The thermal state of the North Atlantic and macro-circulation conditions in the Atlantic-European sector, and changes in sunshine duration in Central Europe

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Abstract
This article explains the reasons for the long-term variability in sunshine duration (SD) in Central Europe. It presents a recently discovered mechanism regulating changes in sunshine duration, not described so far in the literature. The periods of global dimming and global brightening were linked with changes in the annual frequency of the macrotypes of the middle-tropospheric circulation and the variability in the surface component of the thermohaline circulation in the North Atlantic (NA THC). On the basis of the totals of annual sunshine duration from the years 1951–2015 from 21 stations located in the Netherlands, Germany, Denmark, Poland, Switzerland, Austria, the Czech Republic and Slovakia, it was shown that changes in NA THC account for onethird of the variability in sunshine duration, while changes in the frequency of macrotypes W and E, forced by the changes in NA THC, each separately account for about 26 and 22% of the variability in the totals of annual sunshine duration in Central Europe.

KEYWORDS
Central Europe, middle-tropospheric circulation, North Atlantic, sunshine duration, thermohaline circulation

1 | INTRODUCTION

The course of sunshine duration in Europe since the late 1980s has shown a strong upward trend, called global brightening in the climatological literature, as opposed to the earlier period (1950s to 1980s) of global dimming (e.g., Norris and Wild, 2007; Sanchez-Lorenzo et al., 2008; Kitsara et al., 2012; Manara et al., 2015; Sanchez-Lorenzo, 2015). An analysis of trends of sunshine duration over Poland (Bartoszek et al., 2021) confirms the results obtained in other parts of Europe. However, the values of monthly and annual trends based on data from the multiyear period 1971–2018 show some regional and seasonal variation. Positive trends are observed at all stations from April to September, with the strongest in the western part of Poland, while in the cold season negative trends occur especially in the east and north of Poland.

Research on the variability of annual sunshine duration totals in Poland in the years 1966–2018 carried out by Marsz and Styszyńska (2019) showed that in the years 1987–1989 there was a radical change in the sunshine duration regime, manifesting itself in a change in the nature of the course and the scope of its variability. In
the years 1987–1989, there was a sharp increase in annual sunshine duration totals, and then the values of this characteristic gradually increased, creating, from 1988 on, a strong and highly significant positive trend.

In the climatological literature, the positive trend in sunshine duration since the 1980s was most often explained by changes in the content of aerosols in the air, including those of anthropogenic origin (among others Liepert, 2002; Wild et al., 2005; Norris and Wild, 2007; Warren et al., 2007; Ruckstuhl and Norris, 2009; Sanchez-Lorenzo et al., 2009; Stjern et al., 2009; Wild, 2009; Folini and Wild, 2011; Wild, 2012; Wang et al., 2013; Vetter and Wechsung, 2015) and volcanic origin (i.e., Stanhill and Cohen, 2005; Lewik et al., 2010).

There are also publications whose authors explain the long-term variability of sunshine duration by referring to changes in the cloud cover or haze caused by circulation (including Herber et al., 2002; Sanchez-Lorenzo et al., 2008; Stjern et al., 2009; Matuszko, 2014).

The occurrence of the aforementioned discontinuity in the years 1987–1989 in the course of annual totals of sunshine duration in Poland and the appearance of a positive trend in it are associated by Marsz and Styszyńska (2019) with the acting of other factors, that is, a change in the macro-circulation conditions that occurred in those years.

The macro-circulation conditions in the Atlantic-Eurasian circulation sector are described by the frequency structure of the mid-tropospheric circulation macro-types (500 hPa) according to the Wangengejm–Girs classification (Wangengejm, 1952; Girs, 1964). This classification is based on the position of the upper ridges and upper troughs, formed by long waves in the mid-troposphere, and distinguishes three basic forms of macro-types, that is, W (zonal circulation) and E and C (two forms of meridional circulation). A diagram of the arrangement of long waves forming individual macro-types according to this classification (Figure 1) has been published many times (e.g., Lamb, 1972; Przybyłak, 2000; Barry and Carleton, 2001; Gao et al., 2017; Degirmenđić and Kožuchowski, 2019).

