay is 4990 km^2 or 1.3% of the sea area. The average depth of bay is 59 m. The Puck Bay is the westernmost part of the Gdańsk Bay, while the Vistula Lagoon stretches to the east of it (Fig. 1). The Vistula Lagoon has an area of 838 km^2 and the length of 91 km. Most of the lagoon (61%) belongs to Russia, the rest to Poland.

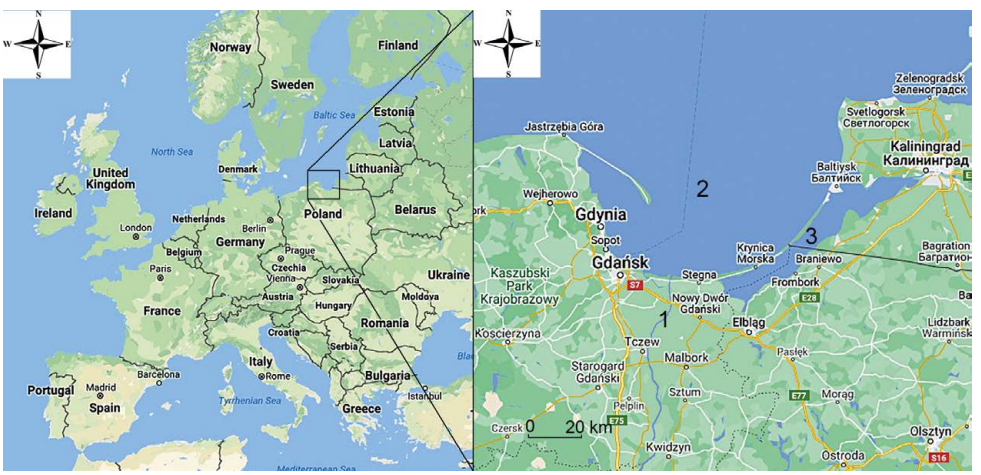

Figure 1. The location of the lower reaches of the Vistula River (1), Gdańsk Bay (2) and the Vistula Lagoon (3)

Separated from the Baltic Sea by a narrow, sandy, forested spit, the Vistula Lagoon is shallow. Its average depth is 2.7 m and the maximum depth is 5.2 m (Szaniawska, 2018).

As a result of human impact the salinity of the Vistula Lagoon has significantly decreased. Nowadays it is about 3.5‰. Since the lagoon is shallow, there is no thermal stratification: the entire water mass has the same temperature and it is well saturated with oxygen. The water contains many organic and inorganic suspended substances raised from bottom sediments under the action of waves. In the warm season the shores are well overgrown, algae bloom is observed. All these effects mean that the highly eutrophic waters of the lagoon are characterized by poor transparency (no more than 1 m) and a brown color.

It should be mentioned about the modern factor impacting the Vistula Lagoon. During 2019-2022 the Vistula Spit canal (official name Nowy Świat ship canal) was built, connecting the Polish section of the lagoon and the Gdańsk Bay. It allows ships to enter the Vistula Lagoon and the port of Elbląg without having to rely on the Russian Strait of Baltiysk, saving a 100 km journey. This construction was completed on September 17, 2022.

Source material

The research used hydrometeorological data from ground measurements, satellite data and the information from the hydrodynamic model of the Polish Baltic coast, which combines data, obtained from the land and satellites.

There are several meteorological stations near the Vistula River mouth and on the shore of the Gdańsk Bay, namely Gdańsk, Gdynia and Hel. The measurements of the sea water temperaure are carried out at Hel, Gdynia, Gdańsk, Tolkmicko hydrological stations located at the Vistula Lagoon and the sea shore. In turn, the water temperature of the Vistula River is observing at Tczew and Świbno hydrological stations (Fig. 2).

Air and water temperature data for this study were obtained mostly from the Institute of Meteorology and Water Management – National Research Institute (Poland).

Figure 2. The location of the studied objects and the network of observaion stations: 1 – the main chanel of the Vistula River, 2 – Dead (Martwa) Vistula branch, 3 – Szkarpawa branch, 4 – Gdańsk Bay, 5 – Vistula Lagoon, 6-8 – meteorological stations Hel, Gdynia and Gdańsk, 9-14 – hydrological stations Hel, Gdynia, Gdańsk, Świbno, Tolkmicko and Tczew

Data on air and water temperature for the period 1961-2020 were processed. In all cases, mean monthly and annual data were processed. Some data on long-term and current water temperature at stations located on the sea shore were also used from the website https://www.seatemperature.org. This site contains the data on mean, maximum and minimum recordered temperature for all months of year. At the same time, the observation period is unknown.

