Problemy Klimatologii Polarnej 19

2009 7 – 31

OCEANIC CONTROL OF THE WARMING PROCESSES IN THE ARCTIC – A DIFFERENT POINT OF VIEW FOR THE REASONS OF CHANGES IN THE ARCTIC CLIMATE

KONTROLA OCEANICZNA PROCESÓW OCIEPLENIA ARKTYKI – ODMIENNY PUNKT SPOJRZENIA NA PRZYCZYNY ZMIAN KLIMATU W ARKTYCE

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Abstract. The paper describes the strong correlation between the sea surface temperature (SST) in the region of the Gulf Stream delta and anomalies in surface air temperature (SAT) in the Arctic over the period 1880-2007. This correlation results from the transfer of a variable amount of heat from the Atlantic tropics into the Arctic through oceanic circulation (AMO – Atlantic Multidecadal Oscillation). Reaction of sea ice is the main mechanism controlling the heat content in water carried to the Arctic and influencing the SAT. Sea ice may either increase or limit the heat flow from the ocean to the atmosphere. The genesis of the 'Great warming of the Arctic' in the 1930s and '40s is the same as that of the present day. Both may be considered to be attributable to natural processes and are not demonstrably associated in any way with a supposed 'Global greenhouse effect'. Changes in the concentration of CO_2 in the atmosphere could only explain 9% of variations in the SAT in the Arctic.

Key words: Arctic, Gulf Stream delta, warming, air temperature, SST, natural factors.

1. Introduction

1.1. Changes in the Arctic air temperature

The course of air temperature anomalies in the Arctic plotted on the anomalies of air temperature in the Northern Hemisphere shows that the amplitude of changes in the Arctic exceeds those several fold. In the instrumental observation period 1880-2007 (when the changes in the Arctic air temperature may be regarded as reasonably reliable; Hansen *et al.* 1999, 2001; Lugina *et al.* 2006; Overland *et al.* 2004a) there are several periods when surface air temperature (SAT) underwent distinctive and repetitive changes. These are (Fig. 1):

1. The period 1880-1918 when the SAT was maintained at a low level - in contrast to the considerable interannual fluctuations in air temperature. Some researchers (e.g. Overpeck *et al.* 1997) regard that period as the last manifestation of the Little Ice Age, delayed at high latitudes in comparison with its termination in the temperate zone.

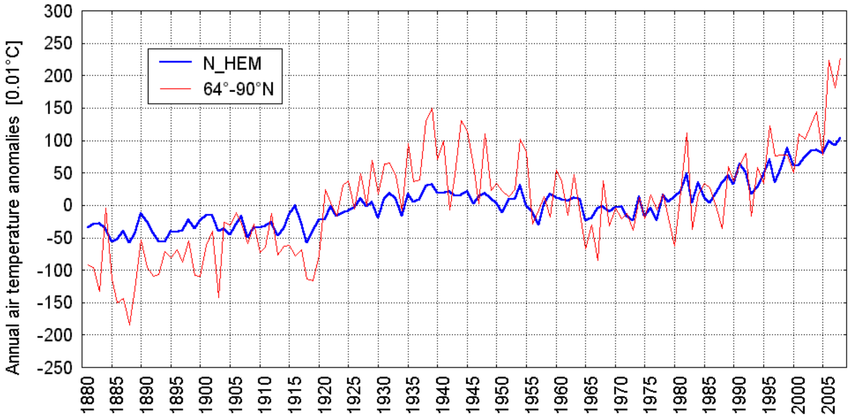

Fig. 1. Annual air temperature anomalies (SAT; 1880-2007) according to GISS-Temp data. N_HEM – Northern Hemisphere, 64°-90°N – at latitudes 64-90°N, regarded as the Arctic

Ryc. 1. Roczne anomalie temperatury powietrza (SAT; 1880-2007) według danych GISS-Temp. N–HEM – półkuli północnej, 64°-90°N – w strefie szerokościowej 64-90°N utożsamianej z Arktyką

