Chapter 16
Changes in Sea Surface Temperature of the South Baltic Sea (1854–2005)

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16.1 Stating the Problem

There have been hundreds of works written on the changes in the air temperature over Poland and neighboring countries. These changes, at least, during instrumental observations are well known. The literature dealing with the changes in sea surface temperature of the Baltic Sea is relatively poor. Soskin (1963) analyses the changes in sea surface temperature (SST) in the period 1900–1950 and notes in the 20s–30s of the twentieth century the increase in temperature in relation to the preceding period. Betin and Preobraženskij (1962) while dealing with the severe character of winters in Europe refer to a series of information about the presence of ice cover in the Baltic Sea and its duration (tenth–eighteenth centuries). This, in an indirect way, gives some information regarding many centuries' changes in winter water temperature. These data however, are not continuous as they base on historic documents (chronicles, diaries, and harbour, merchant and customs documents) and enable to derive only very general conclusions, regarding changes in the temperature of waters of the Baltic Sea, limited solely to winter periods.

Numerous remarks about changes in SST over short periods and in small sea areas can be found in works dealing with biological oceanography and ecology of the Baltic Sea; they concern different periods after the 1960s. Even, the impressive in size, hydro meteorological monograph of the Baltic Sea (Terziev et al. 1992), except for a map illustrating distribution of SST, does not deal with many-year changes in SST. Some Polish monographs on coastal climate or on Polish coastal zone mention changes in SST (e.g. Miętus et al. 2004) in the off shore area. Systematic measures of water temperature at measuring points of IMGW,[1] which in

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most cases are located in port waters and the very reading is done close to the shore or in a distance of a few meters from the shore, provide the data.

In 2003 the authors (Marsz and Styszyńska 2003) making use of the data from COADS[2] presented changes in SST in the sea area covering the Gdańsk Bay and the Gdańsk Deep in the years 1871–1992. They stated that there is statistically significant positive trend in SST in this sea area (+0.009°C year^{-1}, $p < 0.005$) and strong correlation between changes in SST and the character of winter atmospheric circulation observed in the examined period. Zblewski (2006) carried out a detailed analysis of changes in SST in the whole Baltic Sea in the period 1982–2002, in which very strong increase in air temperature was observed over the Baltic Sea and in regions adjacent to the Baltic Sea. The aim of this work was to find out how the strong warming of the atmosphere influences SST. The author noted that strong positive trends, in most cases are statistically significant and what is more, indicate clear seasonal variability in space almost in the entire surface of the Baltic Sea. The annual trends in SST defined by Zblewski turned out to be much stronger than those noted by the authors in the many- year period 1971–1992. Siegel et al. (2006) analyzed changes in SST of the Baltic Sea from Arkona Deep to the end of the Bothnia Bay over the period 1990–2004. The conclusions they have arrived at, are, to a great extent, similar to the results obtained by Zblewski (2006).

The most recent works on changes in SST in the Baltic Sea were published in 2008. Assessment of Climate Change for the Baltic Sea Basin (2008; later referred as ACCBSB) presents the results of modeling of changes in heat amount in the Baltic Sea and its regions which were observed in 1958–2005 and 1970–2005. As it can be seen in the results presented by ACCBSB (2008; Fig. 2.49) a visible increase in the heat amount in the Baltic took place in 1958–2005. Hansson and Omstedt (2008) basing on the data from the twentieth century reconstructed the SST course and Maximum Ice Extent (MIE) for the last 500 years. The above mentioned results indicate that in the twentieth century SST was higher than in the last 500-year period and that the highest decadal values of SST were observed in the 1930s and in the 1730s. The changes in SST and MIE in the Baltic are within the limits of natural climate variability.

Changes in SST in open waters of the Baltic Sea,[3] because of the presence of a specific for this sea density stratification, occur only under the influence of local elements responsible for climate formation. The heat resources transported into the Baltic Sea with waters flowing from the North Sea have no contact with the sea surface and that is why the processes of heat advection with the transported waters are completely neglected for changes in SST. In the same way, changes in the sea surface caused by human activity are neglected. Such activities performed on land by changing the way the land is used, changes in its moisture, forming city islands of warmth may have influence on the temperature of ground and on the air temperature.

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[2] COADS – Comprehensive Ocean-Atmosphere Data Set.

[3] Open, that is, situated in a certain distance from the shore, outside the area being under the influence of processes active in the coastal zone, where the local, especially in the sea areas close to the port and in the regions in the vicinity of river estuaries anthropogenic and natural deformations in the course of SST can be observed. This work completely neglects problems of changes in SST in coastal and sheltered regions, dealing only with changes present in open waters.

Changes in SST are influenced by annual heat balance. On the side of heat gain in the sea surface the only element that matters is the gain of solar radiation and atmospheric re-radiation. On the side of loss there is radiation from the sea surface and heat flux from the sea surface to the atmosphere. The latter is made up of sensible heat flux (turbulent exchange) and of latent heat flux (latent heat of evaporation). The values both of the streams of heat gain, as well as, heat losses are influenced by changes in weather phenomena both periodically and aperiodically. Because of great heat volume of water and large masses of water and at the same time great thermal inertion of the layer of the Baltic waters above halocline, SST 'records' in its course rhythm of changes in weather conditions observed over longer periods and at the same time with different scale of delays, influences the course of these conditions. Taking into consideration the above, it can be stated that changes in SST of the Baltic represent resultant of the changes in regional climatic conditions over the examined period and are free of anthropogenic influence.[4]

The aim of this work is to present the course of changes in annual SST in the southern part of the Baltic Sea, observed over the period of the past 152 years, that is in the period from 1854 to 2005. The analysis of the course of changes in SST of the Baltic Sea carried out for a longer period can solve a lot of problems and the ones which seem to be most important, that is defining the scale of changes in SST, defining the cooling and warming periods observed in the sea surface of the Baltic Sea, defining the concordance of changes in the course of SST and the air temperature on land in the vicinity of the examined sea area and explaining what climatic signal is indicated by changes in SST.