In addition to regular monitoring data, the remote sensing data have been used. In the study were used the images of Landsat 8 satellite, which are available at cite https://earthexplorer.usgs.gov. The images of serie LC08_L1TP_190022 cover the entire Vistula River mouth and the Gdańsk Bay. The time of survey of the studied area is 9:44-9:45 GMT, which is very close to noon of local time. The revisit time is 16 days. The spatial resolution of Landsat 8 satellite B10 thermal band is 100 m.

Unfortunately, significant cloudiness in the studied region means that there are not many good satellite images. During the year, there are only a few images without clouds. So, in total, about a dozen images were processed for the period 2014-2022.

For the analysis, we used data from hydrodynamic models (http://model.ocean.univ.gda.pl/ and http://satbaltyk.iopan.gda.pl), which compile ground data with satellite data of sea surface temperature and air temperature.

Methods

The statistical description of the data was carried out using individual descriptive statistics. Long-term and intra-annual features of air and water temperature were studied on the basis of mean monthly data. The air temperature and its long-term changes were studied according to the data of Gdańsk meteorological station, located near the sea (54.35°N, 18.65°E). The water temperature was studied based on the data of Świbno hydrological station at the mouth of the Vistula River and Gdynia and Hel hydrological stations on the seashore.

Satellite images were processed using ArcMap 10 program. The water surface temperature in degrees of Celsius was determined by dependence t = (1321.08 / (Ln (774.89 / ("LC8_B10.TIF" * 0.0003342) +0.1)) + 1))) – 273.15, which is recommended by NASA. The reliability of this dependence is proved by many researchers (Barsi et al., 2014; Schaeffer et al., 2018; Sharaf et al., 2019).

The territory, which does not belong to water area, was identified using the calculation of Normalized Difference Pond Index (NDPI). This index is calculated by the equation NDPI = (B6 – B3) / (B6 + B3), in which B3 and B6 are the meanings of corresponding bands of Landsat 8 satellite. The territory, which is not the water area, was presented in grey color for better visualization.

The study used the results of the hydrodynamic model (http://model.ocean.univ.gda.pl/), developed for Gdańsk Bay including Vistula Lagoon. The model allows for a 48-hour forecast of hydrological and hydrodynamic conditions for the area, including the fields of surface currents, temperature and salinity of seawater. The analysis takes into account a newer version of the ecohydrodynamic model on the SatBałtyk platform (http://satbaltyk.iopan.gda.pl), in which the sea surface temperature observed by satellite is supplemented by the results of the hydrodynamic model. This ensured higher resolution and greater accuracy of results in relation to temperature.

The results and discussion

Air temperature and its changes

The mean annual air temperature at Gdańsk meteorological station during 1961-2020 is 7.9°C. It is important, that air temperature at this meteorological station increased significantly during the observed period from 1961 to 2020 (Fig. 3).

It can be seen that during the observed period, the increase in the mean annual air temperature is approximately 0.33°C per decade. This icrease coincides with the data published in the paper by Kejna and Rudzki

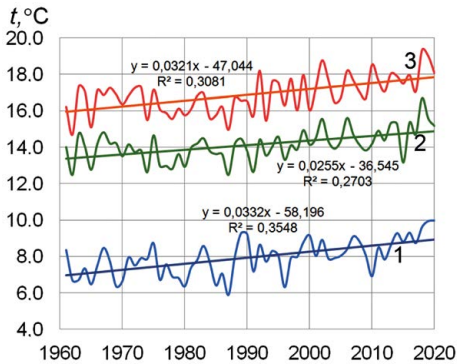

Figure 3. The long-term changes of air temperature at Gdańsk meteorological station in 1961-2020: 1 – annual, 2 – mean for period May-October, 3 – mean for summer period

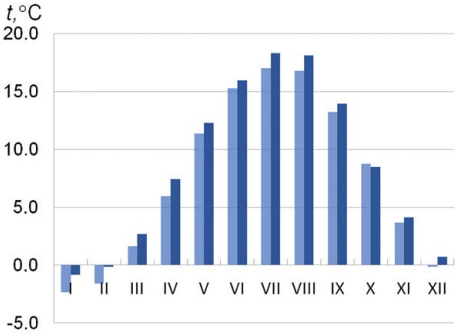

Figure 4. Mean monthly air temperature at Gdańsk meteorological station in 1961-1990 (left columns) and in 1991-2020 (right columns)

(2021). The increase in the summer period and in the warm half of year from May till October is a slightly less than annual.