The frequency structure of the macro-types of the mid-tropospheric circulation, apart from seasonal changes, shows long-term changes as a function of time. Along with the change in this structure, expressed in the maintaining, for a longer period of time (i.e., for several dozen years), of similar proportions between the occurrence of the W, E and C macro-types and the dominance of one of the macro-types, or the dominance of one and sub-dominance of another macro-type, a change in the ‘circulation epoch’ takes place (Girs, 1971; Girs and Kondratovich, 1978). Since the occurrence of each of the macro-types is related to the occurrence of several typical baric field distributions (synoptic situations, SLP fields), a change in the macro-type structure results in a change in the weather structure over a given area. As a result, the frequency of macro-types, by controlling the course of weather processes, also controls changes in sunshine duration.

Changes in macro-circulation conditions are controlled by changes in the spatial distribution of heat resources in the waters of the North Atlantic Ocean (Marsz, 2005, 2012). Changes in the heat resources in waters are, in turn, controlled by changes in the intensity of the component of the surface thermohaline circulation in the North Atlantic (hereinafter NA THC). Therefore, it can be assumed that changes in sunshine duration over Poland are directly related to changes in the index DG3L (Gulf Stream Delta, 3 years; Marsz, 2015), which determines the intensity of NA THC.

So far, it has not been clear as to whether the statistically significant relationships of annual sunshine duration in Poland with changes in the annual frequency of the macro-types of mid-tropospheric circulation and variability of NA THC are only of the nature of local relationships, and perhaps also accidental, or whether they constitute a fragment of the general regularity that affects a greater area.

The macro-scale changes in the mid-tropospheric circulation occur simultaneously on a scale of the entire Atlantic-Eurasian circulation sector. It should, therefore, be expected that changes in sunshine duration occurring...
together with changes in macro-circulation conditions should take place, not only over Poland, but also over much larger areas. The variability of NA THC should also control changes in sunshine duration over an area much larger than Poland. The aim of this study is to clarify whether the relating of changes in annual sunshine duration to changes in macro-circulation conditions and changes in NA THC intensity is a regularity operating in larger areas located in the Atlantic-European circular sector.

2 | RESEARCH AREA AND SOURCE MATERIALS

The research was carried out on the basis of the totals of annual sunshine duration from stations located in the area of ‘Central Europe’, covering approximately the area between 44°N and 56°N and 5°E and 22°E, within the state borders of the Netherlands (NL), Germany (DE), Denmark (DK), Poland (PL), Switzerland (CH), Austria (AT), the Czech Republic (CZ) and Slovakia (SK). These data come from state meteorological services and are stored in various databases (cf. explanations to Table 1).

At the beginning, the sequence was verified in terms of data completeness and station location. The conducted review made it possible to select 21 stations which in the years 1951–2015 had complete (without any measurement gaps) monthly sequences of sunshine duration and stations in which single gaps in monthly data occurred. It was assumed that the stations where the number of gaps in the values of monthly sunshine duration in the observation sequence could not exceed 6 in the entire 780-month period (1951–2015) would be further considered. The selected stations additionally had to meet the condition under which the distribution of gaps data in time would make it possible for them to be supplemented

| No. | Station      | Country | Geographical coordinates | Altitude (m a.s.l.) | Number of gaps of monthly mean values | Data source |
|-----|--------------|---------|--------------------------|--------------------|--------------------------------------|-------------|
| 1   | De Bilt      | NL      | 52.10°N, 5.18°E          | 1                  | 1                                    | ECAD        |
| 2   | Maastricht   | NL      | 50.91°N, 5.76°E          | 53                 | 0                                    | ECAD        |
| 3   | Geneva       | CH      | 46.20°N, 6.15°E          | 405                | 0                                    | ECAD        |
| 4   | Trier-Petrisberg | DE  | 49.75°N, 6.66°E          | 265                | 2                                    | DWD         |
| 5   | Zuerich      | CH      | 47.38°N, 8.57°E          | 555                | 0                                    | ECAD        |
| 6   | Bremen       | DE      | 53.05°N, 8.80°E          | 4                  | 0                                    | DWD         |
| 7   | Hannover     | DE      | 52.47°N, 9.68°E          | 55                 | 1                                    | DWD         |
| 8   | Gottingen    | DE      | 51.50°N, 9.95°E          | 171                | 0                                    | DWD         |
| 9   | Wurzburg     | DE      | 49.77°N, 9.96°E          | 268                | 0                                    | DWD         |
| 10  | Erfurt-Weimar | DE  | 50.98°N, 10.96°E         | 316                | 2                                    | DWD         |
| 11  | Innsbruck    | AT      | 47.26°N, 11.39°E         | 609                | 0                                    | HISTALP     |
| 12  | Copenhagen   | DK      | 56.68°N, 12.53°E         | 9                  | 0                                    | DMI         |
| 13  | Potsdam      | DE      | 52.38°N, 13.06°E         | 81                 | 0                                    | DWD         |
| 14  | Ankara       | DE      | 54.68°N, 13.43°E         | 42                 | 5                                    | DWD         |
| 15  | Kremsmunster | AT      | 48.06°N, 14.13°E         | 382                | 0                                    | HISTALP     |
| 16  | Vienna       | AT      | 48.25°N, 16.36°E         | 209                | 0                                    | HISTALP     |
| 17  | Wroclaw      | PL      | 51.10°N, 16.90°E         | 120                | 0                                    | Bryš, 2013, 2017 |
| 18  | Gdynia       | PL      | 54.52°N, 18.56°E         | 2                  | 2                                    | IMGW-PIB    |
| 19  | Krakow       | PL      | 50.07°N, 19.97°E         | 220                | 0                                    | IGiGP UJ    |
| 20  | Poprad       | SK      | 49.06°N, 20.23°E         | 694                | 1                                    | ECAD        |
| 21  | Pulawy       | PL      | 51.42°N, 21.97°E         | 144                | 0                                    | IMGW-PIB    |