16.2 Data

The basic data were made up of chronological series of monthly values of SST from the data set ER SST v.2.[5] This set contains global values of monthly SST which are average values for areas $2°\phi \times 2°\lambda$, with evenly nominated central points of these areas (grid organization). The set ERSST v.2 for the period 1854–1992 is transformed from COADS SST data, for the later period – high resolution satellite data, calibrated by measurements in situ. How this set is constructed and what techniques are used to get rid of interference, how the mean values and how the climatologic homogeneity are obtained, can be found in works by Smith and Reynolds (2004). The data from this set are less accurate in the preliminary period and from both world wars because of not equal number of data used for estimating mean values.

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[4] The only anthropogenic factor which has influence on changes in SST of the Baltic Sea is the change in the concentration of CO_2 in the atmosphere. This results in changes in elements of the radiation balance. The changes in CO_2 concentration are global so changes of the elements of the radiation balance over the Baltic should be the same as over the area adjacent to this sea.

[5] The full name of the data set NOAA NCDC ERSST version2 is improved extended reconstructed global sea surface temperature data based on COADS data.

The analysis of changes in SST in the Baltic Sea made use of a grid with coordinates 56°N, 18°E whose time series describes the mean SST defined within the limits 55–57°N, 17–19°E. The surface area of the sea area calculated as a flat area is 27,618 km^2. Figure 16.1 presents the location of this surface. The described sea area almost in 100% covers water surface and characterizes open waters of the southern part of the Baltic Sea.

The standard estimation error for the mean monthly SST in the examined sea area in most cases is within the range from ±0.01 to ±0.04°C, maximum errors reach ±0.61°C (data set NOAA NCDC ERSST version2 err). Figure 16.2 presents the distribution of estimation error for annual SST calculated as mean value of monthly errors in a given year. The highest values of standard estimation errors for monthly temperature, except for single cases, are noted in April.

The values of annual temperatures used for this analysis were calculated from the values of mean monthly temperatures as mean arithmetic values. Changes in annual SST in this grid point are very strongly correlated (r = 0.97–0.99)[6] with

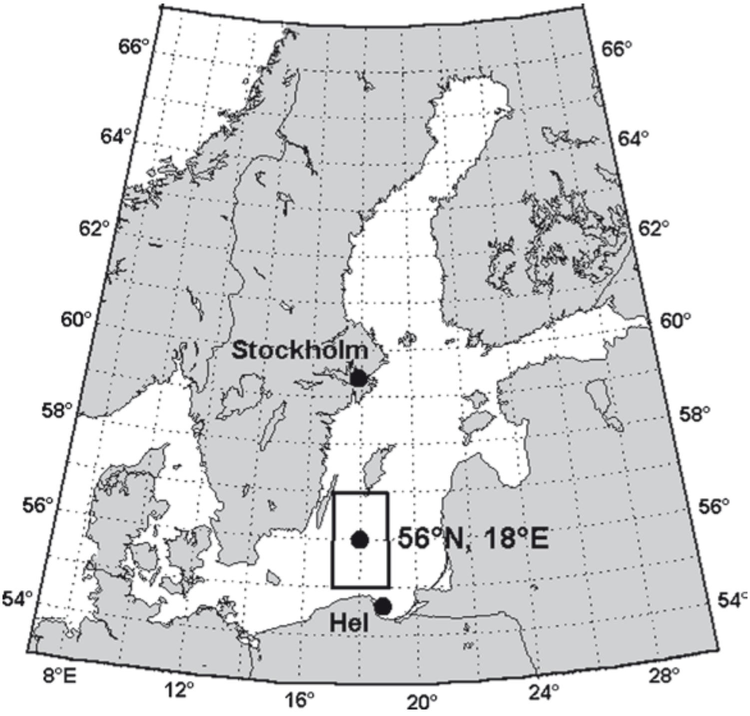

Fig. 16.1 The location of areas whose mean annual temperatures were analysed in this work. Grid 56°N, 18°E is marked with *black point*

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[6] r – Pearson's linear correlation coefficient.

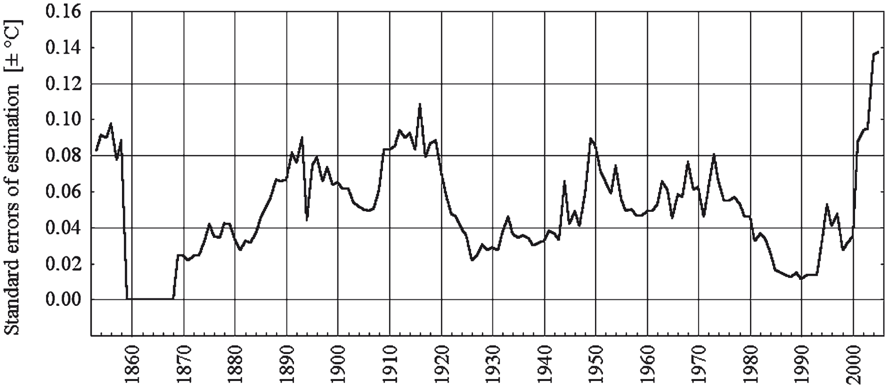

Fig. 16.2 Distribution in time of standard errors of estimation of mean annual SST in grid 56°N, 18°E

the changes in SST in the adjacent to the examined grid points and this makes it possible to state that they are representative for a far greater sea area than the examined surface.

The data showing the air temperature from Stockholm station up to 1889 are derived from the data set GHCN v.2 (Peterson and Vose 1997) and for the year 1890 from the data set Nordklim (Tuomenvirta et al. 2001) The data characterizing the temperature at Hel till the year 1995 are taken from the work by Międtus (1998) and in the following years they were supplemented with official data from IMGW. The quality of these data has been checked by the authors of these series and they are homogeneous. The values of NAO indexes used in this work are taken from the data set accessible in official web sites WWW CRU and J. Hurrell.

