Oceanologia, 67 (4)/2025, 67401
Polish Academy of Sciences
Institute of Oceanology
Open access article under the CC BY license
https://doi.org/10.5697/WECV1208

Impact of climate change on the coastal water temperature of lagoons in the southern Baltic Sea in the period 1951–2020

Bożena Pius

Abstract

The study examines long-term trends in water surface temperature (WST) in the Vistula and Szczecin Lagoons within the southern Baltic Sea from 1951 to 2020. Based on in situ data, temperature variability was assessed using both parametric linear regression and the non-parametric Mann-Kendall test. The results reveal a statistically significant increase in water temperatures, particularly during spring and winter. The average warming rate reached 0.23°C and 0.26°C per decade in the Vistula and Szczecin Lagoons, respectively. A strong correlation ($r = 0.60 - 0.93$) was observed between air and surface water temperature. Extreme temperature events are becoming more frequent, with the lowest percentile values rising markedly over time. Winter temperatures exceeding 3°C are now common, and ice cover has diminished or disappeared. These trends highlight the regional impacts of climate change on coastal lagoon ecosystems and their seasonal dynamics. The findings provide valuable insights for future monitoring and management of vulnerable brackish water environments.

Keywords

Lagoons of the southern Baltic Sea; Water surface temperature (WST); Climate warming; Trend analysis; Warming of the lagoons

Faculty of Earth Sciences and Spatial Management, Department of Hydrology, Cryology and Water Management,
Nicolaus Copernicus University in Toruń, Lwowska 1, 87–100, Toruń, Poland.
***Correspondence**: bpius@umk.pl (B. Pius)

Received: 28 October 2024; **revised:** 19 August 2025; **accepted**: 16 September 2025

1. Introduction

In recent years, significant attention has been focused on the long-term fluctuations of seawater temperatures in the context of global climate change (Galbraith and Larouche, 2013; Goikoetxea et al., 2009; IPCC, 2021; Ridgway and Ling, 2023; Zalewska et al., 2023). As a result of global warming, a gradual increase in water temperatures worldwide has been observed, carrying diverse and sometimes unpredictable effects for seas and oceans. Water temperature fluctuations lead to changes in the distribution, productivity, and mortality of marine organisms (Brierley and Kingsford, 2009; Rijnsdorp et al., 2009; Harley et al., 2006; Calvo et al., 2011; Hoegh-Guldberg et al., 2010; Brennan et al., 2016). Ultimately, ecological changes can impact various economic sectors, such as fisheries and tourism (Neumann et al., 2012; Meier et al., 2019). Therefore, fully characterising and understanding changes in water surface temperature (WST) is crucial. Documentary evidence clearly indicates that the pace of climate warming has significantly accelerated in recent years (Hansen and Sato 2020, IPCC 2021). WST is among the hydrological elements particularly susceptible to climatic changes. WST variability mainly depends on air temperature, cloudiness, and sunlight exposure. The heat stored in water determines the intensity of heat and moisture transfer to the atmosphere. The intensity of heat absorption from water is also affected by atmospheric circulation in winter, which regulates air temperature above the water, its humidity, and wind speed. Changes in cloudiness, especially during summer, affect the heating of the sea surface by solar radiation. Ultimately, these changes determine the annual WST changes, dependent on the heat resources remaining in the waters after the winter cooling period and the increase in heat resources during the summer heating of the sea surface (including Mohseni and Stefan (1999), Webb and Nobilis (2007), van Vliet et al., 2011, Hannah and Garner, 2015, O'Reilly et al., 2015, Marszelewski and Pius (2016), Kędra and Wiejaczka (2018), Graf and Wrzesiński (2020), Fernández-Nóvoa et al. (2021)).

The Baltic lagoons represent a unique and dynamic coastal area of the Baltic Sea, sensitive to climate change. The analysed areas are representative of Baltic lagoons, characterised by specific brackish conditions resulting from limited water exchange with the open sea and freshwater inflow from the land. In the southern Baltic area, lagoons with brackish waters include, among others, the Vistula Lagoon and the Szczecin Lagoon. Due to the poorly documented changes in WST of brackish waters, this seems particularly important due to the uniqueness of the ecosystems, often with individual features found nowhere else in the world. This study is based on in situ coastal WST measurement data collected over a period of 70 years (1951–2020). Most WST studies of marine and brackish waters are based on satellite data or data from ships, and drifting and moored buoys (Kennedy et. al., 2019). Among the undeniable advantages of satellite measurements are their broad spatial coverage, regular acquisition intervals, and the ability to monitor areas that are difficult to access (O'Carroll et al., 2019). Global sea surface temperature estimates based on satellite data involve certain uncertainties, particularly when compared to direct in situ measurements. Researchers lack full consensus on the reliability and applicability of remotely sensed WST measurements, especially in areas such as lagoons. Studies conducted in lagoons of the South Pacific have demonstrated differences between in situ and satellite data, which can exceed 0.3°C (Van Wynsberge et al., 2017). Similarly, discrepancies in WST values have been observed in the Baltic Sea and the Curonian Lagoon, with authors reporting positive biases of approximately 0.49°C (Kozlov et al., 2014) or differences on specific days of up to about 1°C (Graf et al., 2023). Comparative studies of in situ measurements and satellite data have been carried out in many other regions, such as the Persian Gulf and the Gulf of Oman (Al-Shehhi et al., 2022), the Mediterranean Sea (López García, 2020), and off the coasts of Africa (Smit et al., 2013). An analysis of the above studies indicates that the greatest temperature discrepancies occur predominantly in shallow waters up to 30 m and during periods of high air temperatures. Satellite WST measurements capture only the top few millimeters of the surface layer, whose temperature can fluctuate significantly due to daytime conditions such as solar radiation and wind. Traditional measurements cover greater depths, providing a more accurate reflection of the actual temperature of upper water layers and averaging out short-term fluctuations. Moreover, in situ measurements often feature longer data series. Therefore, the usefulness of satellite imagery for calculating long-term temperature trends in shallow lagoon waters involves considerable uncertainty. This uncertainty stems from both the differences between satellite and in situ data and the shorter observation periods associated with satellite imagery. However, satellite data have significant advantages in spatial WST analyses. Spatial variability and trends in WST based on satellite data in the Baltic Sea region have been well-documented (Dutheil et al., 2022). Nonetheless, there remains a lack of available studies based on long-term in situ measurement series. Therefore, this study based on data from coastal in situ measurements is extremely important, as it has been proven that even subtle changes in the way measurements are conducted can lead to systematic errors in the measured trends. Due to the continuity, completeness, and time horizon of the data used in this study, the results obtained constitute a significant contribution to and fill a gap in understanding the changes in coastal water temperature of the lagoons in the southern Baltic Sea, which may be crucial for actions aimed at protecting these unique ecosystems. The study aims to understand the patterns of coastal water temperature changes in the lagoons of the Baltic Sea. The specific objectives include: analyzing the patterns and trends of air temperature changes near the studied lagoons (1), investigating long-term trends and changes in WST based on 70-year time series (2), analyzing WST variability across different subperiods (3), identifying and analyzing extreme WST values, including extreme anomalies (4), determining the values and frequency distribution of WST across various ranges (5).

2. Study area

The study area is located in the southern Baltic Sea region and includes the Vistula Lagoon and the Szczecin Lagoon (Figure 1). These basins share many common morphometric and hydrological characteristics. The lagoons are separated from the Baltic Sea by a spit or an island. The main factor shaping the hydrology of the lagoons is the process of mixing freshwater from rivers flowing from the surrounding areas with seawater coming from the bays of the Baltic Sea.

Due to the dominance of the terrestrial factor, the waters of the lagoons are characterised by low salinity and can be classified as brackish waters. The shallow depths of the basins increase their susceptibility to mixing under the influence of wind. Changes in sea level are an important

Table 1. Basic morphometric and hydrological parameters.

Data	Units	Vistula Lagoon	Szczecin Lagoon
A	km²	838	687
L	km	90.7	55
Width	km	9.2	22
Dmean	m	2.6	3.8
Volume	km²	2.3	2.58
A mean	m	1.6	1.0
Salinity	‰	0.7–4.4	0.5–2.0

Explanatory notes: A – surface area, L – length, S – width, D – average depth, O – volume, Am – average amplitude, Z – salinity

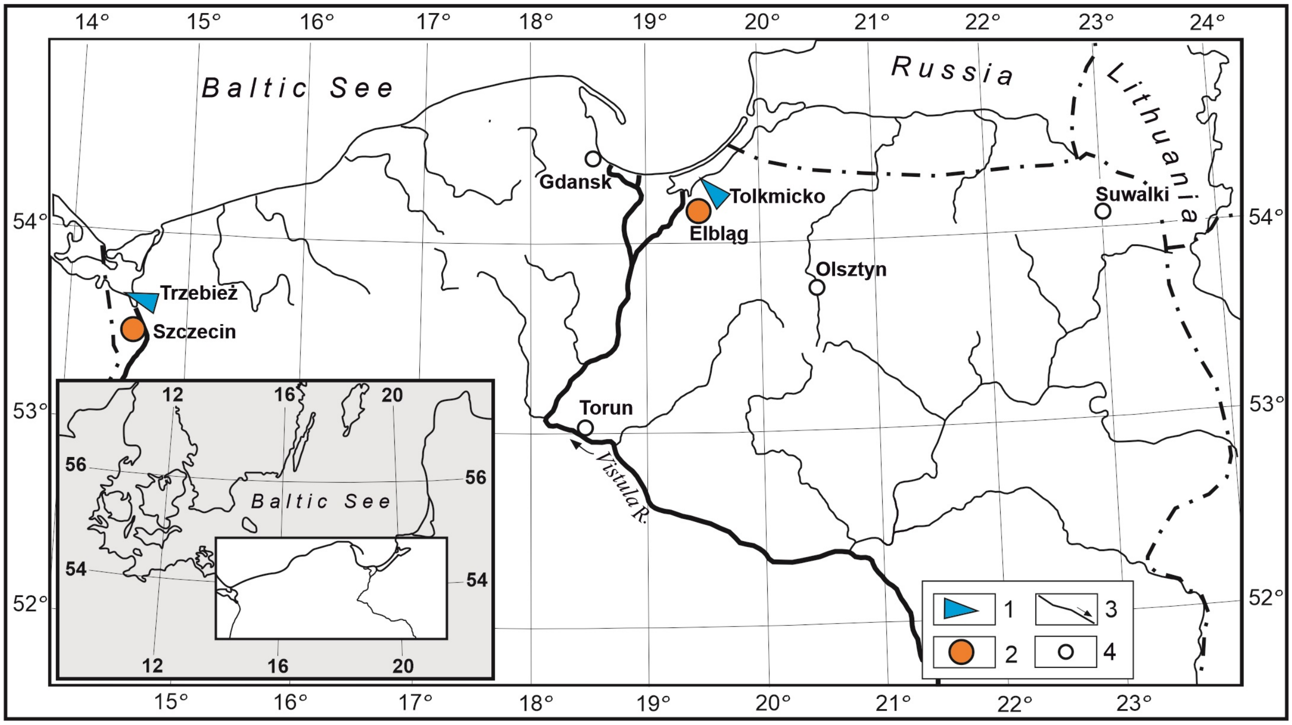


Figure 1. Location of the lagoons of the southern Baltic Sea. 1) Gauging station; 2) Meteorological station; 3) River; 4) City.

Table 2. Average monthly, seasonal, and annual values of air temperature and WST changes (°C per decade) in the period 1951–2020 (statistically significant in bold).

