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How the Hydrometeorological Parameters of the Curonian Lagoon Changed during Two Periods of Standard Climate Normal (1961–1990 and 1991–2020)

Darius Jakimavičius , Diana Šarauskienė and Jūratė Kriaučiūnienė *

Laboratory of Hydrology, Lithuanian Energy Institute, Breslaujos St. 3, LT-44403 Kaunas, Lithuania
* Correspondence: jurate.kriauciuniene@lei.lt

Abstract: Coastal lagoons are recognized as specific and complex water bodies vulnerable to climate change. The focus of this study was the Curonian Lagoon, the largest freshwater lagoon in the Baltic Sea and the whole of Europe. The changes in the hydrometeorological parameters of the lagoon over six decades were evaluated using two periods of climatological standard normal: the most recent 30-year period, i.e., 1991–2020, and the period of 1961–1990. Before statistical analysis, data were checked for homogeneity, and breakpoints were determined by Pettitt and Buishand tests. The Mann–Kendall test was used to determine trends in the data series. The analysis revealed substantial changes in the hydrometeorological parameters of the lagoon during two climate normal periods. An exceptionally high rise in air temperature was detected. A considerable increase was identified in the lagoon water temperature and water level data series. The duration of permanent ice cover on the lagoon declined, as did the ice thickness, whereas the ice breakup advanced. A downward trend in wind speed data was detected, while the change in precipitation had a positive direction. Air and water temperatures were highly correlated with the Arctic Oscillation (AO) index and the water level with the Scandinavia pattern (SCAND).

Keywords: climate change; standard climate normal; hydrometeorological parameters; atmospheric circulation indices; Curonian Lagoon

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1. Introduction

Anthropogenic pressures and climate change's impact on marine ecosystems have significantly increased and are expected to intensify [1–3]. According to the United Nations, about 40% of the world's population lives in coastal areas (within 100 km of the coast). In Europe, 86% of the coastal regions are exposed to the combined effects of multiple human pressures [4]. Damaged marine ecosystems fail to provide essential social goods and ecosystem services to coastal (and remote) communities. The degradation of the environment and climate change are part of the price humanity pays to maintain its prosperity.

A growing body of literature recognizes that coastal lagoons are particularly vulnerable to climate change [1,5–8]. Coastal lagoons are specific complex shallow water bodies between the continent and the sea. In addition to this transitional nature, they are entirely or partially enclosed and separated from the sea by a barrier, land spit, or similar land features [9]. Therefore, they have limited opportunities to exchange water with the open sea. Due to their sheltered characteristics, they have natural conditions for nutrient accumulation and often are at risk of eutrophication [10,11]. Since freshwater (input from rivers) and saltwater intrusion influence create gradients in salinity and other physical and chemical parameters, lagoons show extreme variability in habitats and species composition [12,13].

The Curonian Lagoon is the largest freshwater lagoon in the Baltic Sea and the whole of Europe, with a history of 5000 years [14]. The northern part of the Curonian Lagoon is designated as a NATURA 2000 area (territories protected by the Habitats and Birds

Directives) and is also included in the Baltic Sea area protected by HELCOM. This coastal lagoon is one of many coastal water bodies intensively exploited for fishery, navigation and tourism. The lagoon ecosystem is losing its rich and unique biodiversity; it is highly eutrophicated and polluted due to high loads of nutrients and other chemicals entering this water body directly and through river inflow [15–18]. In addition, it is greatly dependent on the Baltic Sea, which also faces many severe environmental threats and transformations [19–22]. There is no doubt that climate change had and will continue to have a significant direct and indirect impact on the already sensitive and vulnerable ecosystem of the Curonian Lagoon.

Hydrometeorological parameters are vital variables affecting ecologically significant properties and processes such as water salinity, water quality, dissolved oxygen concentration, eutrophication, etc. Since short-term studies do not necessarily indicate remarkable shifts in hydrometeorological parameters over time, the current study aimed to assess changes in these parameters over six decades, using two periods of climatological standard normal: the most recent 30-year period (1991–2020) and the period of 1961–1990, which is recommended by WMO [23] as a standard reference for climate change assessments. We will analyze what kind of variations in hydrometeorological parameters (air and water temperature, precipitation, water level, ice and wind regimes) occurred during the last two cycles of climate normal and how these parameters interacted with and depended on each other.

2. Materials and Methods

Air temperature and precipitation data from Klaipėda and Nida meteorological stations (MS) and wind speed and direction data from Klaipėda MS were used to analyze meteorological conditions at the Curonian Lagoon. For the investigation of the lagoon hydrological conditions, water levels and temperatures were obtained from Klaipėda, Juodkrantė and Nida WGSs, while the ice regime was estimated based only on data from Nida WGS. The locations of these stations are presented in Figure 1. Analysis was accomplished using data from 1961–2020, and this selected period was divided into two equal parts. The first 30-year period corresponds to the climate normal period of 1961–1990 and the second to the most-recent climate normal period (1991–2020). The World Meteorological Organization recommends retaining the period from 1961 to 1990 as a standard reference for long-term climate change assessments [23]. Thus, comparing two data lines of the same length made it possible to assess hydrometeorological changes that may have occurred in the Curonian Lagoon during the last 60 years.

The homogeneity of the data series was checked, and the shift points were determined by applying Pettitt and Buishand tests. The Pettitt method [24] is a rank-based nonparametric test for detecting change points in a time series. The Mann–Whitney statistic is applied to test two samples (before and after the change point), choosing the change point that maximizes the statistic. The ranks ($R_1, R_2, \ldots, R_n$) of the time series ($Y_1, Y_2, \ldots, Y_n$) are used to calculate the test statistic [25]. The Pettitt test is sensitive to breaks in the middle of a time series [26]. The test statistic is calculated as:

$$Z_k = 2\sum_{i=1}^{k} R_i - k(n+1), \;\; k = 1, \ldots, n \tag{1}$$

If the statistic Z_K = max Z_k near the year $k = K$, then a change point occurs in year K. The critical values of the test are given in the study by Pettitt [24].

The Buishand range is a parametric test for change-point detection of a normal variation. This test assumes an independent and identically normally distributed series [25]. The Buishand range is more sensitive to breaks in the middle of a time series [26]. For calculation of the test values, the adjusted partial sums are defined as [27]:

$$S_0^* \; and \; S_k^* = \sum_{i=1}^{k} (Y_i - \overline{Y}), \;\; k = 1, 2, \ldots, n \tag{2}$$

where Y_i is the observation. S_k^* ranges around zero if the series is homogeneous. If there is a change point in year K, then S_k^* reaches a maximum (negative shift) or minimum (positive shift) near the year $k = K$ [27]. The test statistic is defined as follows:

$$Range = \frac{\left[\max S_k^* - \min S_k^*\right]}{s} \quad (3)$$

where s is the standard deviation. The critical values for $\frac{Range}{\sqrt{n}}$ are presented in the study by Buishand [27].

The Mann–Kendall test was used to determine trends when evaluating changes in hydrometeorological parameters in 1961–2020, 1961–1990 and 1991–2020. This test is based on the correlation between the ranks and sequences of the time series. The Mann–Kendall test statistic is calculated according to [28,29]:

$$S = \sum_{i=1}^{n=1} \sum_{j=i+1}^{n} sign(x_j - x_i),\ sign(x_j - x_i) = \begin{cases} +1\ (x_j - x_i) > 0 \\ 0\ (x_j - x_i) = 0 \\ -1\ (x_j - x_i) < 0 \end{cases} \quad (4)$$

A positive S value indicates an increasing trend, while a negative value shows a decreasing trend. The variance (S) of the time series is calculated to obtain the Z value [28,29]:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \quad (5)$$

The normal Z test statistic is calculated by the equation [28,29]:

$$Z = \frac{S \pm 1}{Var(S)^{1/2}} \quad (6)$$

This equation uses $S - 1$ if $S > 0$, $S + 1$ if $S < 0$, and Z is 0 if $S = 0$. A positive value of Z defines an increasing trend, while a negative value indicates a decreasing trend.