This work made use of standard methods in statistical analysis; when analyzing signals a standard analytical methodology of electrical courses was employed (Osiowski and Szabatin 1995). The principle of this method is that the following elements are analyzed one by one, that is the course of deviation from the mean value, low and up band signal envelopes whose aim is to define the components of modulation, spectral analysis of a signal whose aim is to define spectrum of modulating harmonic and harmonic being beating-up of modulating signals[7] and identification of impulse interference.

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[7] In case when two (or more) signals are received in the summing up system, processes of beating up (mixing) of signals forming new harmonics are observed. The basic harmonics of beating up are the sum and difference between primary frequencies. In case when certain phase shifts between primary signals are present, the amplitude of beating up harmonics can be higher than the amplitude of modulating signals. The summing up system in this case is the surface layer of the sea.

16.3 The Course of Mean Annual Value of SST of the Baltic Sea

In the examined 152-year period the mean annual SST is 8.83°C (σn = 0.61; σn – standard deviation). The range of changes in SST is found within the limits from 10.17 (year 1990) to 6.76°C (year 1941) which result in an amplitude equal 3.41°. The course of SST indicates to a great interannual changeability with clearly marked many-year changeability. In order to define the periods of changes in SST it is more convenient to use the standardised[8] course of SST (Fig. 16.3). It can be easily noticed that the characteristic feature of the course of SST in the examined period is asymmetry noted in the frequency of the decreases in SST below −1 and −2 σn in relation to how frequently the limits +1 and +2 σn are exceeded.

Over the period from 1854 to 1933 the frequency in SST drops below −1 σn and is significant (20 times, twice, in this number, the limit was exceeded below −2 σn), whereas the frequency of exceeding the limit +1 σn by SST is scarce (twice and in this number 0 cases when the limit +2 σn was exceeded). From the year 1934 the situation changes, that is more frequent are the cases when SST exceeds the limit +1 σn (18 such cases including the one above +2 σn) when compared to situations when the temperature drops below −1 σn (nine cases including the one below −3 σn). At the turn of 1933/1934 a clear change in the character of the changeability (rhythm) of SST can be observed. In the first period a year-to-year changeability in SST characterised by not too large amplitude can be noted with the 2–3 year periodicity and majority of negative deviations. In the second period (1934–2005) the 5–10 year periodicity is noted and is characterised by large or very large amplitude with majority of positive deviations, thus the year-to-year changeability in SST

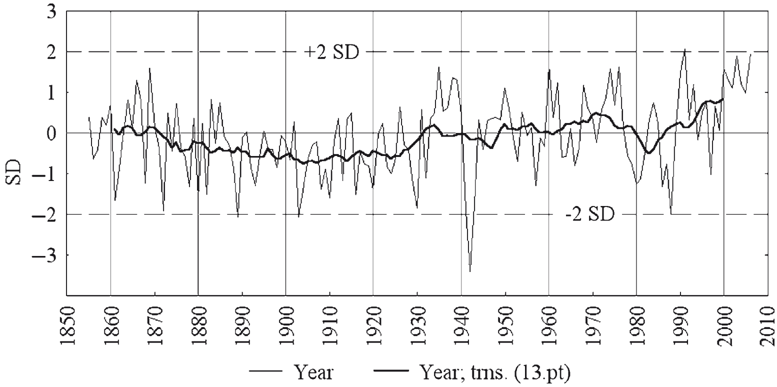

Fig. 16.3 The course of standardized annual SST (in relation to 100-year period 1901–2000) in grid 56°N, 18°E. Marked levels +2 and −2 σn (SD). *Bold line* – course adjusted by 13-point moving average

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[8] Standardization was carried out with reference to mean 100-year value from 1901–2000.

recedes into the background. The negative deviations of SST become more significant than in the former period and take evidently more time.

The course of cumulated deviations from the mean annual many-year value makes it possible to distinguish the following periods in the course of annual SST:

1. The years 1854–1875 – the mean annual value of SST is slightly higher that the mean value of the entire period (~8.88°C), stable in time course of SST (trend around 0; $-9.974 \cdot 10^{-5}$°C/year)
2. The years 1876–1932 – the mean annual value of SST is slightly lower than the mean value of the entire period (~8.56°C), the cooling period (trend −0.002°C/year)
3. The years 1933–1939 – sharp increase in SST, the mean value significantly higher than the mean value of the whole period[9] (9.45°C), trend +0.029°C/year
4. The years 1940–1947 – dramatic cooling, the mean SST value lower than the mean of the entire period (8.41°C), trend −0.013°C/year
5. Years 1948–2005 – gradual increase in SST interrupted by periods of strong cooling, the mean SST, the mean value higher than the mean value of the whole period (~9.10°C), trend +0.009°C/year

If we take the strong cooling period in the 1940s as the minimal value of the course, then the observed in 1941 the absolute minimum, will divide the examined period into two parts, that is the one during which the decrease in SST (−0.002°C/year) was noted and the mean SST is about 8.7°C and the other period in which the increase in SST (+0.012°C/year) is observed and the mean SST is about 9.0°C.

Very strong fluctuations of SST which were observed between the beginning of the 1930s and the end 1940s raise a question about the true limit between both great periods of changes in temperature of the Baltic surface. The analysis of the course of SST in which the short term fluctuations are neglected or/and their amplitude is decreased (adjusted by 13 point moving average), will make it possible to set the limit between these two periods at the turn of 20s and 30s of the twentieth century (see Fig. 16.4a). The warming period in the 1930s, despite being followed by a period of strong cooling of the sea surface, 'fits' the pattern of following warming which is characterised by the fact that the following increases in SST are higher than decreases in SST, even if they are significant. Tentatively it can be assumed that the limits between these periods can fall in the year 1929 which divides the whole period into two equal parts. In such a case in the period 1854–1929 a decrease in annual SST (−0.0065°C/year, $p < 0.013$), can be noted, whereas in the period 1929–2005 an increase, a little higher than the previously observed decrease, (+0.0072°C/year, $p < 0.030$) is noted.