Period	Elbląg	Szczecin	Vistula Lagoon	Szczecin Lagoon
Jan	**0.23**	**0.37**	**0.20**	**0.20**
Feb	**0.42**	**0.56**	**0.20**	**0.20**
Mar	**0.36**	**0.40**	**0.34**	**0.37**
Apr	**0.41**	**0.43**	**0.41**	**0.35**
May	**0.22**	**0.28**	**0.33**	**0.26**
Jun	0.00	0.14	0.10	0.12
Jul	0.16	0.26	0.16	0.16
Aug	**0.25**	**0.35**	**0.20**	**0.30**
Sep	0.13	0.18	0.16	**0.18**
Oct	0.13	0.15	0.12	**0.20**
Nov	0.14	**0.20**	**0.27**	**0.27**
Dec	0.17	**0.28**	**0.22**	**0.19**
WIN	**0.27**	**0.40**	**0.21**	**0.23**
SPR	**0.30**	**0.37**	**0.36**	**0.21**
SUM	**0.14**	**0.25**	**0.16**	**0.19**
AUT	0.09	**0.18**	0.18	**0.23**
Year	**0.20**	**0.30**	**0.23**	**0.26**

factor shaping water levels in the basins, mainly due to the piling effect of the wind in the Baltic Sea. An important factor affecting water levels is the difference between river inflows, the sum of evaporation and atmospheric precipitation, as well as water exchange through the Danish Straits, i.e., the water balance of the Baltic. Variable water levels of the Baltic Sea, along with varied freshwater inflow, affect the salinity of the lagoons, which ranges from 0.5‰ to 4.4‰ (Table 1).

The Vistula Lagoon is located in the eastern part of the southern coast of the Baltic Sea. It is separated from the Baltic Sea by the Vistula Spit and the Sambia Peninsula. The lagoon forms a narrow and long basin. It connects to the sea in the northwestern part, near Baltiysk, through the Baltiysk Channel (in Russian territory). A navigational channel is maintained in the middle of the lagoon, allowing the movement of ships up to the seaport in Kaliningrad. The average depth of the Lagoon is 2.6 meters, with a volume of 2.3 km^3 (Table 2). In the years 2019–2022, a navigational canal was constructed on the western side of the Vistula Spit, connecting the Vistula Lagoon from the west with the Gdańsk Bay.

The Szczecin Lagoon is located in the southern part of the Baltic Sea, on the territory of Poland and Germany. The inflow and outflow of water occur through three straits: the Świna (between the islands of Usedom and Wolin) and the Dziwna (between the island of Wolin and the mainland) leading to the Pomeranian Bay, and the Peene (between the island of Usedom and the mainland) leading to the

Greifswalder Bodden. The average depth of the Szczecin Lagoon is 3.8 meters, and its volume is 5.58 km^3.

3. Data and methods

The study employs daily coastal WST measurements from two water gauge stations, constituting an integral part of the observation network of the Institute of Meteorology and Water Management National Research Institute (IMWM-NRI). The hydrological data were collected from the water gauge stations Tolkmicko on the Vistula Lagoon and Trzebież on the Szczecin Lagoon (Figure 1). It is important to emphasize that WST values obtained from a single point cannot be extrapolated to represent an entire lagoon. However, there is a lack of alternative daily measurement data covering such an extended period and multiple locations that would allow for averaging across the entire lagoon. Remote sensing data, as mentioned in the introduction, often differ significantly from in situ measurements and cover only a small fraction of the time span available for in situ WST measurements. Coastal WST measurements have been conducted for several decades following the IMGW-PIB methodology, ensuring continuity, stability, and repeatability. This consistency makes the obtained time series unique and representative for studying WST variability in the coastal zone. The practice of using point measurements in hydroclimatology has been employed for many years. Similarly, WST measurements in lagoons allow for an assessment of the general thermal regime, though they do not capture the full spatial variability. For a comprehensive analysis, daily air temperature data from two meteorological stations: from Elbląg and Szczecin, were also used (compare Figure 1). Both stations are located in the immediate vicinity of the analysed brackish water bodies and are representative of this type of study. The research period covered 70 years of measurements from 1951–2020.

3.1 Methods

3.1.1 Estimation of trends

Time series trends in the study were estimated using two methods. The long-term variability of WST and air temperatures was assessed using two tests: the non-parametric Mann-Kendall test and the parametric linear regression test. Achieving agreement on the significance of the test allowed for confirmation of the calculated trend. Each method of trend calculation has its drawbacks. Primarily, linear regression has limitations related to requirements for assumptions about normal distribution, homogeneity of variance, and independence of error values in time series. The second of the discussed statistical tests does not require significant assumptions and is often used in hydrometeorological calculations. In the case of linear regression, the test statistic is the Pearson coefficient. In the second test, the statistics are the sum of Kendall's S divided by the square root of the variance:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(X_j - X_i)$$

where: $\operatorname{sgn}(x) = 1$ for $x > 0$, 0 for $x = 0, -1$ for $x < 0$, where x denotes individual data series, and n denotes the total number of years in a time series.

Despite certain limitations, thoroughly discussed by Kundzewicz and Robson (2004), the use of two trend detection tests is justified, as they are among the most commonly used tools in hydrological and climatological analyses.

3.1.2 Detecting abrupt changes in a time series

The Re-scaled Adjusted Partial Sums (RAPS) method was used to identify sub-periods with different water temperatures. This allowed for the identification of the specific moment when the trend changed direction in the time series. Small but systematic changes in time series are often not easily visible. The RAPS method captures fluctuations in time series. This visualisation highlights trends, shifts, data clustering, and irregular fluctuations. It can also provide additional information about the number, size, shape, frequency, and timing of fluctuations (Garbrecht and Fernandez 1994).

The RAPS was calculated according to the formula:

$$\text{RAPS } Y_k = \sum_{t=1}^{k} \frac{X_t - \overline{x}}{\sigma_x} \quad k \in (1, 2 \ldots n)$$

where x_t – element of the studied series, $\overline{x}$ mean value of the studied series, σ_x – mean deviation of the series values, n – number of observations.

To compare the difference in temperatures between the identified sub-periods, a t-test for the difference between means was applied. This test verified the null hypothesis that the means for the sub-periods 1951–87 and 1988–2020 are equal. The t-Student test for independent variables was used, and the homogeneity of variances was checked using Levene's test. A significance level of 0.05 was applied in all tests used in this study.

3.1.3 Innovative trend analysis graphical method

This method is particularly useful for the graphical presentation of trends and is described in detail by Sen (2017). Two obtained time series (sub-periods) should be separately sorted in ascending order. The first sub-series (X_i) is plotted on the horizontal X-axis, while the second sub-series (X_j) is plotted on the vertical Y-axis, using a two-dimensional Cartesian coordinate system (Figure 6).

If the data points on the scatterplot cluster along the 1:1 line (45°), it indicates no trend. If the data points are grouped within the triangular area below the 1:1 line, a downward trend in the time series can be inferred. Conversely, if the data points are located in the triangular area above the 1:1 line, an upward trend in the time series can be concluded. Additionally, the significance of monthly WST value differences was tested using the Student's t-test.

4. Results

4.1 Analysis of patterns and trends in air temperature changes near the studied lagoons

The average annual air temperature for the years 1951–2020 was 7.9°C in Elbląg and 8.9°C in Szczecin. The 1°C difference between the meteorological stations reflects the characteristics of Poland's climate. In shaping the air temperature around Szczecin, the influence of warmer, oceanic air masses from the Atlantic Ocean is clearly evident. Elbląg, located approximately 200 km to the east of Szczecin, is more influenced by continental air masses, which more significantly shape the weather over this region. It is important to emphasise that the properties of the air masses shaping the weather in any given month, season, and year in this part of Europe are highly variable, which is why the climate is described as moderate with transitional characteristics. This is reflected in the course of the average annual air temperature, which shows large fluctuations from year to year (Figure 2).

Significant changes in the average annual air temperatures were especially noted from 1988 onwards, where a noticeable increase was observed compared to previous years (Figure 3). Analysis of the chart allows for the identification of several-year periods of temperature decrease, such as the years 1962–1966 and 1976–1981, as well as periods of accelerated increase, such as the years 1999–2009 and 2011–2020. It is worth noting that the deviations of air temperature from the long-term average in Szczecin are higher than in Elbląg. This suggests that the area of the Szczecin Lagoon is experiencing a faster rate of temperature increase compared to the area of the Vistula Lagoon (Figure 3).

The trends in average annual air temperature show a clear increase, which is consistent with the general trend of global warming. However, the pace of these changes is not uniform seasonally or monthly. Particularly in Szczecin, an increase in air temperature is observed, as evidenced by positive trends for most months, except June and October. In Elbląg, positive trends are recorded from January to May and in August (Table 2).

4.2 Long-term trends and changes in WST based on 70-year time series

During the period 1951–2020, the highest annual average WST in the Vistula Lagoon was recorded in 2018, at 11.6°C, while the lowest was 9.2°C in 1952. This results in a temperature amplitude of 2.4°C, with an average for the entire period being 10.3°C. In the Szczecin Lagoon, the highest WST was observed in 2014, at 12.4°C, and the lowest in 1956, at 9.4°C. The amplitude in this case was 3°C. The average WST for the entire analysed period in the Szczecin Lagoon was 10°C. According to the data, the differences in the annual WST course between the lagoons average 0.4°C. In individual years, these differences can be non-existent or reach up to 1.5°C.

According to Figure 4, clear changes in the average annual WST are visible after 1987. These changes consist of a gradual increase in WST values, which have significantly accelerated since the year 2000. In the years 2018-2020, in the Szczecin Lagoon, the average annual WST exceeded 12°C. Such high WST levels had never been recorded before.

In the seasonal and monthly progression, WST exhibits changes that mimic air temperature. In the Vistula Lagoon, the highest WST occurs in July and August, at 20.7°C and 20.2°C, respectively. Conversely, the lowest WST occurs in the winter months, namely in January and February (1.2–1.3°C). A similar WST distribution is recorded in the Szczecin Lagoon, with the lowest values in January and February (1.3–1.5°C) and the highest in July and August (20.8–20.5°C).

In the annual course of WST, the following characteristic seasons can be distinguished: Winter (from December to March) with an average temperature of up to 3°C. Spring (from April to May) with significant temperature increases of around 5–7°C, and substantial amplitudes exceeding 10°C. Summer (from June to August), with temperature stabilisation at amplitudes of up to 5°C. Autumn (from September to November), marked by significant temperature drops and amplitudes exceeding 10°C.

The analysis of trends in annual WST showed an increase of 0.23°C per decade in the Vistula Lagoon and 0.26°C in the Szczecin Lagoon. The rate of increase was not evenly distributed, with the highest increases noted for the spring and winter months. In the case of the Szczecin Lagoon, additionally high increases occur in autumn (compare Table 2). The largest temperature increases occur in April and March (from 0.41–0.34°C per decade). No WST trends were recorded in June and July, and in the case of the Vistula Lagoon, also in September and October.

The average decadal WST in the Vistula Lagoon increased steadily from 9.7 °C in 1951–1960 to 11.3°C in 2011–2020, with intermediate values of 9.8, 10.0, 10.1, 10.7, and 11.3°C for each subsequent decade. In the Szczecin Lagoon, decadal averages remained stable at 10.2°C for the first three decades, then rose progressively to 10.6, 10.8, 11.3, and 11.8°C in the following periods. These data reflect a clear long-term warming trend in both lagoon systems.