Note: State affiliation of the station according to the ISO 316 code, DWD – Deutscher Wetterdienst (https://www.dwd.de/EN/climate_environment/cdc/cdc.html), DMI – Danish Meteorological Institute (https://www.dmi.dk/vejrarkiv/manedens-sasonens-og-arets-vejr/tekst-kort-og-nogletal-maned/), ECAD – European Climate Assessment & Dataset (https://www.ecad.eu/), HISTALP – Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region (http://www.zamg.ac.at/histalp/), IMGW-PIB – Institute of Meteorology and Water Management – National Research Institute, Poland (https://dane.imgw.pl/), IGiGP UJ – Institute of Geography and Spatial Management – Jagiellonian University in Kraków.
from the data from nearby stations, and to be relatively evenly distributed over the area in question (Figure 2).

The few gaps in the observations were supplemented by calculating the values of monthly sunshine duration using the regression method from data from nearby stations, the course of which in a given month showed a very strong correlation, not lower than 0.84 (explanation of not <70% of the variance). In an exceptional situation, when data from nearby stations in a given month of a given year (this concerns the Arkona station) were not available, the monthly mean values were supplemented using the multiple regression method from more distant stations.

The time sequences of the frequency of the macro-types of the mid-tropospheric circulation according to the Wangengejm–Girs classification, compiled by AARI (Arctic and Antarctic Research Institute, St. Peterburg, RF) covering the period from January 1951 to October 2006 were obtained from Appendix No. 1 to Dimitriev and Belyazo's (2006) study. The remaining parts of the sequences, until December 2015, were obtained directly from AARI.

The values of the DG3L index used in the study were calculated by Marsz (2015). This index is characterized by the intensity of the surface component of the thermohaline circulation in the North Atlantic (NA THC), through information on the intensity of heat transported with the waters from the Atlantic tropics, through the North Atlantic, to the Arctic. The value of the index shows the approximate intensity of heat transport through NA THC compared with the mean for the period 1901–2000. The source of data for the calculation of this index is the monthly sea surface temperature (SST) values derived from the NOAA NCDC ERSST v.3b set (Smith et al., 2008). The physical justification of the index’s construction and the method of its calculation are discussed in detail in the work of Marsz (2015). The temporal resolution of the DG3L index is annual, and the index itself is a weighted value from three consecutive years (a given year and 2 years preceding that year) dated for the given year. The formula for calculating this index and its time series (1880–2018) are published in English in Wrzesiński et al., 2019.

3 | RESEARCH METHODS

The course of sunshine duration at individual stations is often subject to strong local influences. For this reason, the ‘area average’ was calculated as the arithmetic mean value of the total of annual sunshine duration from all the stations listed in Table 1, assuming that the multidirectional local influences will be partially reduced in such an average, and the most general, common features of the inter-annual variability of sunshine duration occurring in the entire area under consideration will be retained. As a result, it made it possible to create a sequence of the average annual total of ‘area’ sunshine duration (SD) in the years 1951–2015 (Figure 3).

To explain the causes of variability in sunshine duration, the time sequences of the annual frequency of the mid-tropospheric circulation macro-types W, E and C according to the Wangengejm–Girs classification (Girs, 1964) and changes in the intensity of the surface
component of thermohaline circulation in the North Atlantic (NA THC) were used, characterized by the time sequence of the index defined by the DG3L acronym (Marsz and Styszyńska, 2009; Marsz, 2015).