2. The period from 1919 to the 1950s, when the SAT having increased rapidly at first (reaching its maximum in 1938-1939 and again in 1944) then rapidly declined. This period has been named previously 'The great warming of the Arctic' (e.g. Budyko 1971). At the warming peak, the annual SAT over the whole area of the Arctic increased by 1.5 to 2°C. The highest increase in the SAT in that period was noted on Svalbard where, according to Scherhag (1939) the SAT from November to March (NDJFM) in 1921-1930 was about 3.5°C higher than the multi-year average. In the same period it was estimated that the annual warming in the region of Svalbard – Franz Joseph Land was at least 2.5°C and a considerable retreat of the sea ice border in the northern part of the Barents Sea, the Kara Sea, the eastern part of the Laptev Sea and the western part of the East Siberian Sea was noted (Lamb 1972, Fig. 7.3, page 261).
3. Period of distinct cooling in the 1960s and 1970s. The SAT in the whole area of the Arctic (excluding only the basin of the Baffin Sea) decreased considerably, as did the interannual fluctuations. Compared with the preceding period the decrease in the annual SAT in the entire Arctic may be estimated as c. 1.0-1.2°C; however the SAT was clearly higher than that observed here on the turn of 19th and 20th century. Significantly, the lowest decreases in temperature were noted in the same region where the greatest increases were observed, i.e. in the Atlantic sector of the Arctic (ASA). Rodewald (following Dickson *et al.* 1996; Fig. 8) stated that in 1961-1970, during the cold season (DJFM) SAT in the region of Spitsbergen – Bjørnøya was 3.4°C lower, and in the region of the Franz Joseph Land 5.7°C lower than in 1951-1960.
4. The second phase of SAT increase has commenced since 1980. The distinct acceleration of SAT has been observed since the turn of 1980s and 1990s. The following local maximum and minimum values in the SAT course were progressive the increases in 1919-1939. In 2005, the mean annual Arctic SAT even exceeded the value which was noted during the 'The great warming of the Arctic' of the 1930s (Przybylak 2007). In 2006 and 2007 this SAT increase continued. Temperature

increase was accompanied by a marked decrease in the sea ice cover at the time of its minimal formation (September) that rapidly accelerated after 1997. After 1998 a rapid decrease in the mean annual sea ice cover extent was observed (Serreze *et al.* 2003, Stroeve *et al.* 2005). This period may be called the contemporary warming of the Arctic. Concurrently, there has been an increase in the SAT, which commenced in the ASA a few years sooner than in the other regions of the Arctic.

1.2. The reasons of the Arctic warming

Changes in the Arctic climate have been a subject of a very controversial debate for many years. The debate concerns both the evidence for and the range of changes but, primarily the reasons for climatic changes and their mechanisms (e.g. Overland *et al.* 2004b; Johannessen *et al.* 2004, Przybylak 2007). The dominance of an increased inflow of the Atlantic Water in the warming of the Arctic in the 1930s was recognized by Vize in 1937 (Alekseev 2003). Later works (e.g. Budyko 1969, 1971, 1974) sought to establish the main reasons for the SAT changes in factors controlling the radiation and thermal balance and focusing on the changes in the inflow of radiation controlled by the changes in the transparency of the atmosphere (e.g. those attributable to volcanism; Budyko 1971). A few works sought a reasons in changes in atmospheric circulation (e.g. Vangengejm 1952).

Recently it has commonly been assumed that the main reason for the observed warming is a ‘global greenhouse’, i.e. climatic changes in the Arctic simply represent a regional manifestation of global-scale anthropogenic influences over climate. High albedo can be observed in the Arctic when the following two conditions are fulfilled, i.e. there is an ice cover in the sea and snow cover on land. This results in very strong feedback between the radiation reaching the ground and air temperature and consequently in changes in sea ice and snow cover. This process leads to another increase in air temperature (e.g. Brooks 1950). This whole process is called ‘Arctic Amplification’ (AA). As a result a weak radiation impulse (input) produces very strong and delayed thermal effect (output). The AA is responsible for the high amplitude of changes in the Arctic SAT (much higher than on the hemispheric scale) whereas the global warming results from an increase in greenhouse gases concentration in the troposphere (Serreze and Francis 2006).