WST in the Szczecin Lagoon and the Vistula Lagoon closely correlates with air temperature. The correlation analysis identified statistically significant relationships between the average monthly values of air temperature and WST. The correlation coefficients range from r= 0.60 to

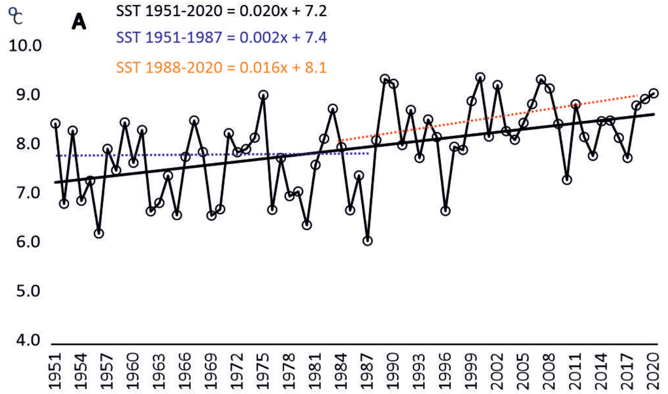


Figure 2. Course of average annual air temperature: A – Elbląg, B – Szczecin.

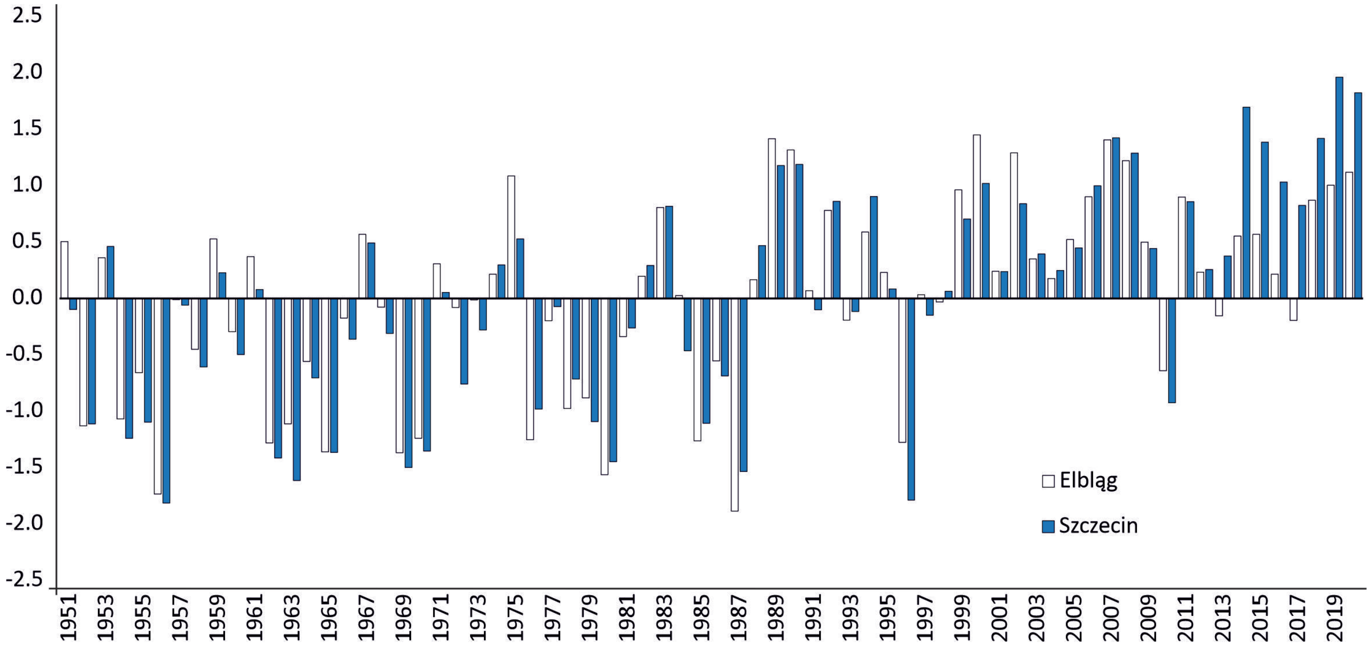


Figure 3. Deviations of annual air temperature from the multiannual average in the period 1951–2020.

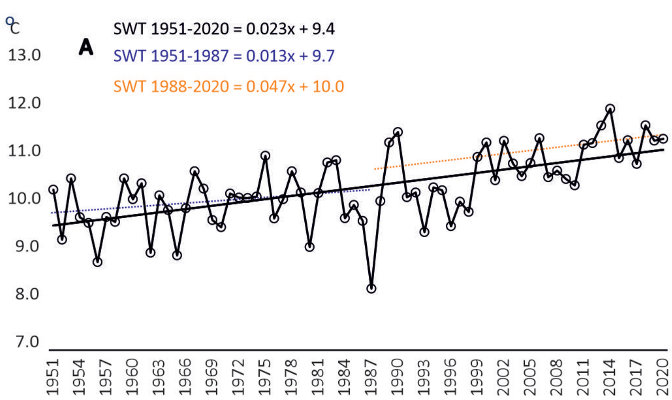


Figure 4. Course of average annual WST: A – Vistula Lagoon, B – Szczecin Lagoon.

Table 3. Coefficients of correlation (r) between air temperature and WST.

Period Period	Vistula Lagoon	Szczecin Lagoon
Jan	0.60	0.79
Feb	0.62	0.82
Mar	0.89	0.93
Apr	0.75	0.88
May	0.84	0.85
Jun	0.79	0.91
Jul	0.88	0.93
Aug	0.80	0.86
Sep	0.86	0.88
Oct	0.79	0.83
Nov	0.73	0.85
Dec	0.69	0.82

0.93 (Table 3). Differences in the correlations between air temperature and the brackish waters of the southern Baltic are due to geographical location. Higher correlations in winter are recorded under oceanic climate conditions. The correlation coefficients between air temperature and WST in the Szczecin Lagoon throughout the year are very high.

4.3 WST variability in different sub-periods

Changes in the average annual WST were not uniform and were characterised by fluctuations in individual years. As shown by the analysis of the cumulative curve (RAPS), permanent changes resulting from increasingly higher average WST occurred from 1988 (Figure 5). However, in recent years, the water temperature has been significantly higher than in the long-term period.

The average WST difference between the periods 1951–1987 and 1988–2020 was 0.8°C in the Vistula Lagoon and 1.1°C in the Szczecin Lagoon, which indicates a clear impact of climate parameter changes in the studied areas. In the first decades of the analysed period (1951–2020), the average annual water temperature remained at around 10°C. However, in each subsequent decade, there was a systematic increase, especially in recent years, where a rapid warming to over 12°C was recorded in the Szczecin Lagoon (compare Figure 4).

The charts (Figure 6) show differences in monthly WST values between two analyzed sub-periods (1951–1987 and 1988–2020) for two lagoons: the Vistula Lagoon (A) and the Szczecin Lagoon (B). Each point represents a monthly WST value: the first sub-period (1951–1987) on the X-axis, the second (1988–2020) on the Y-axis. The dashed 45° line indicates no temperature change between periods. Points above the line indicate a temperature increase; points below, a decrease. Months with statistically significant differences ($p < 0.05$, t-test) are marked in red. The WST changes in the sub-periods were not evenly distributed throughout the year, although, as shown in Figure 6, in every month of the second sub-period (1988–2020), they were higher than in the previous sub-period. A particularly significant increase in WST was observed in the Vistula Lagoon during the spring months, with April recording an increase of 1.67°C. The smallest difference between the sub-periods occurred in June (0.22°C), which was confirmed by the t-test result, which showed no significant differences in WST trends between the analysed sub-periods for this month. In the Szczecin Lagoon, the rate of increase was similar to that of the Vistula Lagoon, peaking in spring, especially in March, when an increase of 1.58°C was recorded. The smallest differences, although still significant, occurred in December (0.56°C). It is worth noting that the rate of WST increase in the Vistula Lagoon was usually lower than in the Szczecin Lagoon, which may result from differences in local hydrological and climatic conditions in these areas (compare Table 2).

4.4 Extreme WST values, including extreme anomalies

The values presented in Table 4 refer to the percentiles of water temperature in different decades, showing a clear upward trend in water temperatures over the years, particularly since 1981.

Table 3 presents changes in water temperature in different percentile ranges (0.05, 0.1, 0.9, 0.95). The percentile ranges represent changes in extreme water temperatures. In the lowest range, represented by the 0.05 percentile, a significant increase is observed in the Vistula Lagoon – from 0.27°C in the 1951–1960 period to 1.30°C in 2011–2022, which represents nearly a fivefold increase. In the Szczecin Lagoon, WST values in the 0.05 percentile were more stable, though a warming trend was also noticeable. In the 1951–1960 period, the temperature in this range was 0.42°C, and in the 2011–2022 decade, it increased to 1.09°C, showing a clear change compared to earlier years.

In the lower range, represented by the 0.1 percentile, a significant increase is also observed in the Vistula Lagoon, from 0.45°C in the 1951–1960 period to 1.67°C in 2011–2022. However, in the 1991–2000 decade, a cooling of 0.14°C was recorded, which deviated from the overall warming trend compared to both earlier and later years. In the Szczecin Lagoon, values increased from 1.19°C in the 1991–2000 period to 2.00°C in 2011–2022, with a noticeable acceleration in warming after 1991.

In the upper range, represented by the 0.9 percentile, WST values in the Vistula Lagoon were relatively stable, oscillating around 20-21°C for most of the analyzed period. The change became particularly evident after 1991, when the temperature increased to 21.6°C in the 2011–2022 decade. In the Szczecin Lagoon, WST values were more varied, but similar to the Vistula Lagoon, a warming trend became noticeable after 1991, reaching 21.7°C in the 2011–2022 decade.

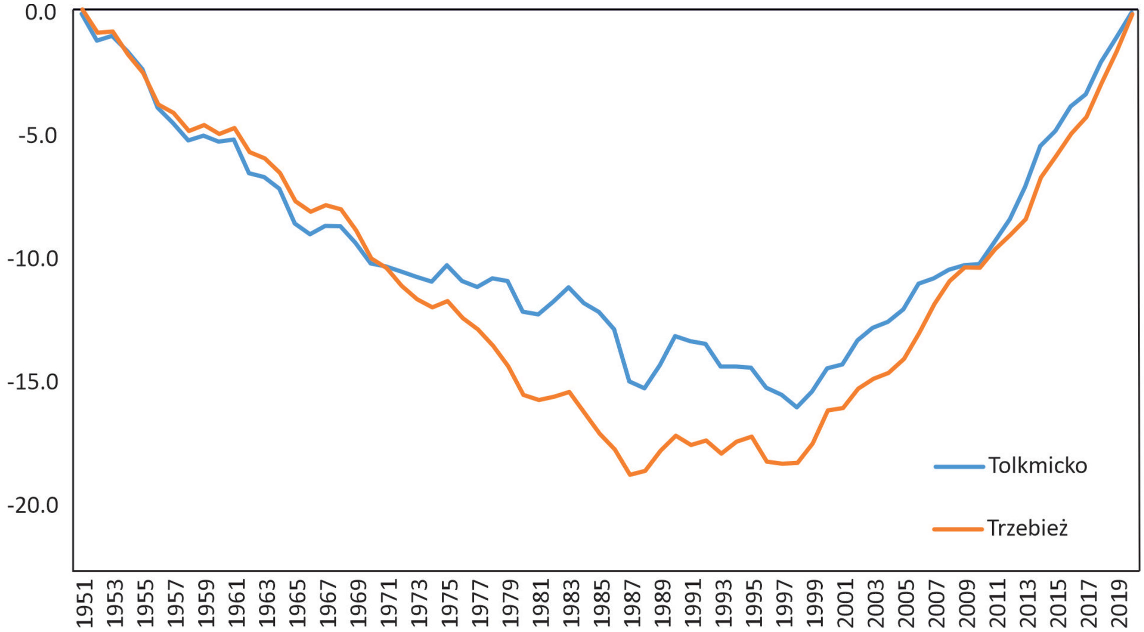


Figure 5. Cumulative deviations of average annual WST from the multiannual value.