The degree of concordance of the changes in time of both courses, that is, circulation macro-types and area sunshine duration, was examined using the method of linear correlation analysis, and the strength of the disturbing factor, here the changes in the frequency of W, E and C macro-types and changes in THC NA intensity, on the changes in annual area sunshine duration, was assessed using the regression analysis and variance analysis.

All calculations were made using the STATISTICA PL calculation program by StatSoft. This program, apart from basic operations, automatically calculates, according to a given calculation procedure, the number of degrees of freedom, test values (t-test, F-test) determining the level of statistical significance of a given relationship.

4 | RESULTS

4.1 | Annual sunshine duration over Central Europe and macro-circulation processes

An analysis of the signal envelope of the course of the mean annual area total of sunshine duration (SD) reveals the occurrence of discontinuities between the years 1987 and 1989 (Figure 3). Between these years, sunshine duration over Central Europe increased sharply, and then, since 1988, a previously non-existent positive trend has emerged. This trend is statistically significant ($p = .014$) and equals $6.0 \pm 2.3$ hr yr$^{-1}$. In the preceding period (1951–1988), there was also a significant trend ($p = .007$), but a negative one ($-4.3 \pm 1.5$ hr yr$^{-1}$).

The analysis of the correlation between the sequences of the annual frequency of macro-types W, E and C according to the Wangengejm–Girs classification and the annual area sunshine duration (SD) gives the results summarized in Table 2.

| Macro-type | W       | E       | C       |
|------------|---------|---------|---------|
| $r$        | 0.49    | −0.52   | 0.15    |
| $p$        | .000    | .000    | .238    |

Note: The $p$ values marked as .000 mean that $p < .001$. The average long-term frequency of macro-types in this period is equal to: W – 106, E – 171 and C – 88 days a year.

The results of this analysis show that the annual area sunshine duration is highly significantly correlated with the annual frequency of macro-type W (positively) and macro-type E (negatively), and also weakly and insignificantly (positively) correlated with the frequency of macro-type C. The dependence of the annual sunshine duration on the frequency changes in macro-types W and E can be considered linear (Figure 4).

The strength of the relationship (values of correlation coefficients) between sunshine duration and the frequency of these two macro-types is reduced by the occurring outliers (marked in Figure 4). The distributions of outliers are different, depending on the analysed macro-types, but three outliers (the years 1959, 1976 and 2003) repeat both in correlations with the sunshine duration of macro-type W and macro-type E. All these outliers are associated with the occurrence of a highly abnormal (anomalous) macro-type structure in a given year.

The values of the correlation coefficients clearly indicate that with the increase in the frequency of macro-type W during the year, sunshine duration over Central Europe increases, and in the case of an increase in the frequency of the E macro-type, annual sunshine duration decreases. Regression analysis shows that an increase in the frequency of macro-type W by 1 day a year entails an increase in SD by $2.06 \pm 0.48$ hr ($p < .001$), and an increase in the frequency of the E macro-type by 1 day a year causes a decrease in the annual area sunshine duration by $1.94 \pm 0.42$ hr ($p < .001$). The change in the frequency of macro-type C by 1 day entails a change in the annual sunshine duration consistent with the change sign, but its value cannot be reliably estimated ($+1.09 \pm 0.86$, $p = .238$).
Relationships between the frequency of individual macro-types and annual sunshine duration (Table 2) may not seem very strong. However, it should be borne in mind that on a given day one and only one macro-type may occur, that is, either W, E or C. The sum of the days in a year is constant, equal to 365. Thus, the annual frequency of a given macro-type, for example W, is:

\[ W \text{ (days)} = 365 - [E \text{ (days)} + C \text{ (days)}], \]

and for example of macro-type E is:

\[ E \text{ (days)} = 365 - [C \text{ (days)} + W \text{ (days)}], \]

which means that in a given year an increase in the frequency of a given macro-type by 1 day automatically results in the same decrease in the frequency of one of the other two macro-types (e.g., an increase in the frequency of macro-type W by 1 day entails a decrease by 1 day in the frequency of macro-type E or macro-type C). In this way, changes in the annual frequency of macro-types, despite the seemingly weak correlation with sunshine duration, bring about its strong changes.