The annual temperature resulting from averaging monthly values of SST depends on changes in these values. In the course of SST observed in the sub-polar latitudes, the annual temperatures are influenced by the heat resources left in the waters after winter cooling of the sea surface as well as by the increase in heat

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[9] Rapid increase in SST in this period causes that the entire decade 1931–1940 is clearly warmer than the average temperature; see Hansson and Omstedt (2008).

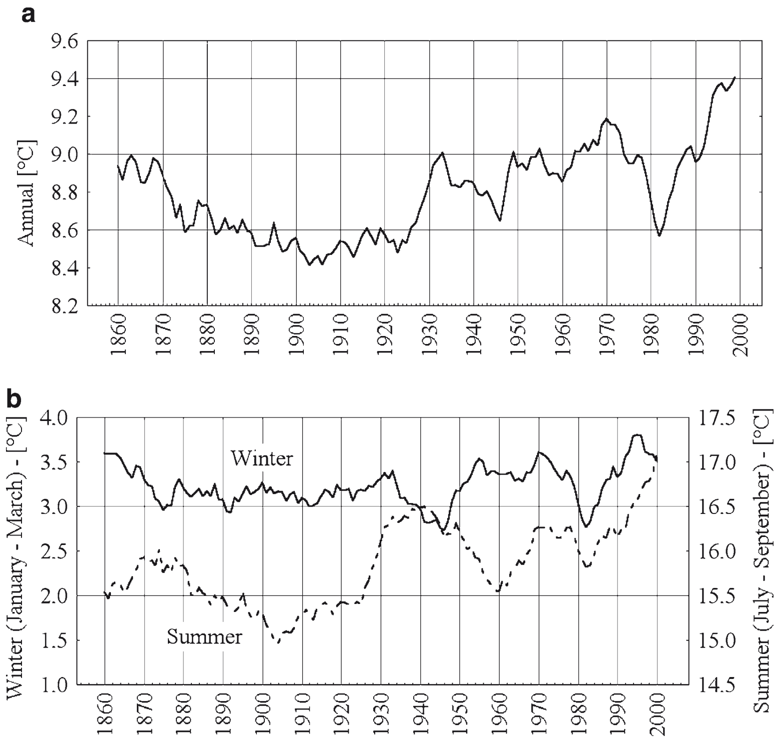

Fig. 16.4 The course of SST in grid 56°N, 18°E adjusted by 13-point moving average. (**a**) the course of annual mean SST, (**b**) the courses of mean SST from the winter cooling (January–March) and summer warming (July–September) of the sea surface. Note – please pay attention to different scaling of SST in each part of the drawing

resources in the sea surface at the end of the summer warming period. In the analysed sea area the maximum SST can be observed in August and July or even in September. The minimum value is noted in March, February or April and exceptionally, in some years in January.

The correlation between the annual SST with the mean values noted in winter cooling periods (mean January–March) and the maximum summer warming (July–September) is very strong in the examined area. It is described with the following formula:

$$\mathrm{SST_A} = 1.103(\pm 0.339) + 0.395(\pm 0.029) \bullet \mathrm{SST_W} + 0.406(\pm 0.023) \bullet \mathrm{SST_S}, \quad (1)$$

where:

$\mathrm{SST_A}$ – mean annual SST in the sea area within the limits of 55–57°N, 17–19°E; °C,

$\mathrm{SST_W}$ – mean SST in the sea area as above from the period January–March (winter),

$\mathrm{SST_S}$ – mean SST in the sea area as above from the period July–September (summer).

This correlation explains 84% of annual variances of SST ($R = 0.91$, $F(2,149) = 385$, $p < 0.0000$).[10] In this formula the summer SST variability explains 63% and winter SST variability 21% of mean annual SST variances.

In order to illustrate to what extent the process of winter cooling and summer warming periods affect the annual changeability in SST in the examined sea area, the courses of changes in SST_W and SST_S adjusted by 13-point moving average are presented (Fig. 16.4b). This problem is not to be discussed here. At this stage what is pointed out are the different courses of both components and the increasing amplitude of winter and summer SST as a function of time. It should also be underlined that summer SST is correlated with winter SST. After the period of winter cooling some smaller or bigger residual heat resources in water are left and they have significant influence on temperature, the water reaches at the end of the summer warming of the sea surface. In the entire, 152-year, series changes in winter mean value of SST (January–March) explain about 10% variances of mean summer SST (July–September) ($R \sim 0.3$, $F(1,151) = 16.4$, $p < 0.0001$). This means that after winter season, when there was lower heat absorption from the sea surface (which is represented by higher SST in March–April), summer SST is higher; the course of winter SST affects the course of summer SST. The changeability in mean winter SST explains about 49% of mean annual SST variances ($R = 0.7$, $F(1,150) = 141$, $p < 0.000001$). If we take into consideration additional influence of winter SST on summer SST then, it turns out that changes in temperature during the winter cooling of the sea surface have important influence on the annual SST. This winter SST depends on weather phenomena present in a given winter.

16.4 Correlation Between Sea Surface Temperatures with NAO

Annual SST of the Baltic indicates strong correlation with the processes of heat absorption in winter season. Because winter atmospheric circulation affects the temperature of air transported over the sea, its humidity and the speed of the wind it has influence on the amount of heat absorbed from the sea surface. That is why the annual SST of the Baltic is relatively strongly correlated with different circulation indexes which characterize the course of winter atmospheric circulation (Koslowski and Glaser 1999; Chen 2000; Marsz and Styszyńska 2000, 2003; Omstedt and Chen 2001; ACCBSB 2008; Hansson and Omstedt 2008).

Because of the length of the analysed series, the only possible index of winter atmospheric circulation to be used and to cover the whole period is NAO CRU index (Gibraltar – SW Iceland; Jones et al. 1997), whose series starts in 1823. Winter Hurrell index (Lisbon – SW Iceland; Hurrell 1995) commences 10 years later than the beginning of the analysed series of SST – namely in 1864.

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[10] R – multiple regression coefficient of correlation, F – value of Fisher-Snedecor test (in brackets degree of freedom), p – statistical significance level (probability of random result).