When analyzing the data time series, not only is the trend direction important, but also its slope. Sen's slope estimator test can be used for trend detection in hydrometeorological data [30]. The trend in this test should be linear. The calculated slope of the time series represents the quantification of the time change. The Sen's slope is calculated as the mean of all pair-wise slopes for any pair of points in the time series. The Sen's slope equation for a number of N data sample pairs is used for calculations [31]:

$$Q_i = \frac{(x_j - x_i)}{j - i},\ i = 1, 2, 3, \ldots,\ n \quad (7)$$

x_j and x_i are data values at time j and i ($j > i$) from the time series of hydrometeorological parameters. If there are n values of x_j in the time series, there will be $N = n(n-1)/2$ slope estimates. The N value of Q_i is sorted from the smallest to the largest, and then Sen's slope uses median Q_i (Q_{med}). The value of Q_{med} at a different confidence interval of 90% and 95% is calculated as follows:

$$Q_{med} = \begin{cases} Q_{\left[\frac{N+1}{2}\right]} & if\ N = odd \\ \frac{Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+1}{2}\right]}}{2} & if\ N = even \end{cases} \quad (8)$$

When analyzing the change in hydrometeorological parameters and determining the reasons for their change, it is useful to compare the long-term series of these parameters with the large-scale atmospheric circulation indices [32,33]. There are many indices of atmospheric circulation; thus, it is appropriate to select only those with the most significant influence on the climate of the Baltic region. It has been established that changes in air temperature and precipitation in Europe are influenced by the North Atlantic Oscillation

(NAO) and Arctic Oscillation (AO) indices [34]. Water level fluctuations in European water bodies are often associated with the Scandinavia pattern (SCAND) [35]. Therefore, considering the previous studies, we decided to determine the relationships between the hydrometeorological parameters of the Curonian Lagoon and the NAO, AO and SCAND indices. The NAO index is the difference in pressure at sea level between two stations located near the centers of the Icelandic lows and the Azores highs [36]. The Arctic Oscillation (AO) is a component of the atmospheric general circulation that shows non-seasonal variations in atmospheric pressure at sea level in the Northern Hemisphere (north of 20° N) [37]. The Scandinavian pattern (SCAND) is a low-frequency teleconnection pattern over the North Atlantic–Eurasian sector [38]. The values of these three indices were taken from the NOA database (https://www.cpc.ncep.noaa.gov/ accessed on 4 January 2023).

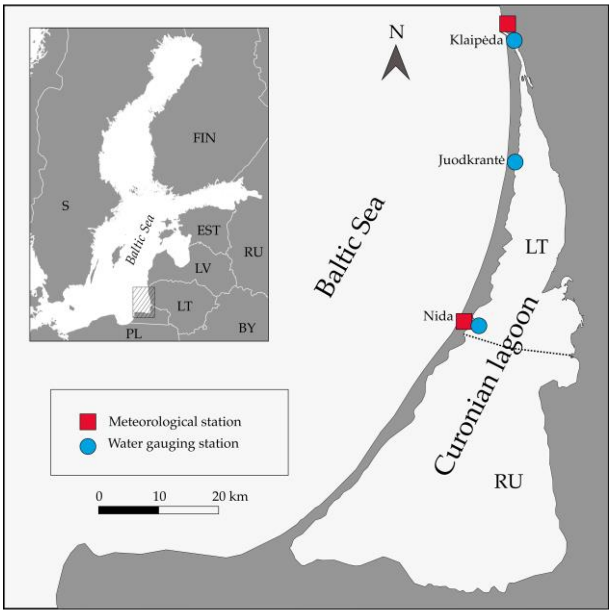

Figure 1. Study area and measurement stations.

3. Results

3.1. Data Homogeneity

Before the statistical analysis of hydrometeorological parameters of the Curonian Lagoon, the data homogeneity was checked by the Pettitt and Buishand tests. The results of these tests are presented in Table 1. Only ice thickness data were found to be homogeneous (p value > 0.05). Breakpoints were identified in all other data series. The homogeneity tests revealed that air and water temperature and ice data series (covering the entire period of 1961–2020) shifted in 1988 (Table 1). Completely different regularities were detected in precipitation, wind speed and water level data. The breaking points of precipitation data from Klaipėda and Nida stations and wind speed data from Klaipėda were determined in 1977 and 1983, respectively. The dates of water level data shift varied considerably between the stations. According to both applied tests, the breakpoint of water level data from Nida was in 1980 and from Juodkrantė in 1977. However, when analyzing the data recorded at Klaipėda, it was found that according to the Pettitt test, the shift occurred in 1987 and, according to the Buishand test, in 1980. The breakpoints were also determined by p values using Monte Carlo resampling. As seen from Table 1, the date of the precipitation shift was somewhat questionable since, according to the Pettitt test, the p value was greater than 0.05, but according to the Buishand test, it was 0.0236. The p values of all the remaining variables' shift dates varied from 0.0001 to 0.017. Considering such p values, we can state that the established change points in the data series of the investigated parameters of the Curonian Lagoon were statistically reliable. Evidently, the most recurring shift date was 1988, i.e., it was very close to the end of the first selected period of climate normal. Therefore, the period of 1961–2020 was quite precisely divided into two 30-year periods, the first of which coincides with the climate normal period of 1961–1990 and the second 30-year period with the most-recent climate normal period of 1991–2020.

Table 1. Results of homogeneity analysis.

Parameters	*p* Value and Year			
	Pettitt	Year	Buishand	Year
Average precipitation	0.0694	1977	0.0236	1977
Average air temperature	<0.0001	1988	<0.0001	1988
Wind speed at Klaipėda	<0.0001	1983	<0.0001	1983
Water level at Klaipėda	<0.0001	1987	<0.0001	1980
Water level at Juodkrantė	0.001	1977	0.0002	1977
Water level at Nida	<0.0001	1980	<0.0001	1980
Water temperature at Klaipėda	0.0000	1988	<0.0001	1988
Water temperature at Juodkrantė	0.0002	1988	<0.0001	1988
Water temperature at Nida	<0.0001	1988	0.0000	1988
Ice cover duration at Nida	0.001	1988	0.001	1988
Ice thickness at Nida	>0.05	1987	>0.05	1987
Ice break-up date at Nida	0.017	1988	0.004	1988

3.2. Changes in Hydrometeorological Parameters

Air temperature. Air temperature analysis at the Curonian Lagoon was carried out based on Klaipėda and Nida meteorological station data. As can be seen from Figure 2, in the first period, the average annual air temperature was 7.1 °C (ranging from 5.3 to 9.2 °C in individual years), and in the second period, 8.4 °C (ranging from 6.2 to 10.2 °C). It increased by 0.029 °C yr^{-1} in 1961–1990 (statistically insignificant increase, $p > 0.05$) and by 0.046 °C yr^{-1} in 1991–2020 (statistically significant increase, $p = 0.007$). Over the entire study period, the air warmed by an average of 0.041 °C yr^{-1} ($p = 0.0001$).

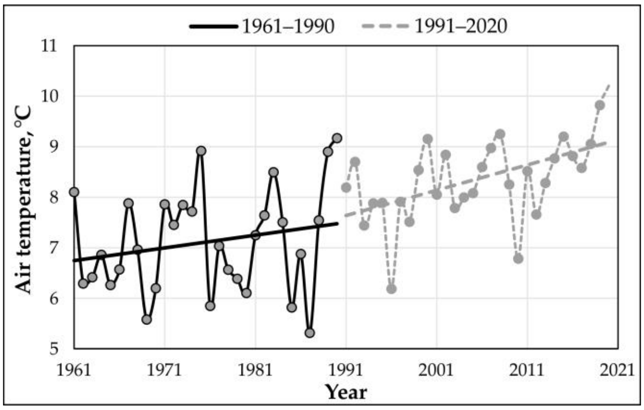

Figure 2. Change in average annual air temperature in 1961–2020 (according to Klaipėda and Nida MS).