The described logical dependencies in the annual frequency of macro-types mean that in the time sequences of macro-type frequency there are strong and highly significant negative correlations between them. Owing to the strong correlation (redundancy) between the independent variables, this makes it impossible to construct a linear equation in which the simultaneous impact of the frequency variability of all macro-types in a year on changes in the annual sunshine duration can be presented. Since the frequency of W and E macro-types has the strongest and highly significant influence on changes in sunshine duration, it is possible, using nonlinear analysis, to present the simultaneous influence of both of these macro-types (Figure 4).

The picture of the dependence of annual sunshine duration on the simultaneous changes in the frequency of macro-types W and E (Figure 5) explains unequivocally that with an increase in the frequency of macro-type W and a simultaneous decrease in the annual frequency of macro-type E, sunshine duration increases in the area of Central Europe (Figure 5), and vice versa, with a decrease in the frequency of macro-type W and an increase in the frequency of macro-type E sunshine duration decreases.

This indicates that changes in sunshine duration over Central Europe occur simultaneously with changes in the annual structure of macro-types. Thus, sunshine duration
should change along with the changes in the circulation epochs, in each of which a specific macro-type structure, different from the previous and next, is maintained. The discontinuity manifesting itself in the course of the annual area sunshine duration (Figure 3) falls in the years 1987–1989. It is in that period that circulation epochs changed.

In the period 1951–2015 considered in this work, circulation epochs changed twice. Savichev et al. (2015) corrected the boundaries of circulation epochs set earlier by Girs (1971) and Girs and Kondratovich (1978), determining the following circulation epochs in the years 1949–2014:

- 1949 – 1965 – epoch E+C,
- 1966 – 1989 – epoch E,
- 1990 – 2014 – epoch W,

while the year 2014 does not constitute the limit of the determined last circular epoch W, but the last year of the sequence of data analysed by Savichev et al. (2015). In fact, circular epoch W lasted at least until 2017.

Similar analyses of the frequency of macro-types W, E and C, aimed at determining the circulation epochs in the years 1891–2010 and their duration, were carried out by Degirmendžić and Kožuchowski (2018; 2019). The boundaries of the circulation epochs in the years 1949–2010 determined by these researchers correspond, with a good approximation, to the boundaries set by Savichev et al. (2015). The epochs themselves are the same in terms of their structure and the dominant macro-types. The differences come down to slight shifts of their boundaries in time (according to Degirmendžić and Kožuchowski, 2018; 2019: 1950–1969 – epoch E + C; 1970–1991 – epoch E; 1992–2010 – epoch W), which is understandable owing to the different lengths of the sequences analysed by these researchers and the different methods of studying the structure of macro-types.

The precise determination of the boundaries of circulation epochs, with the accuracy of a year, so as to create a distributive sequence, is a difficult task, because the changes in the structure of macro-types do not occur rapidly, between 1 year and the next. There are transitional periods between circulation epochs, in which the frequency of the dominant macro-type gradually decreases over the course of 2 or 3 years, and another macro-type gradually enters its place, becoming the dominant one. Despite the use of ‘objective’ grouping methods, this situation forces the adoption of arbitrary solutions.

An analysis of anomalies in the annual frequency of macrotypes W, E and C calculated as deviations from the long-term mean for the period 1951–2015 (Figure 6) makes it possible to correct the boundaries of the circulation epochs in relation to those determined by Savichev et al. (2015): epoch E + C ends in 1965, epoch E begins in 1966 and lasts until 1988, and then, from 1989, circular epoch W begins, lasting until the end of the period under consideration (2015). This is a shift of the epoch boundaries in time by 1 year back in relation to those set by Savichev et al. (2015).

In order to investigate the relationship between sunshine duration and long-term changes in the frequency of macro-types forming the circulation epochs, the sequence of SDs from the years 1951–2015 were divided into sections corresponding to the circulation epochs occurring in those years. The calculated statistical characteristics of the values of SD in the time limits of circulation epochs defined in this way are presented in Table 3.

The differences between the mean values of SD in successive circulation epochs are statistically significant. Tests of the differences between the averages of epoch E + C and epoch E indicate that the difference is significant at $p = .0081$ (one-tailed test) or $p = .0161$ (two-tailed test). The difference between the averages of epoch E and epoch W is significant in both tests at a level of $p<.001$. The differences between the distributions of SD values in subsequent epochs are well illustrated by the ‘box-and-whisker’ diagram (Figure 7). A characteristic feature of this variability is that in all circular epochs, regardless of the variability range between the second and third quartiles, the variability range of the first quartile is much smaller (more than two times or more) than the variability range of the fourth quartile.