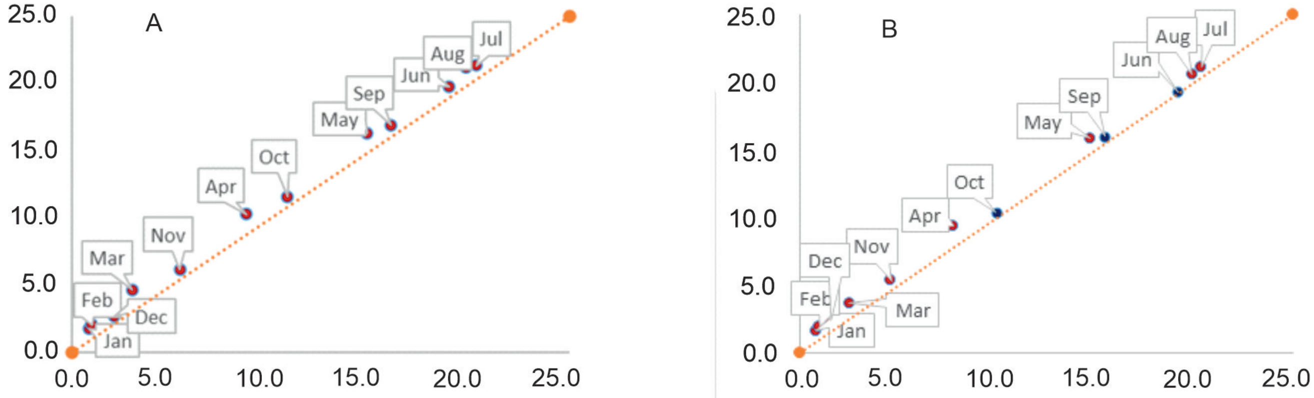


Figure 6. Differences in WST between sub-periods 1951–1987 and 1988–2020 in the Baltic lagoons. Significant differences between WST obtained from the t-test at a confidence level of 0.05 are marked with red colour. A – Vistula Lagoon, B – Szczecin Lagoon

Table 4. Decadal values of extreme WST from 1951 to 2020.

Decade	Percentile value							
	0.05		0.1		0.9		0.95	
	A	B	A	B	A	B	A	B
1951–1960	0.27	0.42	0.45	0.61	20.8	20.5	22.3	21.5
1961–1970	0.35	0.31	0.59	0.50	20.5	20.3	21.6	21.4
1971–1980	0.53	0.46	0.84	0.80	20.8	20.3	22.4	21.5
1981–1990	0.93	0.46	1.29	1.03	20.0	20.5	21.2	21.6
1991–2000	0.82	0.52	1.15	1.19	20.6	21.3	21.9	22.4
2001–2010	0.96	0.57	1.17	0.99	21.3	21.8	22.7	23.0
2011–2020	1.30	1.09	1.67	2.00	21.6	21.7	23.0	22.9

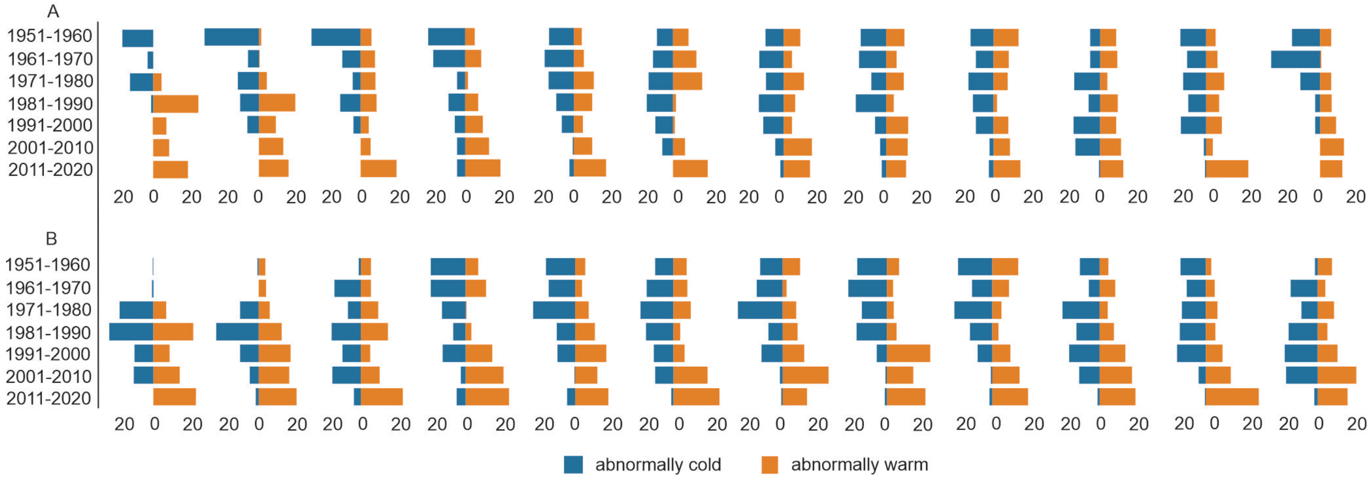


Figure 7. Monthly percent of extreme observations per decade (A – Vistula Lagoon, B – Szczecin Lagoon). Orange columns are of an abnormally warm category exceeding the 90th percentile of 1951–2020, blue columns are of an abnormally cold category negatively exceeding the 10th percentile.

In the highest range, represented by the 0.95 percentile, a steady increase in WST values is observed. In the Vistula Lagoon, the temperature increased from 22.3°C in the 1951–1960 period to 23.0°C in 2011–2022, suggesting an increase in extreme temperature values. In the Szczecin Lagoon, a similar increase was observed, reaching 22.90°C in the last decade, with the most significant changes occurring after 2001.

Figure 7 shows the monthly percentage of extreme water temperature values in the surface layer for seven decades. The individual columns display abnormally warm values (orange, above the 90th percentile) and abnormally cold values (blue, below the 10th percentile). A sharp increase in the observation of abnormally warm values in all months of the year and a decrease with partial disappearance of abnormally cold observations is evident. Summer months of June, July, and August showed the smallest increase in abnormally warm observations in both layers, while winter and spring months (November–May) showed the highest increase, i.e., the greatest change was observed in the winter and spring months. Comparing the two lagoons, it appears that the faster increase in the range of abnormally warm values occurs in the Szczecin Lagoon.

4.5 Values and frequency distribution of WST in different ranges

The greatest differences in WST frequencies between the period 1951–1987 and 1988–2020 are most noticeable in winter and spring. In winter, during the first sub-period, WSTs in the range of 0.1–1.0°C were most frequently observed. In the Vistula Lagoon, these temperatures, characteristic of the winter period, occurred from 50% of days in December to 75% of days in January. However, in the second sub-period (1988–2020), a sharp reduction in these values was observed, the greatest being in January and February (Figure 8). An interesting phenomenon is also the appearance of new WST ranges in February, covering temperatures from 4.1–9.0°C, which were not recorded in the first sub-period. Regarding spring changes, there is mainly a decrease in the frequency of the lowest WSTs. In March, temperatures in the range of 0.1–1.0°C are practically sporadic, whereas they were characteristic in the first sub-period (32% frequency). Significant differences also appear in the case of the highest WST values, especially in April, where new extremes in the range of 17–19°C were not recorded in the first sub-period (compare Figure 8).

During the summer months, the changes in WST between the studied periods are the smallest, which results in the most similar distributions. However, there are noticeable shifts towards an increased frequency of extreme WSTs, especially in the range of 23–24°C in July and August. It is also worth noting that in June, temperatures above 20°C occurred more frequently in the first sub-period than in the second (compare Figure 8). Analysing data from the autumn months, changes in WST frequencies can be observed, especially in October. There has been a shift in WST values from the range of 8.1–10°C to 12.1–14°C. A similar distribution of WST frequencies, with minor differences, was recorded for the Szczecin Lagoon. These observed changes in WST distributions confirm the impact of climate changes on the seasonal characteristics of water temperature in the studied reservoir.

Also in other months there have been shifts in the number of days with specific WSTs, usually an increase in the number of days with warmer water temperatures. Only in months where no significant trend was recorded were changes not well marked (Figure 9).