The trends of air temperature over the selected periods were analyzed by the Mann–Kendall test. Average air temperatures, Sen's slopes and *p* values are provided in Table 2; they represent different seasons (winter consists of December, January and February; spring of March, April and May; summer of June, July and August; autumn of September, October and November). Air temperature during the studied period increased the most in winter and spring (Sen's slope 0.063 and 0.053, respectively). The slight upward direction of its values was estimated in autumn (Sen's slope 0.007) and a slight downward trend in the summer months (Sen's slope −0.017). However, the estimated rise was statistically insignificant, as the Mann–Kendall test indicated *p* values greater than 0.05 for all periods. The situation was somewhat different in the following period: the air temperature went up the most in autumn (Sen's slope 0.079), a little bit less in the summer and spring months (Sen's slope 0.047 and 0.041, respectively) and the least in the winter season (Sen's slope 0.007). The positive trend in the second 30-year period was significant only in summer and autumn, as p values reached 0.032 and 0.001, respectively; p values were higher than 0.05 in the remaining seasons. A comparison of the air temperature between the two periods revealed that it increased the most in winter (1.7 °C), slightly less in spring and summer (1.4 °C, respectively), and the least in autumn (0.5 °C).

Table 2. Overview of mean seasonal and annual air temperature (°C) analysis.

Period	**1961–1990**			**1991–2020**		
	Average	**Sen's Slope**	***p* Value**	**Average**	**Sen's Slope**	***p* Value**
Winter	−2.0	0.063	>0.05	−0.3	0.007	>0.05
Spring	5.4	0.053	>0.05	6.8	0.041	>0.05
Summer	16.3	−0.017	>0.05	17.6	0.047	0.032
Autumn	8.7	0.007	>0.05	9.3	0.079	0.001
Year	7.1	0.029	>0.05	8.4	0.046	0.007

Precipitation. The average precipitation was calculated using Klaipėda and Nida MS data. From the data in Figure 3, it is apparent that the change in precipitation was uneven. During the first period, it ranged from 438 (in 1975) to 1001 mm (in 1981), and in the second, from 541 (in 1996) to 1083 mm (in 2017). Its annual average was 709 and 764 mm, respectively. According to statistical analysis, precipitation increased by 6.6 mm yr^{-1} in 1961–1990 and by 3.1 mm yr^{-1} in 1991–2020 (Table 3). However, this tendency was statistically reliable only in 1961–1990 (p = 0.011), whereas in 1991–2020, the increase was statistically insignificant (p > 0.05).

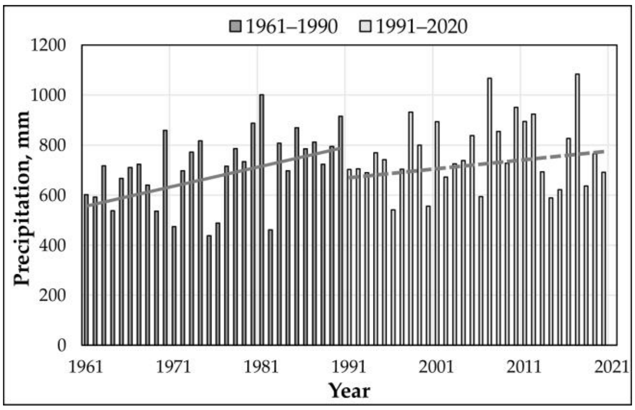

Figure 3. Change in average annual precipitation.

Table 3. Overview of mean seasonal and annual precipitation (mm).

Period	**1961–1990**			**1991–2020**		
	Average	**Sen's Slope**	***p* Value**	**Average**	**Sen's Slope**	***p* Value**
Winter	140.5	2.31	0.012	184.3	1.34	>0.05
Spring	109.1	0.31	>0.05	112.7	−1.29	>0.05
Summer	210.8	1.38	>0.05	212.9	2.01	>0.05
Autumn	249.0	4.11	0.037	254.3	0.10	>0.05
Year	709.3	6.59	0.011	764.2	3.05	>0.05

As for the seasonal values, the analysis revealed that in the first 30-year period, precipitation had positive trends in all seasons. It increased the most in autumn (Sen's slope 4.11) and significantly less during the winter and summer seasons (Sen's slope 2.31 and

1.38, respectively), while the slightest shift to higher values was estimated in spring (Sen's slope 0.31) (Table 3). Over the recent 30-year period, precipitation trends were the most pronounced in summer (Sen's slope 2.01). The average change (but of a different pattern: Sen's slope was 1.34 and −1.29, respectively) was determined in the winter and spring seasons. Precipitation changed the least in autumn (Sen's slope 0.10). When comparing the two periods, statistically significant differences were identified only in the winter and autumn of the first period (p value 0.012 and 0.037, respectively). Precipitation increased the most in winter (43.9 mm) and in the remaining seasons—slightly (up to 5.3 mm) (Table 3).

Wind parameters. The analysis of wind parameters (speed and direction) at the Curonian lagoon was based on the data recorded in Klaipėda MS. As Figure 4 shows, the wind speed decreased: its average value in the first period was 5.1 m/s and ranged from 4.3 m/s in 1989 to 6.3 m/s in 1962; in the second period, it varied from 2.9 m/s in 2013 to 5.5 m/s in 2000, averaging 4.1 m/s. Wind speed declined by 0.041 m/s yr^{-1} in 1961–1990 and by 0.055 m/s yr^{-1} in 1991–2020.

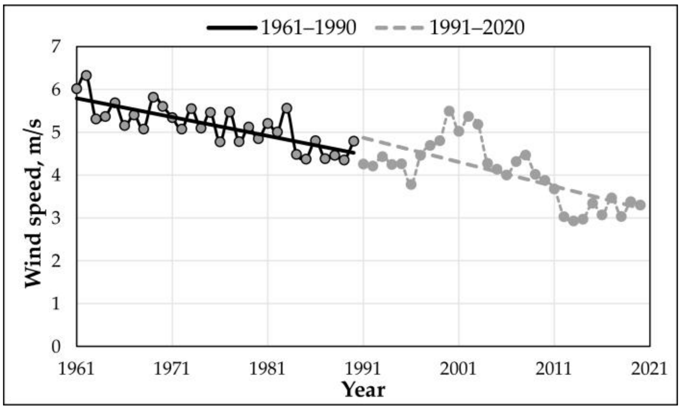

Figure 4. Changes in the average annual wind speed at Klaipėda.

The analysis of seasonal trends in wind speed indicated that this variable experienced the most pronounced changes among all studied meteorological parameters of the lagoon (Table 4). In the first 30-year period, wind speed declined almost equally in the spring, summer and autumn seasons; Sen's slope values were −0.051, −0.054 and −0.047, respectively, whereas in winter, the changes were significantly lower (Sen's slope was only −0.025). The Mann–Kendall test revealed that in all seasons, except for winter, these changes were statistically significant; p values varied from 0.0001 to 0.004. In the second period, on the contrary, the most considerable changes were determined in the winter season (Sen's slope 0.076). In the spring, summer, and autumn seasons, the wind speed decreased very similarly as in the first period, and the Sen's slope values were −0.047, −0.042 and −0.055, respectively. The downward trend in wind speed values in the recent period was statistically significant, and the p values of different seasons varied from 0.0001 to 0.002. Overall, it was found that wind speed diminished the most in autumn, by 1.6 m/s. Meanwhile, it decreased quite similarly in the remaining seasons, by 1.1, 0.9 and 0.8 m/s, respectively.

Table 4. Overview of mean seasonal and annual wind speed (m/s).