The highest mean annual air temperature in the studied region was observed in 2020, when at Gdańsk meteorological station it reached 10.0°C. It is 1.6°C higher, than climatic norma for 1991-2020.

The increase in air temperature is generally similar to the results obtained in many works (Kejna & Rudzki, 2021; Vyshnevskyi et al., 2023; Vyshnevskyi & Shevchuk, 2023). At the same time, the obtained increase is higher, than in papers published 10 or even 5 years ago.

The minimum mean monthly air temperature at Gdańsk meteorological station during 1991-2020 is observed in January – minus 0.8°C, the maximum is observed in July – 18.3°C. These data for 1991-2020 are higher than for the previous period 1961-1990. The increase in air temperature is observed throughout the year, but is most significant in January, February, July and August (Fig. 4).

Water temperature

The location of the sudied objects in the norhern part of Poland determines a fairly low water temperature. Even in July and August, when the water temperature is the highest, the mean water temperature in the Gdańsk Bay, includig the Vistula Lagoon, is rather cool – about 17-18°C. The lowest water temperature in the bay is observed in February and March.

It should be borne in mind that the Vistula River flows from the south to the north. To some extent it causes a certain warming effect. On the other hand, the water temperature in the Gdańsk Bay is under the impact of main water masses of the Baltic Sea, located to the north. As a result, the water temperature in the Vistula River mouth is generally higher, than in the Gdańsk Bay, mainly in April–August (Fig. 5). The same effect on the water temperature is observed in the lower reaches of the Danube River which also flows from the south to the north in Romania (Vyshnevskyi & Shevchuk, 2023).

As can be seen in Fig. 4 and Fig. 5, the water temperature in both the Vistula River and the Gdańsk Bay is much higher than the air temperature. This regularity is typical for almost the entire year. Only in March and April the air temperature can be higher than the water temperature. The water temperature variability in the Vistula River is greater than in the Gdańsk Bay, which can be explained by the difference in water volume. Similar results are obtained in the studies (Vyshnevskyi et al., 2023; Vyshnevskyi & Shevchuk, 2023) devoted to the northwestern part of the Black Sea and the water bodies of the Danube Delta.

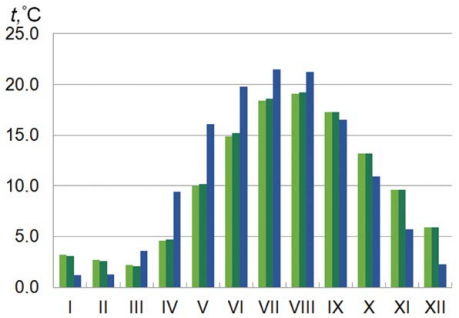

Figure 5. Mean monthly water temperature at Gdynia (left columns), Tolkmicko (central columns) and Świbno (right columns) hydrological stations during 1991-2020

In general, the thermal conditions of the Gdańsk Bay, the Vistula Lagoon and the lower reaches of the Vistula River are characterized by a strong seasonal annual hydrological cycle. The usual pattern is that in spring and summer, the waters of the coastal zone are warmer than the waters of the open Baltic Sea, and in autumn and winter the situation changes. According to Giryatovič (2014), the difference in sea water temperature between summer and winter on the Polish Baltic Sea coast can reach 15°C. According to our research, this difference is even greater.

There is a close relationship between air and water temperatures. The observed increase of air temperature causes the increase in water temperature. At the same time, there is a reverse effect (Fig. 6).

As can be seen in Fig. 6, the speed of increase in water temperature is slightly higher than the trend of increase in air temperature both in summer and in the period from May to October. The largest increase in water temperature at Świbno station is observed in April and May. The main cause of this phenomenon is a significant increase in air temperature in the catchment area of the Vistula River (Kejna & Rudzki, 2021). To some extent, this increase is caused by the observed decrease in the flow of the river during these months.