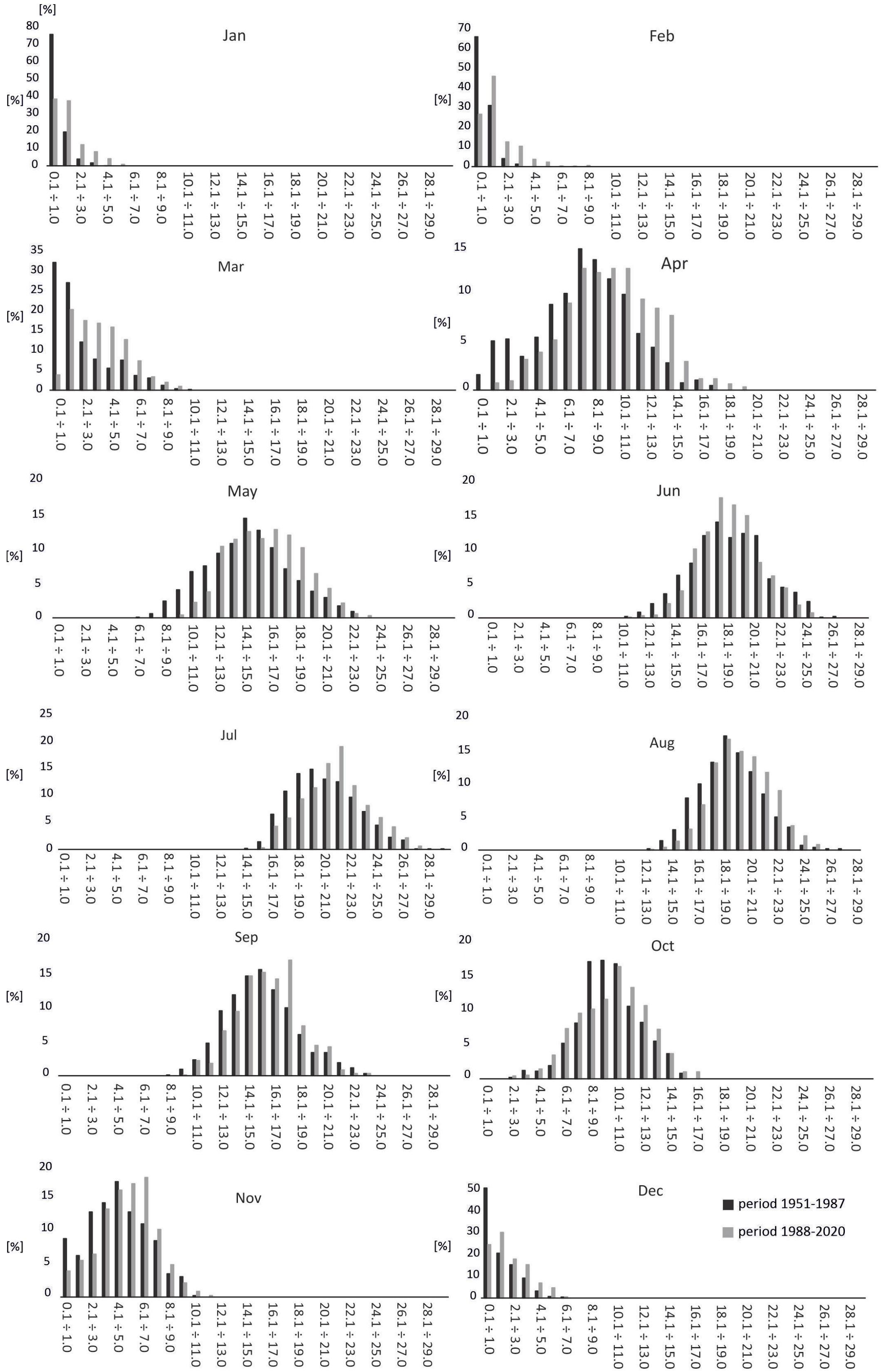
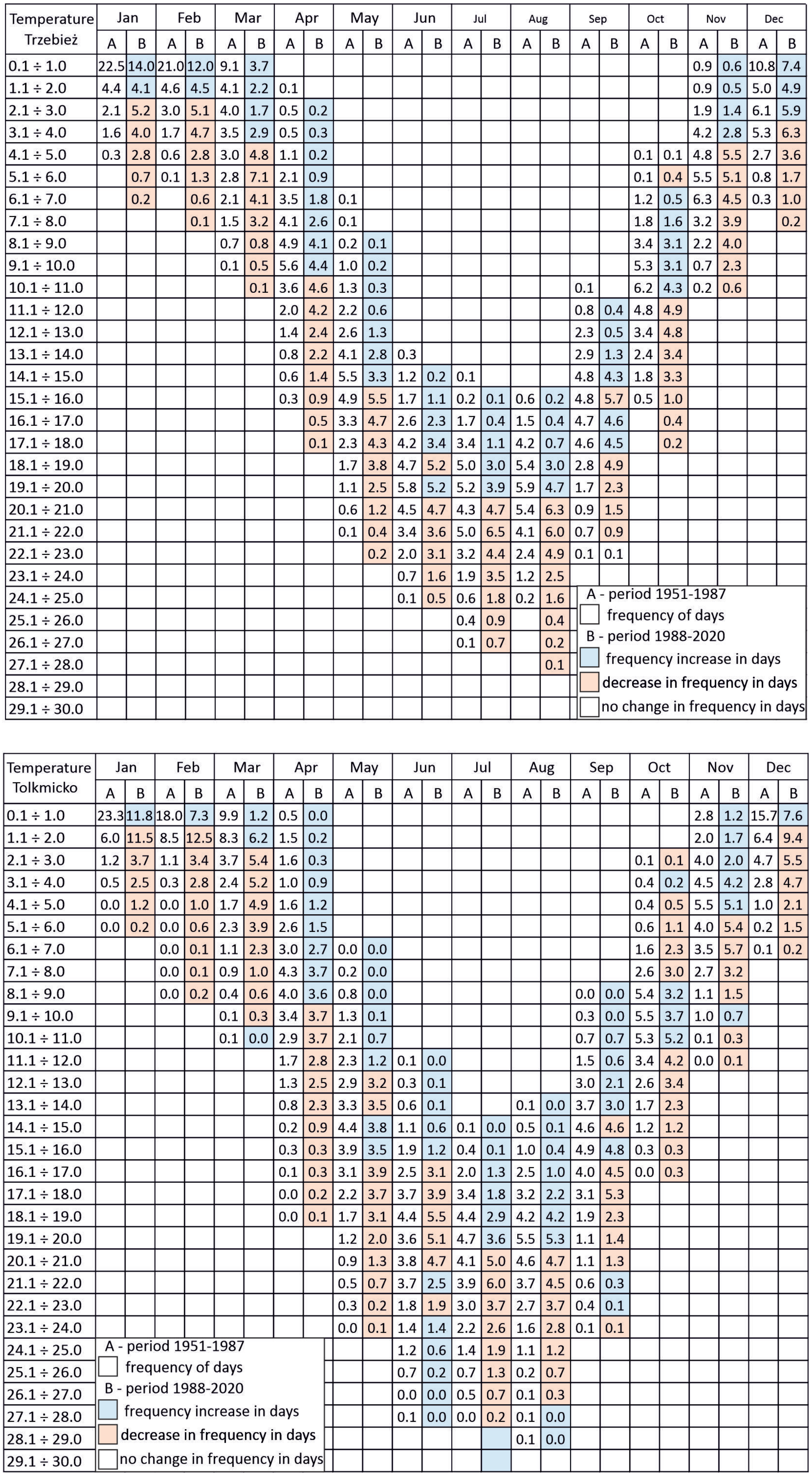


Figure 8. Frequency of WST in the Vistula Lagoon during the periods 1951–1987 and 1988–2020.



Temperature Trzebież	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
0.1 ÷ 1.0	22.5	14.0	21.0	12.0	9.1	3.7															0.9	0.6	10.8	7.4
1.1 ÷ 2.0	4.4	4.1	4.6	4.5	4.1	2.2	0.1														0.9	0.5	5.0	4.9
2.1 ÷ 3.0	2.1	5.2	3.0	5.1	4.0	1.7	0.5	0.2													1.9	1.4	6.1	5.9
3.1 ÷ 4.0	1.6	4.0	1.7	4.7	3.5	2.9	0.5	0.3													4.2	2.8	5.3	6.3
4.1 ÷ 5.0	0.3	2.8	0.6	2.8	3.0	4.8	1.1	0.2											0.1	0.1	4.8	5.5	2.7	3.6
5.1 ÷ 6.0		0.7	0.1	1.3	2.8	7.1	2.1	0.9											0.1	0.4	5.5	5.1	0.8	1.7
6.1 ÷ 7.0		0.2		0.6	2.1	4.1	3.5	1.8	0.1										1.2	0.5	6.3	4.5	0.3	1.0
7.1 ÷ 8.0				0.1	1.5	3.2	4.1	2.6	0.1										1.8	1.6	3.2	3.9		0.2
8.1 ÷ 9.0					0.7	0.8	4.9	4.1	0.2	0.1									3.4	3.1	2.2	4.0		
9.1 ÷ 10.0					0.1	0.5	5.6	4.4	1.0	0.2									5.3	3.1	0.7	2.3		
10.1 ÷ 11.0						0.1	3.6	4.6	1.3	0.3							0.1		6.2	4.3	0.2	0.6		
11.1 ÷ 12.0							2.0	4.2	2.2	0.6							0.8	0.4	4.8	4.9				
12.1 ÷ 13.0							1.4	2.4	2.6	1.3							2.3	0.5	3.4	4.8				
13.1 ÷ 14.0							0.8	2.2	4.1	2.8	0.3						2.9	1.3	2.4	3.4				
14.1 ÷ 15.0							0.6	1.4	5.5	3.3	1.2	0.2	0.1				4.8	4.3	1.8	3.3				
15.1 ÷ 16.0							0.3	0.9	4.9	5.5	1.7	1.1	0.2	0.1	0.6	0.2	4.8	5.7	0.5	1.0				
16.1 ÷ 17.0								0.5	3.3	4.7	2.6	2.3	1.7	0.4	1.5	0.4	4.7	4.6		0.4				
17.1 ÷ 18.0								0.1	2.3	4.3	4.2	3.4	3.4	1.1	4.2	0.7	4.6	4.5		0.2				
18.1 ÷ 19.0									1.7	3.8	4.7	5.2	5.0	3.0	5.4	3.0	2.8	4.9						
19.1 ÷ 20.0									1.1	2.5	5.8	5.2	5.2	3.9	5.9	4.7	1.7	2.3						
20.1 ÷ 21.0									0.6	1.2	4.5	4.7	4.3	4.7	5.4	6.3	0.9	1.5						
21.1 ÷ 22.0									0.1	0.4	3.4	3.6	5.0	6.5	4.1	6.0	0.7	0.9						
22.1 ÷ 23.0										0.2	2.0	3.1	3.2	4.4	2.4	4.9	0.1	0.1						
23.1 ÷ 24.0											0.7	1.6	1.9	3.5	1.2	2.5								
24.1 ÷ 25.0											0.1	0.5	0.6	1.8	0.2	1.6								
25.1 ÷ 26.0													0.4	0.9		0.4								
26.1 ÷ 27.0													0.1	0.7		0.2								
27.1 ÷ 28.0																0.1								
28.1 ÷ 29.0																								
29.1 ÷ 30.0																								

A - period 1951-1987
☐ frequency of days
B - period 1988-2020
🟦 frequency increase in days
🟧 decrease in frequency in days
☐ no change in frequency in days

Temperature Tolkmicko	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
0.1 ÷ 1.0	23.3	11.8	18.0	7.3	9.9	1.2	0.5	0.0													2.8	1.2	15.7	7.6
1.1 ÷ 2.0	6.0	11.5	8.5	12.5	8.3	6.2	1.5	0.2													2.0	1.7	6.4	9.4
2.1 ÷ 3.0	1.2	3.7	1.1	3.4	3.7	5.4	1.6	0.3											0.1	0.1	4.0	2.0	4.7	5.5
3.1 ÷ 4.0	0.5	2.5	0.3	2.8	2.4	5.2	1.0	0.9											0.4	0.2	4.5	4.2	2.8	4.7
4.1 ÷ 5.0	0.0	1.2	0.0	1.0	1.7	4.9	1.6	1.2											0.4	0.5	5.5	5.1	1.0	2.1
5.1 ÷ 6.0	0.0	0.2	0.0	0.6	2.3	3.9	2.6	1.5											0.6	1.1	4.0	5.4	0.2	1.5
6.1 ÷ 7.0			0.0	0.1	1.1	2.3	3.0	2.7	0.0	0.0									1.6	2.3	3.5	5.7	0.1	0.2
7.1 ÷ 8.0			0.0	0.1	0.9	1.0	4.3	3.7	0.2	0.0									2.6	3.0	2.7	3.2		
8.1 ÷ 9.0			0.0	0.2	0.4	0.6	4.0	3.6	0.8	0.0							0.0	0.0	5.4	3.2	1.1	1.5		
9.1 ÷ 10.0					0.1	0.3	3.4	3.7	1.3	0.1							0.3	0.0	5.5	3.7	1.0	0.7		
10.1 ÷ 11.0					0.1	0.0	2.9	3.7	2.1	0.7							0.7	0.7	5.3	5.2	0.1	0.3		
11.1 ÷ 12.0							1.7	2.8	2.3	1.2	0.1	0.0					1.5	0.6	3.4	4.2	0.0	0.1		
12.1 ÷ 13.0							1.3	2.5	2.9	3.2	0.3	0.1					3.0	2.1	2.6	3.4				
13.1 ÷ 14.0							0.8	2.3	3.3	3.5	0.6	0.1			0.1	0.0	3.7	3.0	1.7	2.3				
14.1 ÷ 15.0							0.2	0.9	4.4	3.8	1.1	0.6	0.1	0.0	0.5	0.1	4.6	4.6	1.2	1.2				
15.1 ÷ 16.0							0.3	0.3	3.9	3.5	1.9	1.2	0.4	0.1	1.0	0.4	4.9	4.8	0.3	0.3				
16.1 ÷ 17.0							0.1	0.3	3.1	3.9	2.5	3.1	2.0	1.3	2.5	1.0	4.0	4.5	0.0	0.3				
17.1 ÷ 18.0							0.0	0.2	2.2	3.7	3.7	3.9	3.4	1.8	3.2	2.2	3.1	5.3						
18.1 ÷ 19.0							0.0	0.1	1.7	3.1	4.4	5.5	4.4	2.9	4.2	4.2	1.9	2.3						
19.1 ÷ 20.0									1.2	2.0	3.6	5.1	4.7	3.6	5.5	5.3	1.1	1.4						
20.1 ÷ 21.0									0.9	1.3	3.8	4.7	4.1	5.0	4.6	4.7	1.1	1.3						
21.1 ÷ 22.0									0.5	0.7	3.7	2.5	3.9	6.0	3.7	4.5	0.6	0.3						
22.1 ÷ 23.0									0.3	0.2	1.8	1.9	3.0	3.7	2.7	3.7	0.4	0.1						
23.1 ÷ 24.0									0.0	0.1	1.4	1.4	2.2	2.6	1.6	2.8	0.1	0.1						
24.1 ÷ 25.0											1.2	0.6	1.4	1.9	1.1	1.2								
25.1 ÷ 26.0											0.7	0.2	0.7	1.3	0.2	0.7								
26.1 ÷ 27.0											0.0	0.0	0.5	0.7	0.1	0.3								
27.1 ÷ 28.0											0.1	0.0	0.0	0.2	0.1	0.0								
28.1 ÷ 29.0															0.1	0.0								
29.1 ÷ 30.0																								

A - period 1951-1987
☐ frequency of days
B - period 1988-2020
🟦 frequency increase in days
🟧 decrease in frequency in days
☐ no change in frequency in days

Figure 9. WST frequency for lagoon months in two subperiods.