Period	1961–1990			1991–2020		
	Average	Sen's Slope	p Value	Average	Sen's Slope	p Value
Winter	5.7	−0.025	>0.05	4.9	−0.076	0.0001
Spring	4.5	−0.051	0.0004	3.7	−0.047	0.001
Summer	4.5	−0.054	0.0001	3.4	−0.042	0.001
Autumn	5.9	−0.047	0.004	4.3	−0.055	0.002
Year	5.1	−0.041	0.0001	4.1	−0.055	0.001

Another critical indicator is the recurrence of certain wind directions and the average wind speed of a certain direction. As shown in Figure 5, in the first thirty years, the observed winds were mainly from SE, W, NW and SW. However, the strongest winds blew from W, WSW, SW and WNW. Their average speeds were 6.9, 6.7, 6.2 and 6.1 m/s, respectively (Figure 5c). During the second thirty-year period, the prevailing wind directions changed slightly, resulting in the increased frequency of NW, SW, W and WSW winds (Figure 5b). During this period, the strongest winds were from WSW, SW, W and SSW. Their speed reached 6.1, 5.9, 5.6 and 5.4 m/s, respectively (Figure 5c).

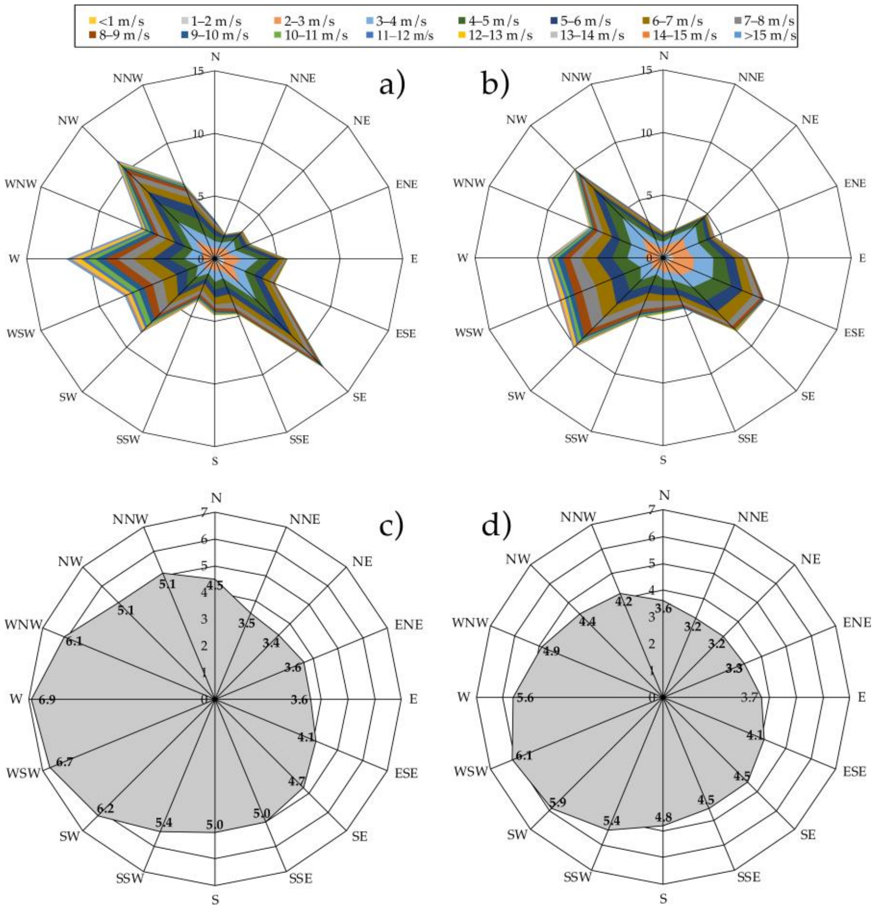

Figure 5. Recurrence of specific wind directions in 1961–1990 (**a**) and 1991–2020 (**b**), average speed (m/s) in 1961–1990 (**c**) and 1991–2020 (**d**) according to Klaipėda MS data.

When analyzing wind indicators, it is important to know the average wind speed and direction and how often winds of particular strength were observed. Wind speeds of 2 to 6 m/s prevailed throughout the entire observation period (Figure 6). These winds accounted for 56.9% of all investigated cases in the first period and 62.8% in the second. The frequency of winds weaker than 2 m/s and stronger than 6 m/s in the first and second periods was very similar, 37.2% and 43.1%, respectively. Winds up to 5 m/s increased recently, but the winds stronger than 5 m/s decreased. This decrease is particularly pronounced in the range of winds stronger than 10 m/s (Figure 6).

Water level. The analysis of the water level of the Curonian Lagoon was carried out according to the data of Klaipėda, Juodkrantė and Nida WGSs. Water level data from Juodkrantė were used only until the end of 2011, as this station was closed later. The analysis revealed that the highest water level is characteristic of the southern part of the lagoon (at Nida), while it gradually decreases toward the Klaipėda Strait (Figure 7). In 1961–1990, the average lagoon level at Nida was 509 cm and varied from 493 to 526 cm (Figure 7c). During the same period, the average water level at Juodkrantė was 506 cm. In individual years, it varied between 492 and 523 cm (Figure 7b). The lowest average annual water level was at Klaipėda at 501 cm and varied from 489 to 518 cm (Figure 7a). In the first period, water level rose in all studied stations. On average, water level increased annually by 0.32 cm at Juodkrantė, 0.47 cm at Klaipėda and 0.48 cm at Nida.

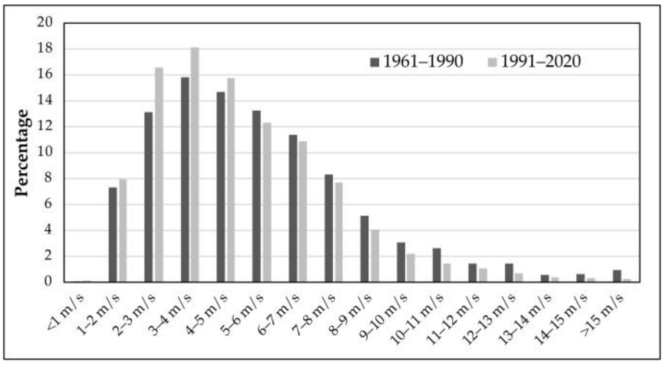

Figure 6. Distribution of wind speed classes in 1961–1991 and 1991–2020.

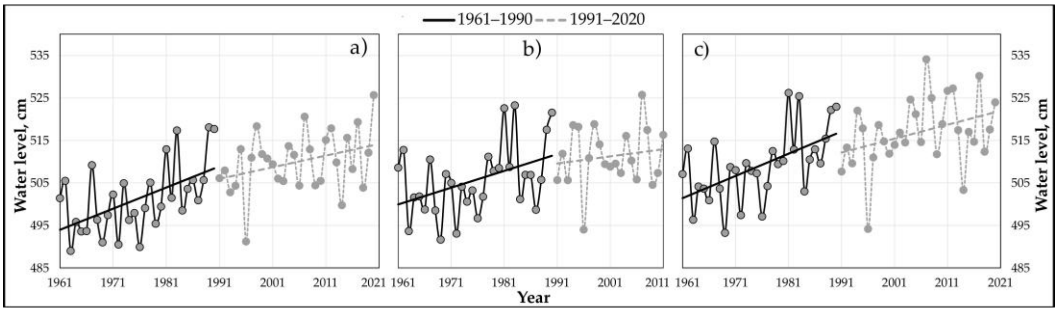

Figure 7. Changes in the average annual water level of the Curonian Lagoon at Klaipėda (**a**), Juodkrantė (**b**) and Nida (**c**).