![Figure 6](https://example.com/figure6.png)
Thus, both the analysis of the differences between the averages and the analysis of the ranges of variability confirm that with the change in the ‘circulation epochs’, that is, the change in periods characterized by individual characteristics of macro-circulation conditions, the sunshine duration regime changes. This statement makes it possible to interpret the observed changes in the annual sunshine duration over the area of Central Europe from the point of view of macro-circulation changes.

In the E + C circulation epoch (1951–1965), an increase in the frequency of macro-types E and C above the long-term standard and a decrease in the frequency of macro-type W below the long-term standard was observed (Figure 6). The decrease in the frequency of macro-type W contributed to the decrease in sunshine duration in this epoch, as did the increase in the frequency of macro-type E, which is related to the decrease in sunshine duration (Figure 5). However, this decrease was partially compensated for by the higher above the standard long-term frequency of macro-type C, which is related to a weak increase in sunshine duration. Rapid increases in the frequency of macro-type W in some years, and in the frequency of macro-type C in this epoch in others, resulted in the fact that some years of that period were characterized by sunshine duration exceeding 1,700 hr (Figure 3).

The next circulation epoch (1966–1988) was characterized by the clear dominance of macro-type E, with the occurrence of which a decrease in sunshine duration is associated. The frequency of macro-types W and C was definitely lower than the long-term average. Such a structure of macro-types meant that in this epoch there was a deep decrease in sunshine duration, which was reflected in a low average value, a low median, and a significant reduction in the range of inter-annual variability in sunshine duration.

Changes in the nature of macro-circulation conditions that occurred in the declining period of circulation epoch E between 1987 and the beginning of circulation epoch W (1989) led to a radical reconstruction of the structure of the macro-types present. In 1987, the frequency of all macro-types approached the long-term average, and then, from 1989, the frequency of macro-type W became higher than the long-term average, and then increased (Figure 6). At the same time, the frequency of macro-type E fell below the long-term average, and the frequency of macro-type C fluctuated around the long-term average. As a result of such behaviour of the macro-type structure at the turn of the circulation epochs, a ‘jump’ (discontinuity) appeared in the course of annual totals of sunshine duration, and then, in the last circular epoch W, a positive trend appeared in the sequences of area sunshine duration, which became statistically significant with time.

In this way, without resorting to looking for other reasons, changes in the macro-circulation conditions in the Atlantic-European circulation sector explain quite well the changes in annual totals of sunshine duration occurring over the area of Central Europe in the years 1951–2015, together with an explanation of the cause of a positive trend in the course of sunshine duration after 1988.

### 4.2 Annual sunshine duration over Central Europe and the thermohaline circulation in the North Atlantic

Stating that changes in the mid-tropospheric circulation are the cause of changes in the annual sunshine duration over Central Europe poses an immediate question, which in turn is the cause of such and not other changes in the

| Circulation epoch | Number of years | Average | Median | Min | Max | SD |
|-------------------|----------------|---------|--------|-----|-----|----|
| E + C 1951–1965   | 15             | 1,583.6 | 1,574.2| 1,422.3 | 1859.2 | 108.6 |
| E 1966–1988       | 23             | 1,501.0 | 1,486.8| 1,367.3 | 1,676.7 | 101.5 |
| W 1989–2015       | 27             | 1,666.6 | 1,650.6| 1,500.5 | 1964.2 | 104.1 |
The values of the correlation coefficients between the DG3L index, characterizing the NA THC intensity, and the annual frequency of macro-types W, E, and C of the mid-tropospheric circulation according to the Wangengejm–Girs classification and the average annual sunshine duration over Central Europe (SD)

|   | W   | E    | C    | SD  |
|---|-----|------|------|-----|
| 0.63 | -0.61 | 0.10 | 0.60 |

Note: Correlation period 1951–2015. p – Significance level of the correlation coefficient.

The variability of the mid-tropospheric circulation in the Atlantic–European circulation sector is controlled by changes in heat resources in the waters of the North Atlantic (Marsz, 2005, 2012). The occurrence of excess heat in waters in certain reservoirs, and shortages of heat in others, determines the size and duration of heat fluxes from the ocean surface to the atmosphere. The weakened or intensified heating of the middle troposphere by heat fluxes from the surface of specific water reservoirs affects the values and spatial distribution of meridional temperature gradients in the middle troposphere, thus affecting the stabilization or destabilization (change in the wave number) of long waves (Rossby waves) – see Fortak (1971, fig. 45). Macro-types W, E and C distinguished by Wangengejm (1952) are nothing more than specific forms of long waves with a relatively typical location of their upper ridges and upper troughs in the space of the Atlantic European circulation sector.