5. Discussion

Over the last hundred years, nearly all land areas have experienced warming, with an average annual increase in air temperature of 0.1°C. The fastest rate of warming was noticeable in the interior areas of continents, with lower indices in coastal areas. This trend is particularly evident in the mid and high latitudes of North America and the mid-latitudes of inner Asia. In the early 20th century (1923–1950), warming was mainly limited to regions of the Northern Hemisphere in mid and high latitudes, while later warming (1977–2014) covered all land areas of the world, including rapid warming of the Arctic on an unprecedented scale (Wang et al., 2018, IPCC 2023). A similar phenomenon is observed in the case of salt and brackish waters (Haase et al., 2023). The increase in air temperature contributes to the greater absorption of heat by the waters of seas and oceans. This process is dependent on the latitude and the depth of the oceanic or marine basin. It is estimated that the fastest WST growth is observed in shallow seas (Cai et al., 2017, Oliver et al., 2018, Kniebusch et al., 2019). Worldwide, lagoons make up about 13% of coastlines and 5.3% of the coastline of Europe. The southeastern coast of the Baltic Sea and the coasts of the Atlantic and Mediterranean in Southern Europe represent the main lagoon regions in Europe. In the Mediterranean basin, coastlines include six hundred lagoons (Gaertner-Mazouni and De Wit 2012), but only about fifty lagoons have available hydrological and ecological data (Pérez-Ruzafa and Marcos 2012). It should be noted that each lagoon, apart from common features (limited water exchange with the sea, shallow depths), is characterized by individual physicochemical and ecological parameters. Lagoons often contain organisms with specific environmental requirements. Therefore, the variability of the lagoon environment is an inherent feature, about which little is known so far (Curiel et al., 2004, Pérez-Ruzafa et al., 2007). For this reason, generalising the results of studies from one lagoon to larger lagoon coast regions is difficult.

5.1 Long-term warming signals in air temperature

An analysis of a 70-year air temperature series clearly indicates the presence of a long-term warming trend in the atmosphere. The rate of air temperature increase in the studied region, represented by meteorological stations in Szczecin, was 0.30°C per decade, while in Elbląg it was slightly lower, at 0.20°C per decade. Although the scale of the increase depends on the length of the analyzed period, the slope of the air temperature trend is consistent with previous research findings for this area (Kejna and Rudzki, 2021). The increasing trends in annual average air temperature observed after 1988 align with broader patterns of climate warming in Central and Eastern Europe (Kundzewicz and Matczak, 2012). These results are also consistent with IPCC reports (IPCC, 2021), which highlight a significant acceleration of warming in the final decades of the 20th century and the early 21st century.

5.2 Long-term WST changes in lagoons

The increase in WST in the studied lagoons is a dynamic phenomenon, noticeable over the years. Analysing the data, it can be seen that the pace of increase differs depending on the geographic location. In the Vistula Lagoon, an average WST increase of 0.23°C per decade was recorded. In the Szczecin Lagoon, the rate of increase is slightly higher, reaching 0.26°C per decade. When attempting to compare the obtained research results to those concerning WST in the Baltic Sea, several challenges arise. Primarily, the analyzed periods are typically shorter, and the results are generally based on satellite measurements (BACC 2015, Stramska et al., 2015). It is worth noting that studies on Baltic Sea water temperatures have paid little to no special attention to lagoons. The focus has been primarily on data from the open sea and bays, while coastal data has largely been derived from information gathered at tide gauge stations located along the marine coastline, excluding brackish waters. More extensive studies have been conducted only for the Curonian Lagoon. In the period 1961–2008, the trend for increase in coastal water temperature in the Curonian Lagoon was estimated at 0.03°C per year (0.3°C per decade). The time series shown in other publications were usually short, making it difficult to compare them (Dailidienė et al., 2011). In contrast, in the latest study concerning the Baltic Sea WST, an increase of up to 0.6°C per decade (Zalewska et al., 2023) was found, whereas in coastal zones the increase was lower, reaching 0.2°C in 1951-2019. In the depths of Utö, WST increased by 0.3°C over a hundred years (Laakso et al. 2018). In the transitional zone between the open sea and the estuary near Storfjärden, the increase in WST between 1927 and 2020 was estimated at 1.8°C (Goebeler et al., 2022). A significant turning point for both lagoons was the year 1988, from which a sustained increase in WST has been observed. This phenomenon aligns with global warming trends and confirms the strong impact of climate change on water temperatures in coastal regions. Smaller seas and especially shallow lagoons are getting warmer much faster than the global ocean temperature (0.02°C year^{-1} over the reference period) (Huang et al., 2015). Furthermore, an increase in surface water temperatures in coastal waters, including lagoons, has been observed in many regions around the globe (IPCC, 2021). For example, in Mediterranean lagoons, the Venetian Lagoon recorded a temperature increase of 0.095°C per decade. After 1980, warming significantly accelerated to 0.65°C per decade (Amos, 2017). In recent years, heatwaves — defined as water temperatures exceeding the 90th percentile and lasting for several consecutive days — have been frequently observed, posing a threat to the viability of ecosystems (Bertoni et al., 2021).

5.3 Seasonal dynamic of WST trends

It should be emphasized, however, that the seasonal pace of increase was not evenly distributed throughout the year. The largest WST increases were recorded in the spring and winter months. Additionally, for the Szczecin Lagoon, increases also occurred in the autumn months (Table 2). For example, the largest WST increases in the Szczecin Lagoon occur in April and March, reaching from 0.41 to 0.34°C per decade. Spring increases in water temperature result from the earlier onset of the growing season and the faster warming of surface water layers following the winter period. This aligns with observations of a shortening of the cold season in temperate regions, representing a significant indicator of climate change. It is important to note the lack of significant WST trends in June and July, and for the Vistula Lagoon also in September and October. The absence of upward trends indicates a stabilization of water temperatures during periods of maximum solar radiation. This may result from the limited potential for further WST increases in conditions where water temperatures approach the thermal tolerance thresholds for the region. For the Vistula Lagoon, a similar lack of trends in September and October suggests that this body of water is less susceptible to autumnal climate changes, likely due to its greater isolation from the Baltic Sea and the more continental nature of the climate in this area. This seasonal asymmetry is consistent with findings from other studies on lake and coastal ecosystems, where spring warming has proven to be particularly dynamic due to lower initial heat content and greater sensitivity to changes in radiation and circulation. (Livingstone and Adrian, 2009; Woolway and Merchant, 2018).

5.4 Correlation between air temperature and WST, and the influence of other factors on WST

The strong alignment of seasonal patterns in air temperature and WST suggests a strong coupling between the atmosphere and the surface water layer. This relationship has been previously described for shallow water bodies and estuaries (Schmid et al., 2014; Kraemer et al., 2017). Although both regions exhibit a warming trend, the scale and distribution of changes differ. A faster rate of increase in both air temperature and WST was recorded in the Szczecin Lagoon area compared to the Vistula Lagoon. Differences in the correlations between air temperature and the brackish waters of the southern Baltic are due to geographical location. The more continental climate over the Vistula Lagoon is reflected in the correlation coefficient values from December to February, which are significantly lower (from 0.60 to 0.69, Table 4) than in other months. This is due to the negative atmospheric air temperatures in the winter period, when the WST of the Vistula Lagoon often reaches 0°C, causing ice cover to form. The ice cover isolates the water from direct atmospheric influence, resulting in a significantly lower correlation coefficient compared to the Szczecin Lagoon, where ice is less frequent, and heat exchange with the atmosphere occurs for most of the year. In other months, the correlation coefficients between WST and air temperature are strong and remain at around 0.9. The significant impact of air temperature on WST is due to the shallow depth of brackish water bodies and the freedom of water mixing under the influence of wind. Water temperature in shallow water bodies responds to changes in air temperature with a delay usually ranging from several hours to a few days. This is due to the high heat capacity of water and its slower rate of heating. Studies have shown that the daily thermal response of water bodies often occurs with a one-day delay relative to air temperature (Ptak et al., 2019).

In the case of the studied lagoons in this paper, the most variable parameters are the inflows of fresh and salt water. A particularly important factor affecting these differences is the regulation and change of the Vistula River course at the beginning of the 20th century, which significantly transformed the hydrological regime of the Vistula Lagoon. As a result of these changes, the annual inflow of fresh water to the Vistula Lagoon reaches about 3.6 km^3 (Łomniewski 1958). In the case of the Szczecin Lagoon, the inflow of fresh water is much larger, estimated at about 16 km^3. Unfortunately, there are no comprehensive, continuous, and up-to-date data (measurements) on seawater transport between the Bays and the Lagoons (Cieśliński et al. 2024). In the case of the Vistula Lagoon, the data in this regard come mainly from the period from 1951 to 1965. The amount of freshwater inflow into the lagoons has not changed, and no large-scale trends have been observed in long-term river runoff in Poland (Venegas-Cordero et al. 2022). Freshwater inflow to the lagoons undergoes long-term natural fluctuations and, if it affects the WST of the studied lagoons, exerts a similar effect throughout the analyzed period. The Vistula Lagoon receives freshwater from the Vistula River, while the Szczecin Lagoon is fed by the Oder River. Both rivers, in their estuarine sections, have annual average water temperatures comparable to the WST of the lagoons — differences do not exceed –0.4°C (for the Vistula Lagoon) and 0.3°C (for the Szczecin Lagoon), respectively. This indicates that the primary factor influencing the WST values of the studied lagoons is their strong dependence on air temperature (high correlation). Previous studies on the WST of the Baltic Sea lagoons focused mainly on the Curonian Lagoon and the eastern part of the Vistula Lagoon (Dailidienė et al., 2011). The obstacle to a fuller understanding of the warming of lagoons is the lack of long-term WST measurements. In situ measurements are only made in a few Baltic lagoons and have a point distribution. These research results significantly fill the research gap in the area of changes in WST of the southern Baltic lagoons.

WST in lagoons can be influenced by persistent changes in salinity, which affect the physical properties of water —

such as density and thermal conductivity — and thereby modify the heat balance of these ecosystems. A decrease in surface water salinity in the Baltic Sea has been observed at numerous locations (Dailidienė and Davulienė, 2008; Stockmaye and Lehmann, 2023). Forecasts predict further freshening of the Baltic, especially in the northern parts, primarily due to increasing river runoff (Meier et al., 2006). According to projections (Bamber et al., 2019; IPCC, 2023), global sea level could rise by 0.28–1.01 m by the end of the 21st century. In the Baltic Sea region, these effects will be particularly pronounced in shallow and enclosed coastal water bodies such as the Vistula Lagoon and the Szczecin Lagoon. Sea level rise may lead to the intrusion of more saline waters into estuarine zones, including lagoons. Research from 1984 to 2005 showed that average annual salinity in the Klaipėda Strait and the northern part of the Curonian Lagoon increased, while coastal waters along Lithuania and the Baltic Proper showed a decline in salinity. These trends were attributed to both natural and anthropogenic factors, including the intensified deepening of the waterway since 1994, which increased the strait's capacity (Dailidienė and Davulienė, 2008). However, more frequent marine inflows into lagoons and, consequently, future increases in their salinity cannot be ruled out. Therefore, detailed studies on water exchange and salinity changes between coastal areas—such as lagoons — and the open sea remain necessary.