In the recent period of 1991–2020, the average water level at Nida was 517 cm, and in individual years, its annual values varied from 494 to 534 cm (Figure 7c). According to the available data (until 2011), it was 511 cm at Juodkrantė and varied from 494 to 526 cm (Figure 7b). The average annual water level at Klaipėda in 1961–1990 was 510 cm and fluctuated between 491 and 526 cm (Figure 7a). In the last 30 years, the water level in all studied stations increased, but not as fast as in 1961–1990. At Juodkrantė, it went up by 0.11 cm yr^{-1}, at Klaipėda by 0.19 cm yr^{-1} and at Nida by 0.28 cm yr^{-1}.

The average water level for different time spans at Klaipėda, Juodkrantė and Nida, Sen's slopes and p values are presented in Table 5. In the first period, the variation of the water level in different stations could be characterized by the same patterns. This parameter increased the most in winter, less in autumn and summer and the least in the spring season. At Juodkrantė, water level data exhibited statistically insignificant positive trends ($p > 0.05$). At Klaipėda and Nida, they were insignificant only in spring ($p > 0.05$), while in other seasons, the p value varied from 0.013 to 0.032 (Table 5). However, when analyzing the water level values in the second period, no common regularities between individual WGSs were found. According to Klaipėda WGS data, the lagoon level rose the most in winter, less in autumn and spring, and least in summer. At Juodkrantė, it increased in summer and autumn but decreased in other seasons. At Nida, same as at Klaipėda, positive changes were estimated in the second 30-year period. The water level increased the most in summer and autumn and least in other seasons. Considering the results of the Mann–Kendall test, the detected changes were statistically insignificant as $p > 0.05$. Throughout the entire period, according to the records of all WGSs, the lagoon water level rose. The most remarkable shift to higher values was observed in spring and winter, 9.9 and 9.6 cm, respectively, and slightly less at 8.1 cm in summer.

Table 5. Overview of mean seasonal and annual water level (cm).

Station	Period	1961–1990			1991–2020		
		Average	**Sen's Slope**	***p* Value**	**Average**	**Sen's Slope**	***p* Value**
Klaipėda	Winter	504.7	0.788	0.022	515.6	0.331	>0.05
	Spring	489.5	0.389	>0.05	502.4	0.208	>0.05
	Summer	500.6	0.429	0.013	509.5	0.116	>0.05
	Autumn	509.9	0.504	0.032	511.4	0.270	>0.05
	Year	501.2	0.474	0.002	509.7	0.194	>0.05
Juodkrantė	Winter	510.7	0.824	>0.05	518.9	−0.231	>0.05
	Spring	499.8	0.108	>0.05	506.8	−0.132	>0.05
	Summer	501.0	0.238	>0.05	508.5	0.320	>0.05
	Autumn	511.2	0.471	>0.05	510.9	0.804	>0.05
	Year	505.7	0.323	0.048	511.3	0.111	>0.05
Nida	Winter	514.4	1.037	0.019	524.9	0.188	>0.05
	Spring	505.4	0.303	>0.05	514.0	0.167	>0.05
	Summer	503.9	0.346	0.017	513.4	0.330	>0.05
	Autumn	512.4	0.600	0.023	515.4	0.491	>0.05
	Year	509.0	0.481	0.001	516.9	0.284	0.028

Water temperature. The analysis of the lagoon water temperature was carried out using data from Klaipėda, Juodkrantė (until 2011) and Nida WGSs. The average annual water temperature is presented in Figure 8. In 1961–1990, its lowest value was observed at Klaipėda, where the lagoon connects to the Baltic Sea. Here, it reached 8.4 °C and varied from 7.5 (1969) to 9.8 °C (1990). Moving away from Klaipėda Strait, the water temperature increased. At Juodkrantė, during the studied period, it averaged 8.6 °C and varied from 7.6 (1987) to 10.1 °C (1990). At Nida, it was the highest, 8.7 °C, and ranged from 7.7 (1962) to 10.2 °C (1990) (Figure 8c). In the second period (1991–2020), the lowest average water temperature was also at Klaipėda, 9.2 °C, and it increased moving away from the strait. It was 9.4 °C at Juodkrantė and 9.7 °C at Nida. At Klaipėda, this parameter varied from 8.1 (1996) to 10.2 °C (2019), at Juodkrantė from 7.8 (1996) to 11.1 °C (2011), and at Nida from 8.2 (1996) to 11.4 °C (2020) (Figure 8). Therefore, during the entire period, the average annual water temperature of the Curonian Lagoon showed rising trends. In the first 30-year period, the increase was not statistically significant. However, in the second period, water temperature increased from 0.047 to 0.070 °C per year, and these changes were statistically significant (p value < 0.000).

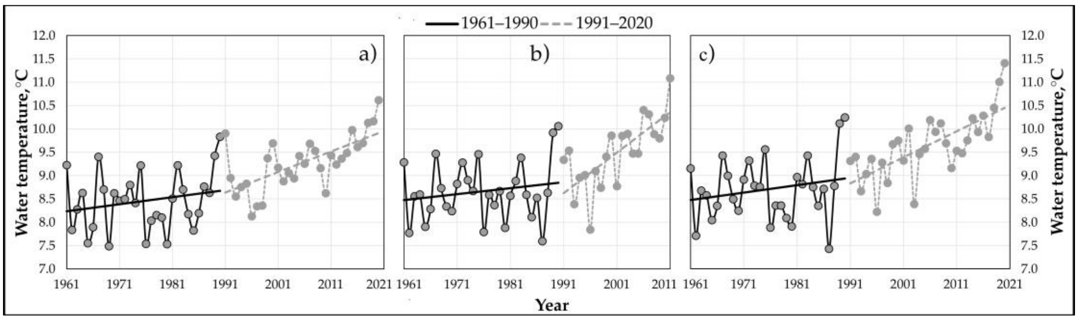

Figure 8. Changes in the average annual water temperature of the Curonian Lagoon at Klaipėda (**a**), Juodkrantė (**b**) and Nida (**c**).

In the first period, the lagoon surface temperature had mixed trends in different seasons (Table 6). At all investigated stations, the temperature decreased in autumn (Sen's slope varied from −0.001 to −0.011), and at Klaipėda and Juodkrantė, also in summer (Sen's slope ranged from −0.0004 to −0.021). However, rising water temperature trends prevailed for the rest of the seasons (Sen's slope varied from 0.007 to 0.036). Only at Klaipėda was the increase statistically significant ($p = 0.011$) in winter; in all other cases, p was greater than 0.05. In the second period, water temperature changes had a positive sign, but no common trends were identified. Minor changes were detected at Klaipėda in winter (Sen's slope 0.006) and the largest at Juodkrantė in autumn (Sen's slope 0.118). The identified changes were statistically insignificant at all stations in winter (in the case of Juodkrantė also in spring, $p > 0.05$) but significant in the remaining seasons ($p < 0.05$). The findings showed that the water surface temperature of the lagoon rose least in winter and autumn (respectively, 0.5 and 0.6 °C) and the most in summer and spring (respectively, 1.1 and 1.0 °C).

Table 6. Overview of mean seasonal and annual water temperature (°C).

Station	Period	1961–1990			1991–2020		
		Average	Sen's Slope	*p* Value	Average	Sen's Slope	*p* Value
Klaipėda	Winter	1.5	0.036	0.011	2.2	0.006	>0.05
	Spring	5.5	0.018	>0.05	6.5	0.045	0.017
	Summer	16.2	−0.021	>0.05	17.4	0.067	0.000
	Autumn	10.2	−0.001	>0.05	10.8	0.049	0.011
	Year	8.4	0.007	>0.05	9.2	0.047	0.000
Juodkrantė	Winter	0.6	0.012	>0.05	1.0	0.017	>0.05
	Spring	6.4	0.033	>0.05	7.5	0.027	>0.05
	Summer	18.3	−0.0004	>0.05	19.4	0.112	0.010
	Autumn	9.3	−0.011	>0.05	9.8	0.118	0.020
	Year	8.6	0.009	>0.05	9.4	0.070	0.000
Nida	Winter	0.6	0.014	>0.05	1.0	0.017	>0.05
	Spring	6.4	0.035	>0.05	8.1	0.071	0.032
	Summer	18.5	0.020	>0.05	19.7	0.061	0.020
	Autumn	9.4	−0.003	>0.05	9.9	0.057	0.002
	Year	8.7	0.012	>0.05	9.7	0.051	0.000

Ice parameters. Data from Nida (1961–2020) were used to analyze the changes in the ice cover on the lagoon. In the port of Klaipėda, a constant ice cover does not form due to shipping; therefore, data from this station were not taken into account. From 1961 to 1990, the permanent ice cover was observed for an average of 86 days, while in 1991–2020, it lasted only 59 days (Figure 9). The duration of ice cover varied greatly in individual years, from 12 to 122 days in the first period and from 0 to 156 days in the second (Figure 9). Based on the data from long-term observations, it was established that the duration of the ice cover on the Curonian Lagoon decreased by 2.5 days every three years (0.82 days annually). The shortening of ice cover duration was statistically significant only during the entire analyzed period of 1961–2020 (p value 0.02), while in 1961–1990 and 1991–2020, p was greater than 0.05.