In the whole series (1854–2005) averaged for the period January–March NAO CRU index is correlated with annual SST of the Baltic Sea and this correlation is highly significant ($p < 0.00001$), however the strength of this correlation is moderate ($r = 0.4156$). Calculated for the same period as the Hurrell index was, that is (December–March), the NAO CRU is correlated with the annual SST with a similar strength within the whole examined period ($r = 0.4049$, $p < 0.00001$). Similar value ($r = 0.4277$, $p < 0.00001$) is obtained for a series 1864–2005 (142 years) for a correlation of annual SST with Hurrell NAO index which is calculated as a mean value from the period December–March.

The analysis carried out for the following 30-year periods of correlations between annual SST and winter NAO CRU index calculated for the period July–March and NAO Hurrell index indicated that they are not stationary. The results of the analysis are presented in Table 16.1.

It has been noted that correlations with NAO CRU index were gradually strengthened in the following 30-year periods, changing from relatively weak and insignificant ones to very strong and statistically very significant. Similar correlations between annual SST and NAO Hurrell index indicate similar course in the following 30-year periods but also here the strongest and most significant correlations are observed in the 30-year period 1971–2000. These differences in the strength of the correlation between SST and both NAO indexes result from different places of the data (Gibraltar, Lisbon) used to create each of these indexes; generally speaking, for the Baltic Sea it is the Hurrell index which provides more precise information about the advection from the sector W-SW (Marsz and Styszyńska 2000).

Weak and statistically not significant correlations of annual SST with NAO CRU index register the situation when the Iceland Low activity was relatively little and the Azores High was located westward causing that the frequency of advection of warm air masses from the Atlantic towards the Baltic Sea in winter was restricted. The research carried out earlier (Marsz and Styszyńska 2000) indicate that in the period from the latter part of the 1860s till the last years of the nineteenth century the Iceland Low was relatively weak. In that period a far greater role had depressions over the Scandinavian Peninsula, which were closely connected with strong advections of cold air from NW-NNW, than that of NAO in the process of

Table 16.1 Values of coefficients of correlation between annual SST and winter NAO CRU index and NAO Hurrell index (r) and the level of their statistical significance (p) for the following 30-year periods. Statistically significant values of correlation are in bold

	NAO CRU Index		NAO Hurrell Index		
Period	r	p	r	p	N
1854–1880	0.3027	0.125	–	–	27
1881–1910	0.3173	0.088	**0.4152**	0.022	30
1911–1940	0.3315	0.074	0.3589	0.051	30
1941–1970	**0.5618**	0.001	**0.3658**	0.047	30
1971–2000	**0.7233**	0.00001	**0.6844**	0.00001	30

winter cooling of the Baltic. Only in the years 1902–1903 a rapid drop in atmospheric pressure was observed in the region of Iceland during winter season.[11] The Icelandic Low activated rapidly. However, the Azores High started moving east and north east already from 1895. In winter more often than previously warm air was transported from the W sector to SW sector and not as it used to happen before from NW-NNW; this was connected with positive phases of NAO. This case was noted by statistically significant correlation of SST with Hurrell index in the period 1881–1910 but it was not noted by correlation with NAO CRU.[12] At the turn of the 20s and 30s of the twentieth century the activity of the Icelandic Low decreased again; the course of winter cooling of the Baltic was influenced by different than NAO circulation processes. At the same time the structure of synoptic processes changed into favourable for warming the ocean surface in summer (strong continentalization). As a result correlations between annual SST and both NAO indexes, although not changing the sign, they stop being statistically significant.

In the following two 30-year periods (1941–1970 and 1971–2000) the activity of NAO increased gradually and this led to the increase in the strength and level of correlation significance between annual SST and NAO. Especially during the last 30-year period (1971–2000) the processes of winter cooling of the surface of the Baltic Sea were influenced by advection of sea air from SW and W controlled the NAO. During this time NAO indexes indicated very high ‘concentration in time’ of high positive values (years 1973, 1981, 1983, 1989–1990, 1992–1995, 1999–2000) and also positive indexes, with values not observed during the whole preceding process of instrumental observations, were noted (years 1989 (5.08); 1990 and 1995 (3.96-twice). In these years ‘winters without winters’ occurred over the south and central Baltic during which the heat absorption from the sea surface was much lower, leaving far greater resources of residual heat in waters. As a result a very high increase in annual SST took place.

The last years (2000–2005) and especially last year (2006) for which there are still some data lacking seem to be different from a pattern of changes in SST typical of the last several dozen of years. The winter cooling intensity increased, when compared to preceding years characterized by very high NAO indexes during winter. However, they still remain weaker than during the last several dozen of years. On the other hand, the intensity of summer warming processes increased considerably when compared to last several dozen of years and this can result from the increased frequency of occurrence of heights accompanied by advection of air masses from SW. High temperature and relatively high humidity of air flowing over

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[11] In the years 1902 to 1903 there was a decrease in winter (July–March) pressure over SW Iceland from ~1004 hPa to ~991 hPa. After the year 1903 the pressure over the SE Iceland started gradually increasing but the level from the years 1870–1900 then was observed as late as at the turn of 20-ties and 30-ties of the twentieth century.

[12] In situation when the Azorean High moves NE, the pressure in Gibraltar can be relatively low (Gibraltar S of the edge of the high) and the value of the NAO CRU index is lower, whereas barometric gradient between Icelandic Low and Azorean High becomes strong (the decreased distance between both atmospheric activity centres) and the sea air is transported farther E-NE than in situation with the centre of the Azorean High locates over the Azores.

the Baltic are accompanied by clear decrease in wind speed and lower cloudiness (effect of stable balance). All this leads to significant reduction in heat loss for evaporation and turbulent exchange resulting in clear increase in SST at the end of the summer warming period and this, in turn, results in high SST in autumn and at the beginning of winter.