5.5 Changes in the distribution and frequency of WST occurrence

The observed changes in the frequency of WST values in the lagoons are one of the key factors influencing changes in lagoon ecosystems. These changes not only affect the phenology of many species of flora and fauna but also facilitate the invasion of alien species (Occhipinti-Ambrogi, 2007; Wolf et al., 2014). Extreme changes in sea surface temperature values are particularly dangerous for the ecology of lagoon waters. This increase is visible across various percentiles of sea surface temperature. The observed rise in extreme WST values, especially in the 90th and 95th percentiles, reflects an intensification of thermal extremes. The increase in the number of days with WST above 23°C in summer, coupled with a simultaneous decrease in cold extremes in winter, aligns with global observations of more frequent heatwaves in aquatic systems (Smol et al., 2005; Jane et al., 2021). The appearance of new temperature ranges, particularly in spring and autumn, indicates not only a change in thermal conditions but also an extension of the annual thermal window, which may lead to ecological mismatches or habitat loss for cold-adapted species.

The temperature ranges for fish are quite well researched, an example being the herring (*Clupea harengus, L.*) found in the waters of the Baltic Sea. Studies, such as those conducted by Gröger, Hinrichsen, and Polte (2014), demonstrate that the impact of water warming correlates with the reproductive success of fish, especially species that spawn simultaneously in one sequence defined by a specific time of year. Herring (*Clupea harengus, L.*) begins spring spawning in lagoons and bays of the Baltic Sea when the water temperature reaches 3.5–4.5°C. In contrast, the burbot (*Lota lota, L.*), a species that prefers colder waters, exhibits reproductive activity at significantly lower temperatures—starting at just 1.5°C (Čerkasova et al., 2024). The discovery of phenological thresholds for these species is particularly significant as it allows for monitoring changes in the range of WST during their key breeding periods. Unfortunately, despite the potentially beneficial extension of the herring (*Clupea harengus, L.*) breeding period through the earlier occurrence of optimal temperature, negative effects are observed. Larvae from accelerated spawning encounter temporal mismatches with plankton (Polte et al., 2014). In the case of the burbot (*Lota lota, L.*), however, the period with optimal WST for this species has clearly shortened. This trend is particularly noticeable in the last few decades (see Figure 8).

6. Conclusions

The conclusions regarding air temperature and surface water temperatures in the lagoons of the southern Baltic Sea are important for understanding the impact of climate change on WST. Water temperature is fundamental for many aspects of the aquatic environment and affects various biological, chemical, and physical processes. 1. Analysis of air temperature data indicates clear differences between Elbląg and Szczecin. This affects the shaping of air temperatures in both locations. The influence of oceanic masses on the temperature around Szczecin is particularly noticeable, while Elbląg is influenced by continental masses. The recorded changes in average annual air temperatures, especially the increase since 1988, are consistent with the general trend of global warming. The differences in temperature trends between Elbląg and Szczecin suggest that the Szczecin Lagoon area is subject to a faster rate of temperature increase than the Vistula Lagoon area. 2. Analysis of WST indicates significant changes, especially since 1988. The increase in average annual WST and changes in WST value frequencies underscore the impact of climate change on the ecosystems of the Vistula Lagoon and Szczecin Lagoon. The frequency of extreme WSTs, especially in the winter and spring periods, has undergone significant changes, which may affect marine organisms and the dynamics of ecosystems in both basins. In warmer months, such as summer, the warming is less pronounced, which may suggest that these changes could be related to a reduced ability to further raise temperatures during already warm periods.

In summary, the analysis of climate data indicates clear changes in air temperature and surface water temperatures in the Vistula Lagoon and the Szczecin Lagoon. Particularly the precise ability to analyse the shift in the number of days with increasingly higher WST fills a research gap in this area, enabling accurate tracking of changes and patterns. These changes have significant consequences for the environment, as the ability of species to adapt to future environmental conditions remains uncertain. It is also worth noting that further research in this area is crucial for understanding the full scope of these changes.

Conflict of interest

None declared.

References

Al-Shehhi, M. R., 2022. *Uncertainty in satellite sea surface temperature with respect to air temperature, dust level, wind speed and solar position*, Reg. Stud. Mar. Sci. 53, 102385. https://doi.org/10.1016/j.rsma.2022.102385

Amos, C.L., Umgiesser, G., Ghezzo, M., Kassem, H., Ferrarin, C., 2017. *Sea surface temperature trends in Venice Lagoon and the adjacent waters*. J. Coast. Res. 33(2), 385–395. https://doi.org/10.2112/JCOASTRES-D-16-00017.1

BACC I., Team A. (Eds.), 2015. *Second assessment of climate change for the Baltic Sea basin*, Springer Open.

Bertolini, C. and Pastres, R., 2021. *Tolerance landscapes can be used to predict species-specific responses to climate change beyond the marine heatwave concept: Using tolerance landscape models for an ecologically meaningful classification of extreme climate events*. Estuar. Coast. Shelf Sci. 252, p.107284. https://doi.org/10.1016/j.ecss.2021.107284

Bamber, J. L., Oppenheimer, M., Kopp, R. E., et al., 2019. *Ice sheet contributions to future sea-level rise from structured expert judgment*. Proc. Nat. Acad. Sci. 116(23), 11195–11200. https://doi.org/10.1073/pnas.1817205116

Brennan, C. E., Blanchard, H., Fennel, K., 2016. *Putting temperature and oxygen thresholds of marine animals in context of environmental change: a regional perspective for the Scotian Shelf and Gulf of St. Lawrence*, PLoS One 11(12), e0167411. https://doi.org/10.1371/journal.pone.0167411

Brierley, A. S., Kingsford, M. J., 2009. *Impacts of climate change on marine organisms and ecosystems*, Curr. Biol. 19(14), R602–R614. https://doi.org/10.1016/j.cub.2009.05.046

Cai, R. S., Tan, H. J., Kontoyiannis, H., 2017. *Robust surface warming in offshore China seas and its relationship to the East Asian Monsoon wind field and ocean forcing on inter-decadal time scales*, J. Clim. 30(22), 8987–9005. https://doi.org/10.1175/JCLI-D-16-0016.1

Calvo, E., Simó, R., Coma, R., et al., 2011. *Effects of climate change on Mediterranean marine ecosystems: the case of the Catalan Sea*, Clim. Res. 50(1), 1–29. https://doi.org/10.3354/cr01040

Cieśliński, R., Chlost, I., Szydłowski, M., 2024. *Impact of new, navigable canal through the Vistula Spit on the hydrologic balance of the Vistula Lagoon (Baltic Sea)*, J. Mar. Syst. 241, 103908. https://doi.org/10.1016/j.jmarsys.2023.103908

Curiel, D., Rismondo, A., Bellemo, G., et al., 2004. *Macroalgal biomass and species variations in the Lagoon of Venice (Northern Adriatic Sea, Italy): 1981–1998*, Sci. Mar. 68(1), 57–67. https://doi.org/10.3989/scimar.2004.68n157

Čerkasova, N., Mėžinė, J., Idzelytė, R., et al., 2024. *Exploring variability in climate change projections on the Nemunas River and Curonian Lagoon: coupled SWAT and SHYFEM modeling approach*, Ocean Sci. 20(5), 1123–1147. https://doi.org/10.5194/os-20-1123-2024

Dailidienė, I., Baudler, H., Chubarenko, B., Navrotskaya, S., 2011. *Long term water level and surface temperature changes in the lagoons of the southern and eastern Baltic*, Oceanologia 53(1–TI), 293–308. https://doi.org/10.5697/oc.53-1-TI.293

Dailidienė, I., Davulienė, L., 2008. *Salinity trend and variation in the Baltic Sea near the Lithuanian coast and in the Curonian Lagoon in 1984–2005*. J. Marine Syst. 74, S20-S29. https://doi.org/10.1016/j.jmarsys.2008.01.014

Dutheil, C., Meier, H. E. M., Gröger, M., et al., 2022. *Understanding past and future sea surface temperature trends in the Baltic Sea*, Clim. Dynam. 58(11), 3021–3039. https://doi.org/10.1007/s00382-021-06084-1

Fernández-Nóvoa, D., Costoya, X., DeCastro, M., et al., 2021. *Influence of the mightiest rivers worldwide on coastal sea surface temperature warming*, Sci. Total Environ. 768, 144915. https://doi.org/10.1016/j.scitotenv.2020.144915

Gaertner-Mazouni, N., De Wit, R., 2012. *Exploring new issues for coastal lagoons monitoring and management*, Estuar. Coast. Shelf Sci. 114, 1–6. https://doi.org/10.1016/j.ecss.2012.07.008

Galbraith, P. S., Larouche, P., 2013. *Trends and variability in air and sea surface temperatures in eastern Canada*, [in:] *Aspects of Climate Change in the Northwest Atlantic off Canada*, Can. Tech. Rep. Fish. Aquat. Sci. 3045, 1–18.

Garbrecht, J., Fernandez, G. P., 1994. *Visualization of trends and fluctuations in climatic records*, Water Resour. Bull. 30(2), 297–306. https://doi.org/10.1111/j.1752-1688.1994.tb03292.x

Goebeler, N., Norkko, A., Norkko, J., 2022. *Ninety years of coastal monitoring reveals baseline and extreme ocean temperatures are increasing off the Finnish coast*, Commun. Earth Environ. 3, 215.

https://doi.org/10.1038/s43247-022-00545-z

Goikoetxea, N., Borja, Á., Fontán, A., et al., 2009. *Trends and anomalies in sea-surface temperature, observed over the last 60 years, within the southeastern Bay of Biscay*, Cont. Shelf Res. 29(8), 1060–1069. https://doi.org/10.1016/j.csr.2008.11.014

Graf, R., Vyshnevskyi, V., 2023. *Thermal regime of the Vistula River mouth and the Gda/nsk Bay*, Geogr. Pol. 96(4), 459–471. https://doi.org/10.7163/GPol.0264

Graf, R., Wrzesiński, D., 2020. *Detecting patterns of changes in river water temperature in Poland*, Water 12(5), 1442. https://doi.org/10.3390/w12051327

Grebmeier, J. M., 2012. *Shifting patterns of life in the Pacific Arctic and sub-Arctic seas*, Annu. Rev. Mar. Sci. 4, 63–78. https://doi.org/10.1146/annurev-marine-120710-100926

Gröger, J. P., Hinrichsen, H.-H., Polte, P., 2014. *Broad-scale climate influences on spring-spawning herring (Clupea harengus L.) recruitment in the Western Baltic Sea*, PLoS One 9, e87525. https://doi.org/10.1371/journal.pone.0087525

Haase, P., Bowler, D. E., Baker, N. J., et al., 2023. *The recovery of European freshwater biodiversity has come to a halt*, Nature 620(7974), 582–588. https://doi.org/10.1038/s41586-023-06400-1

Hannah, D. M., Garner, G., 2015. *River water temperature in the United Kingdom: changes over the 20th century and possible changes over the 21st century*, Prog. Phys. Geogr. 39(1), 68–92. https://doi.org/10.1177/0309133314550669

Hansen, J., Sato, M., 2020. *Global warming acceleration*, Earth Inst., Columbia Univ., 14 pp.