As we can see from Figure 10, some years have missing data on ice thickness. In these cases, the lagoon was covered with such a thin layer of ice that measurements could not be taken for safety reasons. During the first period, the average thickness of the lagoon ice cover was 28.5 cm and varied from 10.5 (1961) to 54.0 cm (1987) (Figure 10). During the following period, it was 22.4 cm and ranged between 10.0 cm in 2008 and 43.3 cm in 2003 (Figure 10). Ice cover thinned by 0.14 cm annually during the whole analyzed period. Even though the lagoon ice thickness was decreasing, statistical analysis revealed that these changes in the selected periods (1961–2020, 1961–1990, and 1991–2020) were statistically insignificant, $p > 0.05$.

The breakup time of the ice also changed over time. Figure 11 shows that in the first 30 years, the ice melted on average on March 19 and during the second 30-year period on March 1. However, the freeze-up dates varied considerably from year to year. In the first period, the ice melted on 17 February at the earliest and on 13 April at the latest. Meanwhile, during the second period, the years with the earliest (4 January) and the latest ice breakup

(22 April) were identified. Despite the large scatter in the recent period (1991–2020), the ice breakup dates showed a negative trend, and the ice melt date moved forward by four days every nine years (or 0.44 days per year). The advance of breakup dates was statistically significant only in 1961–2020 (at p value 0.03). Changes in both periods were statistically insignificant, $p > 0.05$.

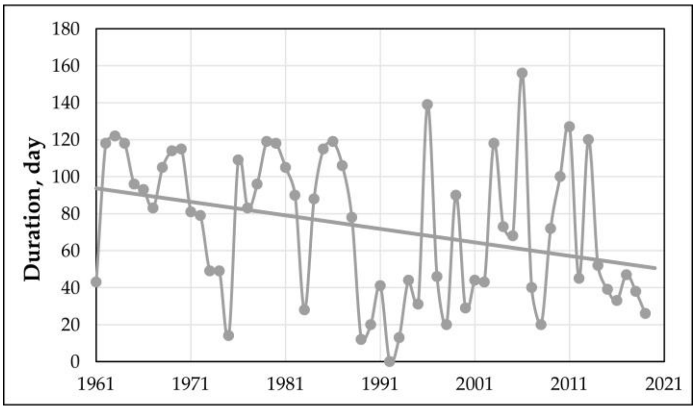

Figure 9. Duration of the Curonian Lagoon ice cover in 1960–2020.

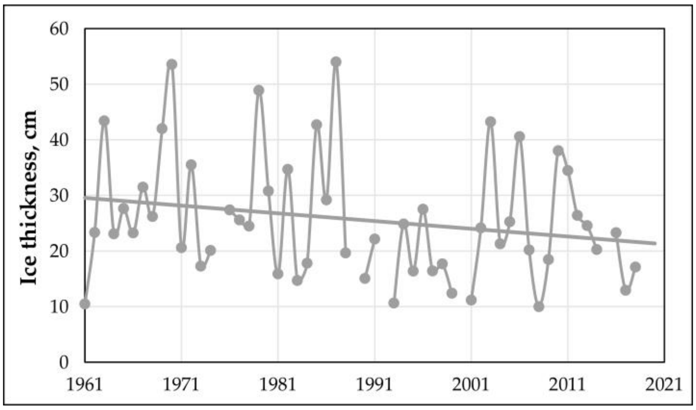

Figure 10. Thickness of ice cover of the Curonian Lagoon in 1961–2020.

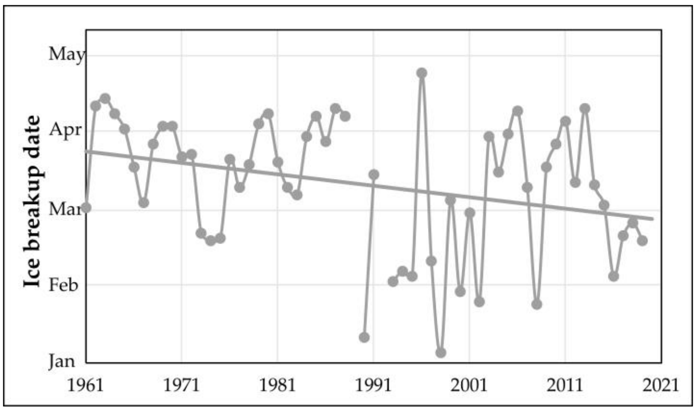

Figure 11. The dates of the breakup of the Curonian Lagoon ice cover in 1961–2020.

3.3. Relations between Hydrometeorological Parameters and Atmospheric Circulation Indices

To determine whether there was a relationship between individual hydrometeorological parameters of the Curonian Lagoon, a correlation matrix was created, also including atmospheric circulation indices. The strongest correlations are shown in Figure 12, and all values are presented in Appendix A.

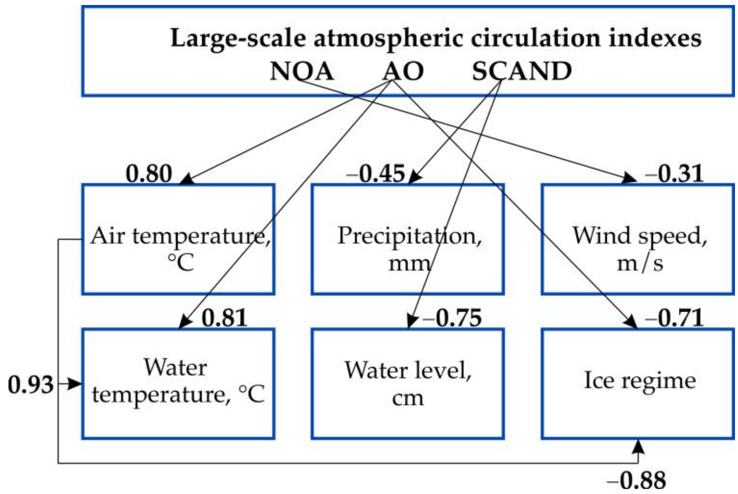

Figure 12. Correlation coefficients between large-scale atmospheric circulation indices and hydrometeorological parameters of the Curonian Lagoon.