16.5 Correlations of SST with the Frequency of Occurrence of Synoptic Situations of a Certain Type

It can be assumed that the annual temperature of the Baltic Sea surface should indicate correlations with synoptic situations present over this sea area. From the point of view of the mechanisms responsible for the changes in SST, it seems interesting to define what synoptic situation was and when it had the greatest influence on the value of SST. In order to provide answers to these questions an analysis of correlations between the frequency of atmospheric circulation of Osuchowska-Klein types (1978, 1991) and annual SST in the examined grid was carried out (Osuchowska-Klein 1978, 1991). This analysis, because of the fact that the catalogue with low circulation types by Osuchowska-Klein comprises data from the period from 1901 to 1990, does not cover the whole examined period of changes in SST (1854–2005) but provides an extensive (90 years) although covering only 90 years, reliable sample of the occurring correlations.

This analysis was carried out in this way that it was assumed that the annual SST (SST_A) in a given examined period is the function of frequency of Osuchowska-Klein, individual types of low circulation from January to December. The character of this function is described by linear function (multiple regression). The consecutive monthly frequencies (from January to December) of all circulation types (A, CB, D, B, F, C2D, D2C, G, E2C, E0, E, E1 and BE) without type X (unmarked) are taken as independent variables and that gives a potential equation with 156 independent variables. Using the method of gradual regression, taking F to use ≥ 10.0 and tolerance ≥ 0.1, the values of constant term and regression coefficients were estimated, limiting the number of independent variables of this equation to the first four starting in the sequence of entering (more than 20 cases for one independent variable). As a result of the above described procedure the following equation is formed:

$$\begin{aligned} SST_A &= 8.4389(\pm 0.0094) - 0.0916(\pm 0.0179)E0_{01} + 0.0633(\pm 0.0099) \\ &\quad E_{08} + 0.0876(\pm 0.0189)C2D_{02} + 0.0795(\pm 0.0232)D2C_{02}, \end{aligned} \tag{2}$$

and its statistical characteristic is as follows: R = 0.72, adj. $R^2 = 0.50$, F(4.85) = 23.1, BSE = 0.44.

This relation indicates that 50% of variances of annual SST explain the frequency of four types of lower circulation types- number of days with E0 circulation type in January ($E0_{01}$), E type in August (E_{08}), C2D type in February ($C2D_{02}$) and

D2C type in February ($D2C_{02}$). The changeability in frequency: of E0 type in January explains 16.3% of changeability in annual SST, E type in August – 17.1%, C2D type in February – 12.1%, and of D2C type in February – 6.6%.

Equation [2] explains that the processes of winter cooling of the sea surface (three out of four variables originate from the winter season) have the greatest influence on the changeability in annual SST. Such findings are compliant with the earlier results of research into relations between the annual SST and winter and summer SST and into the influence the winter atmospheric circulation has on the value of annual SST. The determining influence of the frequency of circulation E type in August (high pressure over the Scandinavian Peninsula and over the Baltic during the maximum warming of the sea surface) and the frequency E0 type in January (north-east and east anticyclone circulation during the most intensive winter cooling) on the changeability of annual SST is both clear and comprehensible. However, the great role of warm circulation types in February – C2D and D2C which affect the changeability of annual SST is quite astonishing. The occurrence of these circulation types in February restricts the heat absorption from water surface thus, it makes further stronger decrease in SST impossible and in this way it contributes to the increase in the residual heat resources in water after 'winter'. The increased number of these types of circulation in February eliminates also the possibility of occurrence of other, 'cooler' types of circulations.

16.6 Relations of Air Temperature Over Coastal Areas with SST

Changes in SST which cause that over vast areas exchange of heat between the ground and atmosphere takes place, have direct influence on air temperature. What is more, SST by having influence on the type of atmospheric balance and in this way also on cloudiness may be said to have influence on the air temperature in an indirect way. In turn, the air temperature by controlling the heat import from the sea surface affects SST. In this way the courses of both physical values over a given sea area are correlated with one another.

The air temperature over coastal stations quite accurately, though not perfectly, reflects changes in SST. This work is limited to presenting the changes between annual SST and annual temperature at two stations located close to the Baltic coastline, that is at Stockholm and at Hel. The courses of annual air temperature at the stations located on the South and Central Baltic Sea are strongly correlated with each other. Dealing with greater number of stations will not contribute to the analysis.

In the whole, 152-year observational, period the coefficients of correlation between annual SST and annual air temperature at Hel and Stockholm are almost exactly the same (r equals 0.7611 and 0.7562 respectively) and what is obvious they are highly significant. In the same period the annual temperature at Stockholm and Hel indicates visibly stronger correlation ($r = 0.8675$, $p < 0.000001$). It should be pointed out that the forced decrease in the amplitude of changes in SST in the range of minus temperatures causes that the value of coefficient of correlation between both annual values of temperature becomes lower and the correlation between annual air temperature and SST cannot be perfect. It happens because SST cannot drop below the freezing point/temperature of water of given salinity, whereas the winter air temperature can fall considerably below 0°C.

The course of annual air temperature at Stockholm and Hel stations and annual SST adjusted by 13-point moving average is presented by Fig. 16.5. It can be clearly seen that there is considerable decrease in amplitude of SST in relation to the amplitude of air temperature.

Greater discrepancies between the course of air temperature and SST are marked at the initial segment of the examined course – more or less[13] to the 1920s. The air temperature in this period increases and SST drops. Also in the period 1854–1894 more significant differences in the course of annual air temperatures between Stockholm and Hel are noted. It is difficult to find the reasons for such discrepancies at this stage. However, it is worth mentioning that the series of annual air temperature at Stockholm before making the series homogeneous[14] shows clearly fewer discrepancies with the course of annual SST in the period from 1900 to 1950, and in the whole period 1854–2000 in which the data were not verified and made homogeneous, the series is a little more correlated with annual SST ($r = 0.7812$, $p < 0.000001$) than the verified series.