It can be added that speed of air temperature increase during 1991-2020 was greater than during 1961-2020.

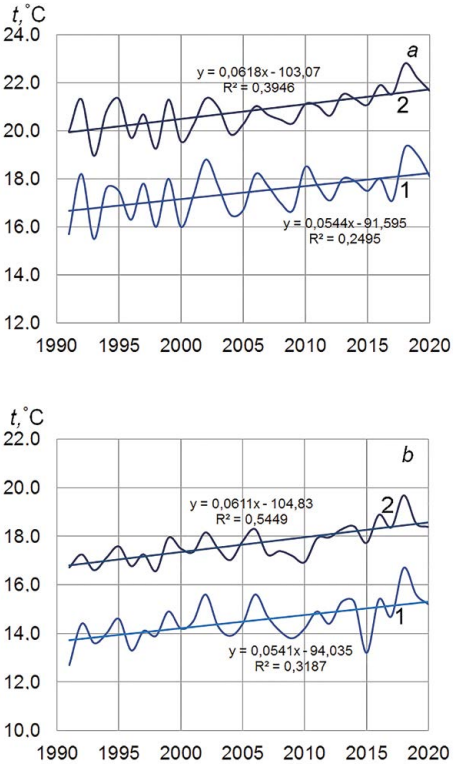

Figure 6. The long-term changes in mean air temperature at Gdańsk meteorological station (1) and water temperature at Świbno hydrological station in the Vistula River mouth (2) during 1991-2020: *a* – June-August, *b* – May-October

The obtained results regarding the increase of water temperature in various objects (bay, lagoon, river) correspond to the previously obtained data (von Storch et al., 2015). A statistically significant increase in sea water temperature in the southern Baltic in late winter and spring was also confirmed by the research of Zblewski (2007), who pointed out the direct impact of winter weather conditions on the sea surface temperature.

The available observation data at hydrological stations make it possible to characterize the main temporal features of the Vistula River mouth and the Gdańsk Bay. At the same time, spatial features remain unexplored. For this, the remote sensing data, namely the images taken by Landsat 8 satellite, were used.

Data from B10 thermal band of Landsat satellite, as well as the usual monitoring data, show that in the spring, namely in April, the water temperature is generally cool – especially in the Baltic Sea itself. At this time, the warmest water is observed in the Vistula River mouth and in the shallow Vistula Lagoon. The water temperature in the Puck Bay, which is separated from the rest of the Baltic Sea by spit, is sligtly warmer than in the neighboring part of the Baltic Sea (Fig. 7).

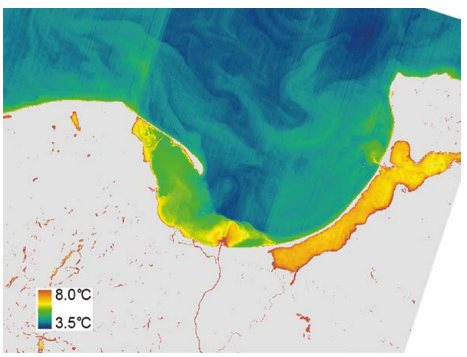

Figure 7. Spatial features of surface water temperature of the Vistula River mouth and the Gdańsk Bay on 16.04.2019, according to Landsat 8 satellite data

The water temperature measured at time of the satellite observation on 16.04.2019 at Hel and Gdynia hydrological stations was 5.5°C and 6.2°C respectively. As can be seen, there is a good correspondence between measured and satellite data of the water temperature.

The image on Fig. 7 shows that during the spring flood on the Vistula River, which is usually observed in April, there is a rather important impact of river water on the water temperature in the southern part of the Gdańsk Bay. At this time, the water temperaure of the Vistula River, which flows from the south to the north, is much higher than in the Gdańsk Bay. The same can be said about the Vistula Lagoon. Fig. 7 shows that the warm water from the lagoon flows into the Gdańsk Bay.

These results, based on actual measurements and remote sensing data, can be compared with the modelling results found at the site http://satbaltyk.iopan.gda.pl (Fig. 8).