This analysis revealed a close relationship between some of the investigated hydrometeorological parameters. For example, between air and water temperatures, in individual cases, *r* reached 0.93 (Appendix A, Table A1). Meanwhile, the relations between these temperatures and water level, as well as water level and precipitation, in some cases, were 0.62 and 0.60, respectively (Appendix A, Table A1). This could be explained by the fact that these parameters are independent but have a common accelerator that drives them. Regarding the relationships with the atmospheric circulation indices, the air temperature was found to correlate the best with the AO index; during the entire studied period, the *r* coefficient between these variables was 0.69, reaching 0.80 in the first period and 0.62 in the second (Appendix A, Tables A1–A3). A slightly weaker relationship was associated with water temperature and the AO index. The highest value of the coefficient was 0.60 in 1961–2020, 0.81 in 1961–1990, and 0.43 in 1991–2020 (Appendix A, Tables A1–A3). The water level was the next parameter that correlated well with atmospheric circulation indices. A close inverse relationship between the water level and the SCAND index was established, ranging from −0.74 to −0.75 depending on the period (Appendix A, Tables A1–A3). A completely different situation was found when analyzing the amount of precipitation and wind speed. These two parameters correlated very weakly with the atmospheric circulation indices. The highest correlation coefficient determined between the amount of precipitation and the SCAND index was equal to −0.45, and between the wind speed and the NAO −0.31 (Appendix A, Tables A1–A3). The lagoon ice cover and atmospheric circulation indices were also correlated, but the relation was not strong, except for the first period. During 1961–1990, the strongest correlations were between ice cover duration, breakup dates and the AO index (*r* −0.71 and −0.70, respectively, Appendix A, Table A2). It was also estimated that the duration of the ice cover and the breakup dates correlated well with air temperature, especially with the sum of negative air temperature values. The correlation between the ice duration and the sum of negative air temperatures, depending on the period, varied from −0.82 to −0.89, and between the dates of breakup and the sum of negative air temperatures, from −0.71 to −0.76 (Appendix A, Tables A1–A3).

4. Discussion

In the course of this study, it was established that significant changes in the hydrometeorological parameters of the Curonian Lagoon took place during two climate normal periods. Particularly significant changes were found in air temperature. It rose on average by 0.029 °C yr^{-1} in 1961–1990 and by 0.046 °C yr^{-1} in 1991–2020. During the entire analyzed period, the air temperature increased by 0.041 °C yr^{-1}. Air temperatures rose in other parts of the world as well. Similar trends for this meteorological parameter were found by Kostka and Zając [39]. They calculated that the average air temperature in Warsaw increased by 0.040 °C yr^{-1} in 1961–2020. During the first thirty-year period, the air temperature in Warsaw grew very similar to that in Lithuania (0.031 °C yr^{-1}), but in the second period, the growth rate was significantly higher (0.060 °C yr^{-1}). Despite the large regional changes, the global changes were much smaller. According to NOAA [40] multi-year research data, the average temperature of the Earth increased by 0.008 °C yr^{-1} during 1880–2020 and by 0.018 °C yr^{-1} in 1981–2020.

The question is how will rising air temperatures affect water bodies? Globally rising air temperature directly influences water temperature, ice regime and lagoon water level (due to the thermal expansion of water and melting of glaciers). During this study, it was established that the water temperature of the Curonian Lagoon increased by 0.01 °C yr^{-1} in both WGSs during the period of 1961–1990 and from 0.05 (at Klaipėda) to 0.09 (at Nida) °C yr^{-1} in 1991–2020. The water temperature has also changed in other lagoons of the Baltic Sea, but it is difficult to compare the changes due to the different analyzed periods. Nevertheless, the identified changes are similar. Dailidienė et al. [41] estimated that the water temperature on southern and southeastern Baltic coasts grew from 0.03 °C yr^{-1} in the Vistula Lagoon to 0.09 °C yr^{-1} in Darss-Zingst Bodden Chain in 1961–2008. Meanwhile, global ocean SST rose by 0.02 °C yr^{-1} in 1961–1990 and by 0.03 °C yr^{-1} in 1991–2020 [42].

From 1961 to 2020, the duration of permanent ice cover of the Curonian Lagoon decreased by 0.83 days yr^{-1}, the ice thickness declined by 0.14 cm yr^{-1}, and the ice breakup advanced by 0.45 days yr^{-1}. According to Kļaviņš et al. [43], during 1949–2013, the ice season in the Baltic Sea shortened by 0.83 days yr^{-1} near Liepaja and by 1.23 days yr^{-1} in the Gulf of Riga. In the same period, the breakup advanced by 0.64 days yr^{-1}.

No less significant changes were detected in the water level of the Curonian Lagoon. A comparison of two thirty-year periods (1961–1990, 1991–2020) revealed that the water level rose the least at Juodkrantė, 0.36 cm yr^{-1} in the first period and 0.01 cm yr^{-1} in the second (since Juodkrantė WGS was closed in 2011). At Klaipėda, the water level rose slightly more, in 1961–1990 by 0.50 cm yr^{-1} and in 1991–2020 by 0.24 cm yr^{-1}. The water level increased the most at Nida, 0.51 and 0.31 cm yr^{-1}, respectively. Dailidienė et al. [41] estimated that the water level of the other Baltic Sea lagoon—the Vistula Lagoon—increased by 0.4 cm yr^{-1} from 1961 to 2008. Meanwhile, the global ocean level rose 0.11 cm yr^{-1} in 1961–1990 and 0.22 cm yr^{-1} in 1991–2020, according to Grinsted and Christensen [44]. In the second period, the water level of the Curonian Lagoon grew less than in the first. This could result from the reduced inflow of rivers into the lagoon, which accounts for about 80% of the water balance income [45–47].

Another critical climate parameter is precipitation. Comparing the periods of 1961–1990 and 1991–2020, it was found that the amount of precipitation at the Curonian Lagoon increased by 7.8% over the most recent 30-year period. A similar positive change was found for changes in precipitation data in Sweden [48]. This study showed a 6.7% higher amount of precipitation in 1991–2020 than in 1961–1990. Smaller differences were detected by Orság et al. [49] while studying climate changes in the southeast of the Czech Republic. They discovered that it increased by only 2.3% in 1991–2020 compared to 1961–1990. Globally, precipitation has changed somewhat less. Benestad et al. [50], using ERA5 reanalysis data, found that the global precipitation increased by only 1.7% in 1991–2020 compared to 1961–1990.

The wind climate analysis (near Klaipėda) revealed a trend of decreasing wind speed over the last thirty years. In the first period (1961–1990), the average wind speed was 5.1 m/s, and in the second (1991–2020), 4.1 m/s, i.e., it decreased by 19.6%. The decrease in wind speed was also estimated in other studies. Brázdil et al. [51] found that in the Czech Republic, the average annual wind speed decreased by 8% in 1991–2020 compared to 1961–1990.

This study used the NAO, AO and SCAND indices characterized by pressure anomalies in the North Atlantic, Europe and Asia regions that significantly impact the hydrometeorological parameters [52–54]. The created correlation matrix revealed that the air and water temperatures were highly dependent on the AO index (r up to 0.69), and the water level on the SCAND index (r up to −0.75). Similar trends have been detected in other studies. Vihma et al. [55] estimated that air temperatures in Northern Europe were strongly affected by NAO and AO. The correlation between air temperature and AO was up to 0.6, and with NAO, up to 0.5. Plewa et al. [35] also found a strong negative (up to −0.8) correlation between the SCAND index and water levels in Polish lakes.

The changes in the hydrometeorological parameters of the Curonian Lagoon during the two climate normal periods are obvious, but how will these changes affect the lagoon ecosystem? Water temperature is one of the key factors affecting fish abundance. Rising water temperatures have been shown to have negative consequences for the abundance of top predatory fish [56]. Warming water benefits eurythermal fish species but endangers stenothermal species (resulting in severe declines in grey seals, cod, herring and haddock) [57]. Based on the simulation results, it was found that if the water temperature rises by 5 degrees, the relative abundance of eurythermal fish will increase up to 30%, but stenothermal fish may become extinct [58]. The ice cover duration also influences fish communities. Early ice breakup positively affects fish, as they have more time to grow and reach large sizes, which is necessary to survive until the next season [59,60]. However, the shortening of the ice cover negatively affects the ecology of the lagoons [61]. A shorter period of ice cover has been found to cause lagoons to lose the time needed to convert suspended solids to sediment, resulting in accelerated eutrophication due to higher nutrient concentrations [62,63]. The rising water level of the lagoons has a negative impact on coastal ecosystems—territories are flooded, seawater invasions are increasing, and as a result, the biodiversity of the lagoons is changing [64].