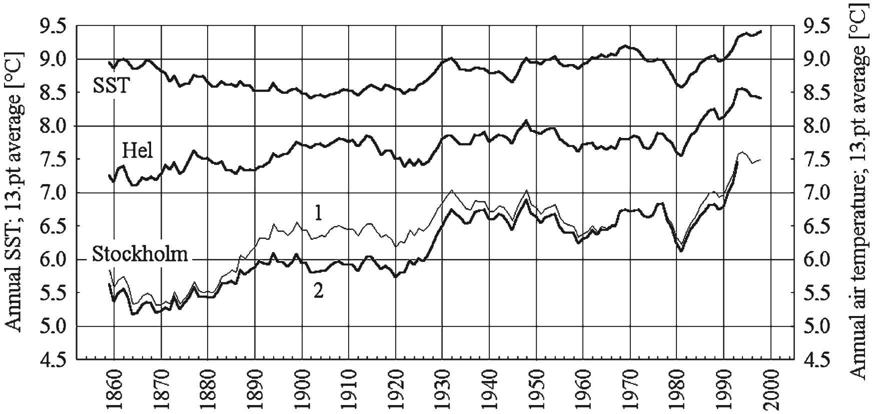

Fig. 16.5 The course of annual SST in grid 56°N, 18°E and annual air temperature at Hel station and Stockholm (1 – homogeneous series, 2 – series not made homogeneous). The courses adjusted by 13-point moving average

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[13] As both courses have been adjusted by 13-point moving average, more precise defining the limit of discrepancies is unnecessary.

[14] It a series from the period 1854–1995, from the year 1996 to 2000 amended with official data from the station in Stockholm.

Table 16.2 Values of coefficients of correlation (r) between annual SST and annual air temperature at Stockholm and Hel stations (Stockholm 1 – a series of data verified and made homogeneous, Stockholm 2 – a series without statistical filtering) and Hel (a series of data verified and made homogeneous) in consecutive 30-year periods. All values of coefficients of correlation in the table are statistically significant with $p<0.005$, larger than 0.6 with $p < 0.000$

Period	n	Stockholm 1	Stockholm 2	Hel
1854–1880	27	0.6665	0.6612	0.5529
1881–1910	30	0.6085	0.7022	0.7287
1911–1940	30	0.8950	0.9044	0.8272
1941–1970	30	0.8098	0.8240	0.7381
1971–2000	30	0.9276	0.9262	0.9137

The analysis of correlations between annual air temperatures at Stockholm and Hel and SST in the examined grid carried out for consecutive 30-year periods (the same for which the analysis of correlations with NAO was made) indicates that these correlations are non stationary in the function of time. The values of correlation coefficients are presented in Table 16.2.

It can be noted that the strength of the correlations of annual air temperature at the Baltic stations is greatest in the 30-year period 1971–2000. As opposed to correlation between SST and NAO in the years 1911–1940 when the strength considerably decreased (see Table 16.1), the relations between the air temperature and SST in the same 30-year period were clearly stronger and the statistically significant decrease in the strength of the correlations was observed in 30-year period 1941–1970. Due to the fact that the period 1971–2000 is characterised by mild winters and the period 1941–1970 by severe winters, it can be assumed that in the periods in which there is an increase in the frequency of mild winters there is also stronger convergence of the course of annual air temperature with the annual SST of the Baltic Sea.

16.7 The Problem of Climatic Signal in Series of Values of Mean Annual SST of the Baltic Sea

In order to explain what signal or climatic signals are carried in annual SST of the Baltic Sea, the series was analyzed in a way that is typical of signals analysis used in tracing courses of electric values (Osiowski and Szabatin 1995). Because it is not clear what the interference and what the signal in the course of annual SST of the Baltic Sea is, it is not acceptable to make any *a priori* assumptions in this respect. That is why it is also unacceptable to employ preliminary filtering of the series of data and the analysis is carried out on standard data without their further transformation.

The spectral analysis detects in the examined series presence of periodicity. Apart from long term periodicity, equal to the whole length of the series (152 years), a half of the length (76 years) and a quarter of the length of the series (35.5

years), which are normal statistical artifacts connected with Fourier analysis, indicates also short term periodicity. They ar e ~12.4-year periodicity, ~7.7-year periodicity, ~5.0- year periodicity and about 2-year periodicity.

The 12.4 periodicity is dominating as far as amplitude is concerned; on a spectral density scale it reaches the value of about 5.4 and is higher than all long term harmonics (see Fig. 16.6). Smaller amplitude can be noted in 7.7 – year and 5.0-year periodicity (4.7 and 4.9 on the scale of spectral density respectively). The smallest amplitude has the approximately 2-year periodicity (2.9 on the scale of spectral density).

12.4-year periodicity whose peak is made up of 13.1-year, 12.4-year and 11.3-year periodicities can be associated with the changing activity of the Sun. It falls into the range 10–13 years characteristic for the variability of Wolf number whose average periodicity in the years 1700–1995 was defined as 11.1 years. A great number of works (e.g. Boryczka 1998; Black et al. 1999; White et al. 1997; Boryczka et al. 2001; Coughlin and Tung 2004) indicate that there are statistically significant correlations between the changeability of the Sun activity and changeability of individual climatic elements and the intensity of some oceanic and troposphere processes. In spite of the fact that the changeability of solar constant connected with the changeability of the Wolf number is very small (less or about 0.1% of the constant; Kristjansson et al. 2002) and the changes in radiation can only be observed in UV band, which causes that the mechanisms of this changeability influence on the course of atmospheric processes are not clear, Foukal (2002) shows that these little changes in radiation explain about 20% variances of changes in global temperature in the period 1915–1998.