Harley, C. D., Hughes, A. R., Hultgren, K. M., et al., 2006. *The impacts of climate change in coastal marine systems*, Ecol. Lett. 9(2), 228–241. https://doi.org/10.1111/j.1461-0248.2005.00871.x

Hoegh-Guldberg, O., Bruno, J. F., 2010. *The impact of climate change on the world's marine ecosystems*, Science 328(5985), 1523–1528. https://doi.org/10.1126/science.1189930

Huang, B., Thorne, P., Smith, T., et al., 2015a. *Further exploring and quantifying uncertainties for extended reconstructed sea surface temperature (ERSST) version 4 (v4)*, J. Climate 29, 3119–3142. https://doi.org/10.1175/JCLI-D-15-0430.1

IPCC, 2021. *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., Zhai, P., Pirani, A., et al. (eds.)], Cambridge Univ. Press, Cambridge, UK; New York, NY, USA. https://doi.org/10.1017/9781009157896

IPCC, 2023. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Lee, H., Romero, J. (eds.)], IPCC, Geneva, Switzerland, 184 pp. https://doi.org/10.59327/IPCC/AR6-9789291691647

Jane, S. F., Hansen, G. J. A., Kraemer, B. M. et al., 2021. *Widespread deoxygenation of temperate lakes*. Nature 594(7861), 66–70. https://doi.org/10.1038/s41586-021-03550-y

Jaswal, A. K., Singh, V., Bhambak, S. R., 2012. *Relationship between sea surface temperature and surface air temperature over Arabian Sea, Bay of Bengal and Indian Ocean*, J. Indian Geophys. Union 16(2), 41–53.

Kędra, M., Wiejaczka, Ł., 2018. *Climatic and dam-induced impacts on river water temperature: assessment and management implications*, Sci. Total Environ. 626, 1474–1483. https://doi.org/10.1016/j.scitotenv.2017.10.044

Kejna, M., Rudzki, M., 2021. *Spatial diversity of air temperature changes in Poland in 1961–2018*, Theor. Appl. Climatol. 143(3–4), 1361–1379. https://doi.org/10.1007/s00704-020-03487-8

Kennedy, J. J., Rayner, N. A., Atkinson, C. P., 2019. *An ensemble data set of sea-surface temperature change from 1850: the Met Office Hadley Centre HadSST.4.0.0.0 data set*, J. Geophys. Res. Atmos. 124(14), 7719–7763. https://doi.org/10.1029/2018JD029867

Kniebusch, M., Meier, H. M., Neumann, T., Börgel, F., 2019. *Temperature variability of the Baltic Sea since 1850 and attribution to atmospheric forcing variables*, J. Geophys. Res. Oceans 124(6), 4168–4187. https://doi.org/10.1029/2018JC013948

Kozlov, I., Dailidienė, I., Korosov, A., Klemas, V., Mingėlaitė, T., 2014. *MODIS-based sea surface temperature of the Baltic Sea Curonian Lagoon*, J. Mar. Syst. 129, 157–165. https://doi.org/10.1016/j.jmarsys.2012.05.011

Kundzewicz, Z. W., Matczak, P., 2012. *Climate change regional review: Poland*. WIREs Climate Change, 3(4), 297–311. https://doi.org/10.1002/wcc.179

Kundzewicz, Z. W., Robson, A. J., 2004. *Change detection in hydrological records—a review of the methodology*. Hydrol. Sci. J. 49(1), 7–19. https://doi.org/10.1623/hysj.49.1.7.53993

Laakso, L., Mikkonen, S., Drebs, A., et al., 2018. *100 years of atmospheric and marine observations at the Finnish Utö Island in the Baltic Sea*, Ocean Sci. 14(4), 617–632. https://doi.org/10.5194/os-14-617-2018

Lehmann, A., Myrberg, K., Post, P., Chubarenko, I., Dailidiene, I., Hinrichsen, H.H., Hüssy, K., Liblik, T., Meier, H.M., Lips, U., Bukanova, T., 2022. *Salinity dynamics of the Baltic Sea*. Earth Syst. Dynamk. 13(1), 373–392.

https://doi.org/10.5194/esd-13-373-2022

López García, M. J., 2020. *SST Comparison of AVHRR and MODIS Time Series in the Western Mediterranean Sea*, Remote Sens. 12(14), 2241. https://doi.org/10.3390/rs12142241

Łomniewski, K., 1958. *Zalew Wiślany*, PWN, Warszawa, 117 pp.

Marszelewski, W., Pius, B., 2016. *Long-term changes in temperature of river waters in the transitional zone of the temperate climate: a case study of Polish rivers*, Hydrol. Sci. J. 61(8), 1430–1442. https://doi.org/10.1080/02626667.2015.1040800

Meier, H. M., Dieterich, C., Eilola, K., et al., 2019. *Future projections of record-breaking sea surface temperature and cyanobacteria bloom events in the Baltic Sea*. Ambio 48, 1362–1376. https://doi.org/10.1007/s13280-019-01235-5

Meier M., Kjellström E., Graham P., 2006. *Estimating uncertainties of projected Baltic sea salinity in the late 21st century*. Geophys. Res. Lett. 33, https://doi.org/10.1029/2006GL026488

Mohseni, O., Stefan, H. G., 1999. *Stream temperature/air temperature relationship: a physical interpretation*, J. Hydrol. 218(3–4), 128–141. https://doi.org/10.1016/S0022-1694(99)00034-7

Morrill, J. C., Bales, R. C., Conklin, M. H., 2005. *Estimating stream temperature from air temperature: implications for future water quality*, J. Environ. Eng. 131(1), 139–146. https://doi.org/10.1061/(ASCE)0733-9372(2005)131:1(139)

Neumann, T., Eilola, K., Gustafsson, B., et al., 2012. *Extremes of temperature, oxygen and blooms in the Baltic Sea in a changing climate*, Ambio 41, 574–585. https://doi.org/10.1007/s13280-012-0321-2

O'carroll, A.G., Armstrong, E.M., Beggs, H.M., et al., 2019. *Observational needs of sea surface temperature*. Front. Mar. Sci. 6, p. 420. https://doi.org/10.3389/fmars.2019.00420

Occhipinti-Ambrogi, A., 2007. *Global change and marine communities: alien species and climate change*, Mar. Pollut. Bull. 55(7–9), 342–352. https://doi.org/10.1016/j.marpolbul.2006.11.014

Oliver, E. C. J., Donat, M. G., Burrows, M. T., et al., 2018. *Longer and more frequent marine heatwaves over the past century*, Nat. Commun. 9, 1324. https://doi.org/10.1038/s41467-018-03732-9

O'Reilly, C. M., Sharma, S., Gray, D. K., et al., 2015. *Rapid and highly variable warming of lake surface waters around the globe*, Geophys. Res. Lett. 42(24), 10773–10781. https://doi.org/10.1002/2015GL066235

Pérez-Ruzafa A., Marcos C., Pérez-Ruzafa I.M., Barcala E., Hegazi M.I., Quispe J., 2007. *Detecting changes resulting from human pressure in a naturally quick-changing and heterogeneous environment: spatial and temporal scales of variability in coastal lagoons*. Estuar. Coast. Shelf Sci. 75, 175–188. https://doi.org/10.1016/j.ecss.2007.04.030

Pérez-Ruzafa A., Marcos C., 2012. *Fisheries in coastal lagoons: An assumed but poorly researched aspect of the ecology and functioning of coastal lagoons*. Estuar. Coast. Shelf Sci. 110, 15–31. https://doi.org/10.1016/j.ecss.2012.05.025

Pilgrim J.M., Fang X., Stefan H.G., 1998. *Stream temperature correlations with air temperatures in Minnesota: implications for climate warming*. J. Am. Water Resour. Assoc. 34(5), 1109–1121. https://doi.org/10.1111/j.1752-1688.1998.tb04158.x

Polte P., Kotterba P., Hammer C., Gröhsler T., 2014. *Survival bottlenecks in the early ontogenesis of Atlantic herring (Clupea harengus, L.) in coastal lagoon spawning areas of the western Baltic Sea*. ICES J. Mar. Sci. 71, 982–990. https://doi.org/10.1093/icesjms/fst050

Ptak, M., Sojka, M., Nowak, B., 2019. *Characteristics of daily water temperature fluctuations in Lake Kierskie (West Poland)*. Quaestiones Geographicae 38(2), 97–107. https://doi.org/10.2478/quageo-2019-0017

Ridgway K.R., Ling S.D., 2023. *Three decades of variability and warming of nearshore waters around Tasmania*. Prog. Oceanogr. 215, 102902. https://doi.org/10.1016/j.pocean.2023.103046

Rijnsdorp A.D., Peck M.A., Engelhard G.H., Möllmann C., Pinnegar J.K., 2009. *Resolving the effect of climate change on fish populations*. ICES J. Mar. Sci. 66(7), 1570–1583. https://doi.org/10.1093/icesjms/fsp056

Smit A.J., Roberts M., Anderson R.J., Dufois F., Dudley S.F., Bornman T.G., Olbers J., Bolton J.J., 2013. *A coastal seawater temperature dataset for biogeographical studies: large biases between in situ and remotely-sensed data sets around the coast of South Africa*. PLoS One 8(12), e81944. https://doi.org/10.1371/journal.pone.0081944

Smol, J. P., Wolfe, A. P., Birks, H. J. B., et al., 2005. *Climate-driven regime shifts in the biological communities of arctic lakes*. Proc. Nat. Acad. Sci. 102(12), 4397–4402. https://doi.org/10.1073/pnas.0500245102

Stockmayer, V., Lehmann, A., 2023. *Variations of temperature, salinity and oxygen of the Baltic Sea for the period 1950 to 2020*. Oceanologia 65(3), 466–483. https://doi.org/10.1016/j.oceano.2023.02.002

Stramska M., Białogrodzka J., 2015. *Spatial and temporal variability of sea surface temperature in the Baltic Sea based on 32 years (1982–2013) of satellite data*. Oceanologia 57(3), 223–235. https://doi.org/10.1016/j.oceano.2015.04.004

Şen Z., 2017. *Innovative trend methodologies in science and engineering*. Springer Int. Publ., New York, 349 pp. https://doi.org/10.1007/978-3-319-52338-5

Van Vliet M.T.H., Ludwig F., Zwolsman J.J.G., Weedon G.P., Kabat P., 2011. *Global river temperatures and sensitivity to atmospheric warming and changes in river flow*. Water Resour. Res. 47(2), W02544. https://doi.org/10.1029/2010WR009198

Van Wynsberge S., Menkes C., Le Gendre R., Passfield T., Andréfouët S., 2017. *Are sea surface temperature satellite measurements reliable proxies of lagoon temperature in the South Pacific?* Estuar. Coast. Shelf Sci. 199, 117–124. https://doi.org/10.1016/j.ecss.2017.09.033

Venegas-Cordero N., Kundzewicz Z.W., Jamro S., et. al., 2022. *Detection of trends in observed river floods in Poland*. J. Hydrol. Reg. Stud. 41, 101098. https://doi.org/10.1016/j.ejrh.2022.101098

Wang J., Xu C., Hu M., Li Q., Yan Z., Jones P., 2018. *Global land surface air temperature dynamics since 1880*. Int. J. Climatol. 38(S1), e466–e474. https://doi.org/10.1002/joc.5384

Webb B.W., Nobilis F., 2007. *Long-term changes in river temperature and the influence of climatic and hydrological factors*. Hydrol. Sci. J. 52(1), 74–85. https://doi.org/10.1623/hysj.52.1.74

Wolf M.A., Sfriso A., Moro I., 2014. *Thermal pollution and settlement of new tropical alien species: the case of Grateloupia yinggehaiensis (Rhodophyta) in the Venice Lagoon*. Estuar. Coast. Shelf Sci. 147, 11–16. https://doi.org/10.1016/j.ecss.2014.05.020

Zalewska T., Wilman B., Łapeta B., Marosz M., Biernacik D., Wochna A., Iwaniak M., 2023. *Seawater temperature changes in the southern Baltic Sea (1959–2019) forced by climate change*. Oceanologia 66(1), 37–55. https://doi.org/10.1016/j.oceano.2023.08.001