The estimated changes in the hydrometeorological parameters of the Curonian Lagoon over 60 years (two non-overlapping periods of climatological standard normal) can be successfully used as input information for predictions of future evolution in the unique ecosystem of the Curonian Lagoon.

5. Conclusions

1. The data series of the hydrometeorological indicators of the Curonian Lagoon were checked by the Pettitt and Buishand tests. The 60-year data series were found to be non-homogeneous. The shift date of these data series is usually set at 1988. This date is very close to the middle of the two selected climate normal periods.
2. Significant changes in the hydrometeorological parameters of the Curonian Lagoon were determined in the most recent climate normal period (1991–2020). Air and water warmed by 1.3 and 0.9 °C, respectively, precipitation amount increased by 55 mm, wind speed decreased by 1 m/s, water level grew by 8 cm, ice cover decreased by 27 days, ice thinned by 5 cm, and breakup started 18 days earlier compared to the climate normal period (1961–1990).
3. This analysis revealed that there was a strong positive correlation between the AO index and air and water temperatures (up to 0.81) and negative correlations between the AO index and ice parameters (up to −0.71) and the SCAND index and water level (up to −0.75).

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Appendix A

Table A1. Correlation between hydrometeorological parameters and atmospheric circulation indices in 1961–2020.

	P, mm	T Air, °C	T Air NEG SUM, °C	Wind Speed, m/s	Water Level Avg, cm	H_2O T Avg, °C	Ice Cover Duration, Days	Ice Thickness, cm	Ice Breakup Date, Days	NAO	AO	SCAND
P, mm	1.00	0.07	0.04	−0.24	0.60	0.15	−0.15	0.11	−0.17	−0.15	−0.05	−0.38
T air, °C	0.07	1.00	0.77	−0.43	0.62	0.93	−0.68	−0.19	−0.61	0.39	0.69	−0.35
T air NEG SUM, °C	0.04	0.77	1.00	−0.13	0.52	0.56	−0.84	−0.13	−0.73	0.32	0.56	−0.29
Wind speed, m/s	−0.24	−0.43	−0.13	1.00	−0.38	−0.57	0.18	0.17	0.07	−0.15	−0.20	0.21
Water level Avg, cm	0.60	0.62	0.52	−0.38	1.00	0.61	−0.46	0.05	−0.44	0.19	0.49	−0.75
H_2O T Avg, °C	0.15	0.93	0.56	−0.57	0.61	1.00	−0.52	−0.20	−0.45	0.31	0.60	−0.35
Ice cover duration, days	−0.15	−0.68	−0.84	0.18	−0.46	−0.52	1.00	0.22	0.86	−0.28	−0.47	0.26
Ice thickness, cm	0.11	−0.19	−0.13	0.17	0.05	−0.20	0.22	1.00	0.32	−0.11	−0.07	−0.09
Ice breakup date, days	−0.17	−0.61	−0.73	0.07	−0.44	−0.45	0.86	0.32	1.00	−0.20	−0.44	0.23
NAO	−0.15	0.39	0.32	−0.15	0.19	0.31	−0.28	−0.11	−0.20	1.00	0.71	−0.04
AO	−0.05	0.69	0.56	−0.20	0.49	0.60	−0.47	−0.07	−0.44	0.71	1.00	−0.35
SCAND	−0.38	−0.35	−0.29	0.21	−0.75	−0.35	0.26	−0.09	0.23	−0.04	−0.35	1.00

Table A2. Correlation between hydrometeorological parameters and atmospheric circulation indices in 1961–1990.

	P, mm	T Air, °C	T Air NEG SUM, °C	Wind Speed, m/s	Water Level Avg, cm	H_2O T Avg, °C	Ice Cover Duration, Days	Ice Thickness, cm	Ice Breakup Date, Days	NAO	AO	SCAND
P, mm	1.00	−0.02	−0.10	−0.35	0.50	0.05	−0.01	0.06	−0.08	0.04	−0.06	−0.28
T air, °C	−0.02	1.00	0.85	0.01	0.54	0.91	−0.88	0.03	−0.79	0.49	0.80	−0.17
T air NEG SUM, °C	−0.10	0.85	1.00	0.09	0.48	0.62	−0.82	0.04	−0.71	0.42	0.64	−0.08
Wind speed, m/s	−0.35	0.01	0.09	1.00	−0.13	−0.06	0.01	0.02	−0.08	−0.31	−0.16	0.00
Water level Avg, cm	0.50	0.54	0.48	−0.13	1.00	0.50	−0.45	0.10	−0.40	0.38	0.54	−0.74
H_2O T Avg, °C	0.05	0.91	0.62	−0.06	0.50	1.00	−0.79	0.01	−0.75	0.51	0.81	−0.20
Ice cover duration, days	−0.01	−0.88	−0.82	0.01	−0.45	−0.79	1.00	0.06	0.85	−0.46	−0.71	0.09
Ice thickness, cm	0.06	0.03	0.04	0.02	0.10	0.01	0.06	1.00	0.11	−0.16	−0.04	−0.14
Ice breakup date, days	−0.08	−0.79	−0.71	−0.08	−0.40	−0.75	0.85	0.11	1.00	−0.44	−0.70	0.04
NAO	0.04	0.49	0.42	−0.31	0.38	0.51	−0.46	−0.16	−0.44	1.00	0.72	−0.01
AO	−0.06	0.80	0.64	−0.16	0.54	0.81	−0.70	−0.04	−0.70	0.72	1.00	−0.28
SCAND	−0.28	−0.17	−0.08	0.00	−0.74	−0.20	0.09	−0.14	0.04	−0.01	−0.28	1.00

Table A3. Correlation between hydrometeorological parameters and atmospheric circulation indices in 1991–2020.

	P, mm	T Air, °C	T Air NEG SUM, °C	Wind Speed, m/s	Water Level Avg, cm	H_2O T Avg, °C	Ice Cover Duration, Days	Ice Thickness, cm	Ice Breakup Date, Days	NAO	AO	SCAND
P, mm	1.00	−0.08	0.10	−0.01	0.68	0.04	−0.16	0.37	−0.13	−0.33	−0.12	−0.45
T air, °C	−0.08	1.00	0.62	−0.17	0.43	0.89	−0.37	−0.03	−0.31	0.41	0.62	−0.39
T air NEG SUM, °C	0.10	0.62	1.00	0.13	0.40	0.34	−0.89	−0.20	−0.76	0.24	0.36	−0.51
Wind speed, m/s	−0.01	−0.17	0.13	1.00	−0.09	−0.41	−0.11	−0.22	−0.34	−0.10	−0.08	0.10
Water level Avg, cm	0.68	0.43	0.40	−0.09	1.00	0.43	−0.28	0.50	−0.28	0.02	0.36	−0.75
H_2O T Avg, °C	0.04	0.89	0.34	−0.41	0.43	1.00	−0.08	0.09	0.02	0.24	0.43	−0.34
Ice cover duration, days	−0.16	−0.37	−0.89	−0.11	−0.28	−0.08	1.00	0.21	0.84	−0.17	−0.18	0.35
Ice thickness, cm	0.37	−0.03	−0.20	−0.22	0.50	0.09	0.21	1.00	0.33	−0.02	0.10	−0.27
Ice breakup date, days	−0.13	−0.31	−0.76	−0.34	−0.28	0.02	0.84	0.33	1.00	−0.05	−0.15	0.32
NAO	−0.33	0.41	0.24	−0.10	0.02	0.24	−0.17	−0.02	−0.05	1.00	0.74	−0.06
AO	−0.12	0.62	0.36	−0.08	0.36	0.43	−0.18	0.10	−0.15	0.74	1.00	−0.37
SCAND	−0.45	−0.39	−0.51	0.10	−0.75	−0.34	0.35	−0.27	0.32	−0.06	−0.37	1.00

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