The surface component of the thermohaline circulation in the North Atlantic (NA THC) determines the large-scale spatial distribution of heat resources in the North Atlantic waters, and thus the size and spatial distribution of heat fluxes from the ocean to the atmosphere (Delworth and Greatbatch, 2000; Latif et al., 2004; Knight et al., 2005; Zhang et al., 2006; Dima and Lohmann, 2007; Grossmann and Klotzbach, 2009; Zhang et al., 2013, 2019). As a result, the variability of THC NA has a regulating effect on the course of the mid-tropospheric circulation, and thus on the frequency of macro-types W and E (Table 4), thus also controlling changes in sunshine duration.

The distribution of signs of correlation coefficients between the DG3L index, characterizing the NA THC intensity, and the annual frequency of W, E and C macro-types according to the Wangengejm–Girs classification (Table 4) is the same as in the case of the relationship between solar radiation and the frequency of macro-types. Changes in THC NA have a statistically significant, opposite effect on the frequency of macro-types W and E. The frequency of macro-type C shows no correlation with changes in the intensity of NA THC (cf. Table 4 with Table 2).

The existence of an asymmetric transitive relationship between the intensity of NA THC, the frequency of macro-types W and E, and SD determines the direct correlation between the DG3L index (cause) and the annual area sunshine duration over Central Europe (SD; effect).

The presented diagram of the distribution of empirical points in the common space of DG3L and SD (Figure 7) explains that the relationship can be treated as linear. The variability of NA THC explains about 1/3 of the variance in the annual area sunshine duration in Central Europe. A change in the value of the DG3L index by one unit entails a change in SD by 64.6 (±10.7) hr with the same sign. The standard error of estimating the value of annual area sunshine duration is equal to ±101.1 hr, which is about 6.5% of the long-term average (1951–2015) SD value. The relationships found can be considered quite strong and relatively close, despite the presence of two outliers (Figure 8, the years 1959 and 2003).

A comparison of the course of sunshine duration over Central Europe with the course of the DG3L index (Figure 9) shows that the relationships between these values differ, depending on the time scale in which they are studied. Short-term relationships, construed as occurring in the same year, are relatively weak. Cases of antiphase changes are often observed, and there is no constant relationship between the relative amplitudes of changes in both quantities.
functioning is characterized by enormous inertia and heterogeneity (Rossby, 1996; Lumpkin et al., 2008). The transportation of waters from the Gulf Stream Delta (~38–42°N, 48–40°W) to the Arctic (~70–74°N, 10–20°E) takes about 3–4 years. It is with this delay that waters carrying the warmth of the tropics will arrive in the Arctic, north of the Lofoten Islands, where they will contribute to an increase in SST on the border of the Barents Sea and the northern Norwegian Sea (Orvik and Skagseth, 2005; Muilwijk et al., 2018). Changes in heat resources in waters and changes in SST in these reservoirs also have an impact on the amount of sunshine duration in Central Europe. As a result, in the same year, the DG3L signal from a given year and a strongly distorted DG3L signal from 3 or 4 years ago will affect sunshine duration in Central Europe. Additionally, it should be borne in mind that during the whole time of transportation through the North Atlantic and the Norwegian Sea, these waters give off heat to the atmosphere and affect the SST on its way.

If changes in THC NA result in changes in macro-circulation conditions, and thus changes in sunshine duration, earlier than the year in which the relationship is considered, changes in the DG3L index may affect the strength of the relationship. An analysis of the correlation of the beginning of the sequences of the DG3L index with shifts by 1 year (1950, 1949, 1948, ..., 1941) in relation to the SD sequence showed that the sequence of the index 11 years earlier is significantly ($r = 0.27$, $p = .027$) correlated with annual area sunshine duration. Presumably, these long-term interactions, subject to natural attenuation as a function of time, are the cause of a lower consistency of the year-to-year (inter-annual) changes and a much better compliance of long-term courses. The clarification of this issue requires an analysis of the correlation of the SST sequences characterizing the temperature field of the ocean surface with the SD sequence, making it possible to detect reservoirs where SST changes, not being strongly correlated with the DG3L index, may make it possible to explain the significant percentage of short-term variability.

Regardless of the doubts raised here, it is the conclusion of the above that the change in the intensity of the thermohaline circulation in the North Atlantic is the primary factor controlling changes in sunshine duration over Central Europe, by triggering and controlling the entire chain of events in climate processes.