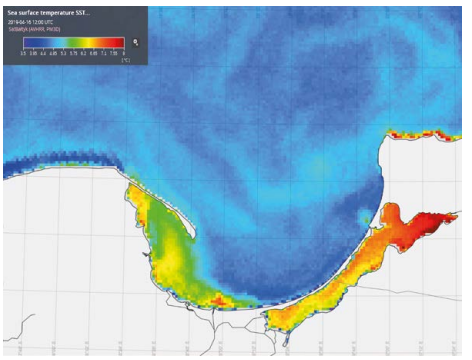

Figure 8. Spatial features of surface water temperature of the Gdańsk Bay on 16.04.2019 in accordance with the site http://satbaltyk.iopan.gda.pl (data provided by System SatBałtyk)

In general, there is a good correlation between actual and model data. The largest difference is observed near the Vistula River mouth, where actual zone with comparatively high temperature was larger than the modeled one.

At the end of spring the water temperature significally increases both in the Vistula River mouth and in the Gdańsk Bay. At this time, the water temperaure in the Vistula Lagoon can exceed 20°C. Simultaneously, the surface water temperature in the Baltic Sea is much lower than in the Vistula River and in the Vistula Lagoon. At this time and early June, the difference in surface water temperature between the Vistula River, including the Vistula Lagoon and the Gdańsk Bay, is the largest. It can reach 10°C (Fig. 9).

The water temperature measured on 31.05.2018 at Hel and Gdynia hydrological stations was 19.5°C and 21.0°C respectively. This rather high water temperature was caused by both high air temperature and wind from the east. In general, there is a good correlation of actual water temperature and calculated on the basis of remote sensing.

These data can be compared with the results of above mentioned model on the same data and time. In this case, modelling

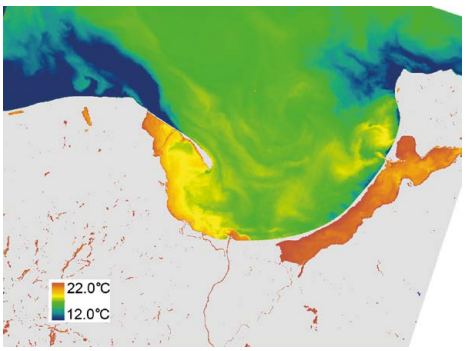

Figure 9. Spatial features of surface water temperature of the Vistula River mouth and the Gdańsk Bay on 31.05.2018, according to Landsat 8 satellite data

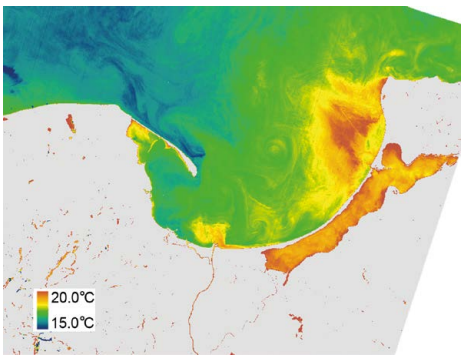

Figure 11. Spatial features of surface water temperature of the Vistula River mouth and the Gdańsk Bay on 07.07.2014, according to Landsat 8 satellite data

results show a wider range of water temperatures than in the case of remote sensing data. For example, the water temperature simulated in the Vistula lagoon was 23°C and satellite data showed about 21°C. There are some differences in the water temperature on the opposite side of the sand spit that separate the lagoon from the Gdańsk Bay (Fig. 10).

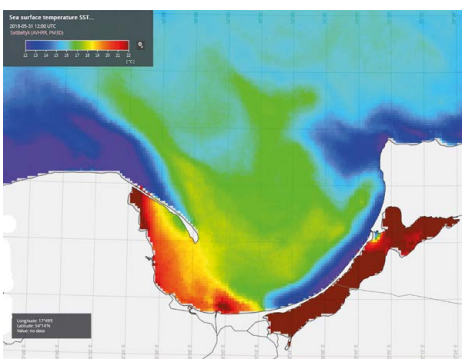

Figure 10. Spatial features of surface water temperature of the Gdańsk Bay on 31.05.2018, according to the site http://satbaltyk.iopan.gda.pl (data provided by System SatBałtyk)

In July and August, the temperature difference between the mouth of the Vistula River and the Gdańsk Bay is decreasing. Obviously, the highest water temperature is observed in the shallow Vistula Lagoon. To a large extent it depends on the air temperature (Fig. 11).