The ~7.7-year periodicity, with the peak values of spectral density made up of 7.3-year, 7.7-year and 8.0-year periodicity can be associated with, so called,

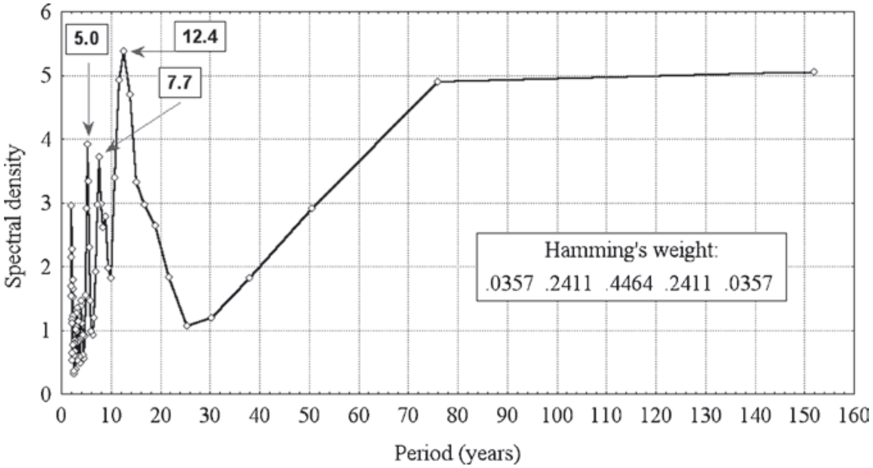

Fig. 16.6 The results of spectral analysis of standardized annual SST (adjusted by 5-element Hamming filter). The marked periodicity of peak values of spectral density (years)

'quasi -8-year periodicity',[15] commonly recognised from the course of air temperature over Poland and the neighbouring regions (Kożuchowski and Marciniak 1994; Żmudzka 1995; Boryczka 1998; Kożuchowski 2000; Fortuniak et al. 2001) and the course of some natural processes indicating stronger correlation with the course of air temperature (e.g. sea ice formation; see Kożuchowski and Girjatowicz 1997) or with the increase in wind speed (e.g. the number of winter storms over the Baltic Sea).

The quasi -8-year periodicity marked in the course of temperature is connected with the course of circulation processes present over the region of the Atlantic and NW Europe- primarily with NAO. Boryczka et al. (2000, 2001) define the periodicity of NAO CRU index (Jones et al. 1997) for the period from December to March as 7.7-year periodicity and for one year as 7.8-year. Marsz (1999) finds 7.78-year periodicity for one year in the course of Hurrell NAO index. Fortuniak (2000) appoints the limit of statistically significant quasi-7-year (7.37) periodicity in the course of air temperature over Europe; the area of the South Baltic Sea is covered by this scope.

The ~12-year and ~7–8-year periodicity are so strong that their presence can be found in the course of annual SST of the Baltic Sea adjusted by 13-point moving average. This kind of filtering, to a great extent, suppresses periodicity shorter than 13 years.

The ~5-year oscillation noted in the course of annual SST of the Baltic most probably originates from beating up (sum) of basic harmonics; ~7.8 years and ~12.4 years. The occurrence of about 2-year oscillation in connected with the changeability of SST of the Baltic Sea from year to year.

If the 12-year periodicity is really connected with the changing activity of the Sun (Wolf numbers) then it would mean that this signal is most clearly marked in periodical components of changes in annual SST. However, the changeability in the number of sunspots in the examined period is very weakly correlated with the course of the annual SST ($r = 0.18$, $p < 0.02$). The changeability of the number of sunspots[16] explains only 3.3% variances of annual SST in the entire 152-year period. The winter atmospheric circulation is on the second place with regard to amplitude of modulating signal, despite being strongly correlated with the course of annual SST, it explains a dozen or so % variances of SST in the same period. It is a kind of paradox.

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[15] In a yearly course in a series made up of 152 consecutive values a strong signal of 7.7-year period is detected. In the course of seasonal values of SST (January–March, July–September, and October–December) and in monthly courses of the same duration statistically significant or less frequently not significant periodicity falling into the periods from 8.09 years to 7.19 years can be found. The authors think that too much attention should not be paid to slight differences in the duration of the periods noted here. It is enough to change the length of the analyzed series (shorten) by 1-5 and the spectral analysis detects in the same series periodicity about 0.1–0.3 years different from the one defined earlier

[16] Data from National Geophysical Data Center, Solar-Terrestrial Physics Division (E/GC2), Boulder, Colorado.

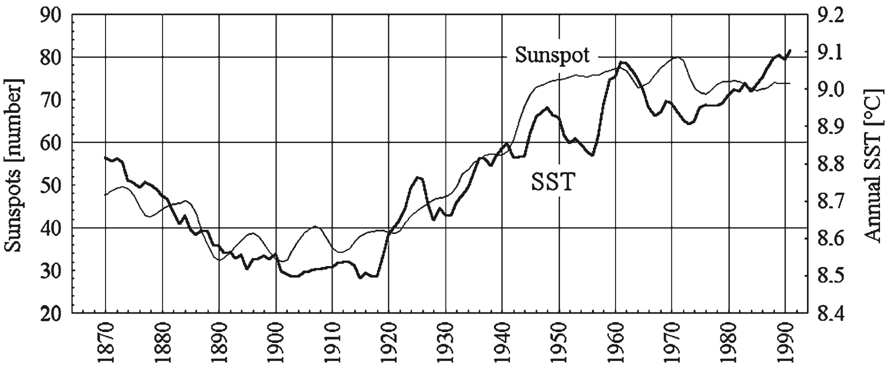

Fig. 16.7 Adjusted by 31-point moving average courses of annual values of SST in grid 56°N, 18°E and annual number of sunspots (1854–2005)

However, if the problem of long term activity of both modulating components is considered, this paradox becomes even more puzzling. Because the periodicity connected with the changing activity of the Sun falls within the limits of 11–13 years, in order to filter this changeability and to find out sub-trends a longer filter of doubled periodicity should be used. Here 31-point moving average of chronological series of sunspots number and annual SST was used. The picture that is obtained (see Fig. 16.7) seems to suggest that the long term changeability in the number of sunspots can really attribute, together with changeability in the character of winter atmospheric circulation, to long term changes in SST of the Baltic Sea and influence the occurrence of long term sub-trends in series of SST. If this conclusion is true, it can mean that the increase in annual SST from the 20s to the 30s of the twentieth century can also be influenced by the increase in the Sun activity. The same analysis carried out to explain if there are similar correlations between winter (January–March) NAO CRU index and the changing activity of the Sun does not find any correlations between these elements.

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