5 | DISCUSSION OF THE RESULTS

The observed strong influence of NA THC on the forming of changes in sunshine duration raises the issue of addressing the causes of long-term changes in the

![Figure 9](image-url)
temperature of the North Atlantic surface. This is a secondary problem in this work, but important for the assessment of the widely discussed role of aerosols in the formation of long-term variability in sunshine duration.

Mann and Emanuel (2006) put forward the thesis that changes in SST and heat resources in the waters of the North Atlantic take place owing to anthropogenic factors; the increase in SST under the influence of global warming is combined with the nonperiodic cooling effect of anthropogenic aerosol. As a result of the operation of these processes in the course of SST, a quasi-periodic variability is revealed, which is Atlantic Multidecadal Oscillation (AMO; Kerr, 2000; Enfield et al., 2001). The thesis on the cooling effect of increasing aerosol concentrations put forward by Mann and Emanuel (2006) was confirmed by Booth et al. (2012). Even now, a number of studies (e.g., Birkel et al., 2018; Qin et al., 2020) indicate aerosols of anthropogenic and volcanic origin as the cause of long-term fluctuations in the temperature of the surface of the North Atlantic Ocean.

If this were the case, the real, primary cause of the described relationships between changes in THC NA intensity and sunshine duration would be the varied aerosol concentration in the atmosphere described in the literature cited earlier.

The long-term variability of the temperature of the North Atlantic has long been explored and has been the subject of extensive research into its causes (Delworth et al., 1993; Kushnir, 1994). Already the first model work (Delworth and Knutson, 2000; Delworth and Mann, 2000) explained that temperature oscillations in the North Atlantic are the result of the internal dynamics of the system and not of external influences. A number of works, not cited here, explained the relationship between the three modes of SST variability and the heat resources in the North Atlantic waters (AMO – Atlantic Multidecadal Oscillation, AMM – Atlantic Meridional Mode and AMOC – Atlantic Meridional Overturning Circulation), reaching the conclusion that these modes are various aspects of NA THC manifestation. A synthetic, critical review of these articles is provided in the work of Grossmann and Klotzbach (2009).

Zhang (2007) engaged in controversy over the thesis of Mann and Emanuel (2006), demonstrating that their thesis is inconsistent with both empirical data and modelling results, and that aerosols could not be the cause of rhythmic changes in the temperature of the surface of the North Atlantic. The same subject, disputing the thesis of Mann and Emanuel (2006) and the work of Booth et al. (2012), was tackled again by an international team of researchers specializing in both ocean heat balance studies and model studies (Zhang et al., 2013), proving that the thesis about the influence of aerosols on the formation of long-term changes in SST in the North Atlantic is not reflected in reality, and these changes are a manifestation of AMOC (Atlantic Meridional Overturning Circulation), which is the same as NA THC.

It may be added here that numerous studies (cf. e.g., Gray et al., 2004; Knudsen et al., 2011; Wei and Lohmann, 2012; and the literature cited therein) showed that the quasi-cyclic transitions of the thermal condition of the North Atlantic from ‘warm’ to ‘cool’, which is typical of AMO, occurred in this reservoir of water throughout the Holocene. AMO is a manifestation of NA THC.

The analysis of the relationship between sunshine duration and THC NA presented in this study shows that the large part of the variability in SD can be explained by natural factors without reference to anthropogenic aerosol.

6 | CONCLUSIONS

The described changes in macro-circulation conditions and changes in the intensity of thermohaline circulation explain the significant percentage of variance in the annual sunshine duration over Central Europe. Changes in THC NA explain 1/3 of the variance of SD, changes in the frequency of macro-types W and E, forced by changes in THC NA, explain, each of them separately, about 22 and 26% of the variability of the annual totals of sunshine duration. Changes in the same interrelated factors also explain fairly well and coherently the behaviour of long-term changes in sunshine duration over Central Europe, with a decrease in SD in the 1960s–1980s and the emergence of a statistically significant positive trend in the 1990s, and in the early 21st century.

The explanation of the variability of sunshine duration by the described processes is far from explaining its total variability. There is no doubt that the variability of sunshine duration is also influenced by the variability of other factors, mainly cloud cover. The impact of these factors, especially the impact of changes in macro-circulation conditions on the changes in cloud cover, was not considered in this study. However, the conducted research made it possible to discover a new mechanism regulating sunshine duration, not described so far. The conducted analysis shows that in the ocean–atmosphere climate system, relatively simple intra-system processes function, the operation of which, through a longer chain of events, is regulated by a significant percentage of changes in sunshine duration.

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