The water temperature measured on 07.07.2014 at Hel and Gdynia hydrological stations was 18.1°C and 18.8°C respectively. This temperature was slightly higher than calculated using satellite imagery. One of the reasons for this is that coastal strip is warmer than the open sea. Similar effect was also registered in other studies (Alcântara et al., 2010; Vyshnevskyi & Shevchuk, 2023).

It can be added that water temperature in July is generally the highest. In this month the highest temperature, registered at Tolkmicko station on the shore of the Vistula Lagoon, reaches 22.0°C (https://www.seatemperature.org). In general, such conditions are suitable for swimming and touristic activity.

At the beginning of autumn the water temperature in the Vistula River mouth and in the Gdańsk Bay becomes similar. More than that, in the Gdańsk Bay it can be even higher than in the Vistula Lagoon. At this time, the impact of the Vistula River on the water temperature in the Gdańsk Bay is small, as a result of small water discharge of the river (Fig. 12).

The water temperature measured on 06.09.2013 at Hel and Gdynia hydrological stations was 18.0°C and 18.9°C respectively.

In October, when the air temperature decreases significantly, the most obvious decrease of water temperature is observed in the shallow Vistula Lagoon. At this time, the water temperature in the Gdańsk Bay can

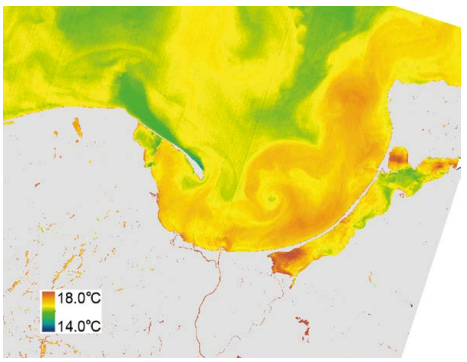

Figure 12. Spatial features of surface water temperature of the Vistula River mouth and Gdańsk Bay on 06.09.2013, according to Landsat 8 satellite data

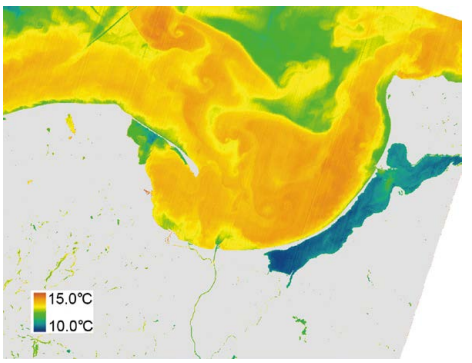

Figure 13. Spatial features of surface water temperature of the Vistula River mouth and Gdańsk Bay on 06.10.2018, according to Landsat 9 satellite data

be higher than in the Vistula River. The main reason for this phenomenon is the slow cooling of the large volume of water in the bay (Fig. 13).

The water temperature measured on 06.10.2018 at Hel and Gdynia hydrological stations was 13.5°C and 13.7°C respectively. As can be seen on Fig. 13, in this and other cases there is a close correlation between measured temperature and calculated on the basis of satellite images.

In general, the obtained results show a good considence between the data of direct measurements of the water temperature, satellite data and the results of the hydrodynamic model. Some inconsistencies with the hydrodynamic model sometimes occurs as a result of data use with different averaging.

Conclusions

The thermal regime of the Vistula River mouth and the Gdańsk Bay (including the Vistula Lagoon) depends on many factors such as season, water discharge of the river, water depth, weather conditions. All year around the water temperature in the Vistula River and the Gdańsk Bay is much higher than air temperature. Generally, the water temperature of the Vistula River which flows from the south to the north, is higher than in the Gdańsk Bay.

However, the relationship between the water temperature in the Vistula River and the Gdańsk Bay (including the Vistula Lagoon) is different in different seasons. In cold seasons the coldest water is observed in the Vistula Lagoon, in warm seasons vice versa. In recent decades, the water temperature in the Vistula River mouth and the Gdańsk Bay has increased significantly. In the warm season, it can exceed 20°C. The newly built canal connecting the Gdańsk Bay and the Vistula Lagoon is a factor to be considered in future research.

In general, the data of remote sensing, regular monitoring, and hydrodynamic models show good correlation.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the author's, on the basis of their own research.

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