The supposed warming in the Arctic induced by a human activity is a concept well-supported by various models many of which incorporate an AA. However, when the greenhouse effect is assumed to be the principal factor, serious problems arise in respect of ‘The great Arctic warming’ of the 1930s. Most of the models do not attempt to reconstruct this warming because this increase in temperature was not accompanied by an increase in CO_2 concentration in the troposphere. Other models give too low rate of the SAT increase, different SAT trends and weaker than observed changes in atmospheric pressure (e.g. Moritz *et al.* 2002).

Delworth and Knutson (2000) have modeled changes in global temperature andreached a quite accurate reconstruction of the warming in the 1930s. In a regional context this was most clearly demonstrable in the highest latitudes of the Northern Hemisphere but it could not be applied to the lower latitudes. Because this simulation assumed the intensity of solar radiation to be constant and volcanic activity was neglected, Delworth and Knutson (2000) interpreted this warming period as the result of a very strong multi-decadal internal variability in the ocean-atmosphere system combined with a ‘greenhouse effect’.

The warming of the 1930s was also attributed to natural factors such as the increase in the frequency of W and SW winds over the Barents Sea, which led to the retreat of sea ice cover and resulted in a 'self-driven' mechanism of further increase of SAT in the ASA (Bengtsson *et al.* 2004). Alekseev *et al.* (2003) and Johannessen *et al.* (2004) supported this notion. However when analyzing the contemporary phase of warming they noted that the influence of a supposed 'greenhouse effect' must be greater than natural factors.

Venegas and Mysak (2000) noted a relatively strong periodicity lasting 6-7, 9-10, 16-20 and 30-50 years in the course of both ice development and atmospheric pressure. These periodicities explain 60-70% of the variation in multiannual courses and their character shows that there must be a natural variability. Polyakov and Johnson (2000), Polyakov *et al.* (2003b), Polyakov *et al.* (2004, 2005) have shown the activity of multidecadal climatic variability (LFO – Low Frequency Oscillation) that combines changes in the SAT, atmospheric pressure, winds, drifts, the extent of the sea ice and the circulation of the Arctic Ocean waters. . According to Polyakov *et al.* (2005) this LFO mechanism lasting 60-80 years has an internal character thus the temperature variability (at least in ASA) may have a natural character. This mechanism results partly from the interaction between the ocean and the atmosphere but oceanic processes (e.g. changes in water density) prevail (Polyakov *et al.* 2004; pages 4492-4493 and Fig. 4). Both phases of the Arctic warming are supposed to occur during a positive phase of the LFO whereas the negative LFO phases correspond to cooling periods. The positive (cyclonic) LFO phase creates conditions forcing an increased flow of Atlantic Water and heat into the Arctic (Polyakov *et al.* 2004).

Numerous researchers have noted that (regardless of any supposed 'global warming' effect) it is atmospheric circulation that has the principal influence on the variability of Arctic SAT. The NAO (North Atlantic Oscillation) or the AO (Arctic Oscillation) are treated as the prime drivers of the climatic changes (e.g. Overland *et al.* 2004b). It is frequently concluded that atmospheric circulation must control the SAT , whether directly or indirectly by influencing the direction and velocity of ice drift (Rigor *et al.* 2002), with or without any influence on the advection of Atlantic Water (Dickson *et al.* 2000, Houssais *et al.* 2007). However, such conclusions are normally found only in works which are based on a relatively short observation data, in most cases these starting after 1970 (see Rigor *et al.* 2000). It was noted that there is no consistence between the NAO phases and increases or decreases of SAT (Johannessen *et al.* 2004, Polyakov *et al.* 2003a, Styszyńska 2005, 2007). In the 1930s negative NAO indices prevailed, whereas in the period of contemporary warming NAO phases were strongly positive. In the long series (>100 years) the correlations between SAT at the Arctic stations and the NAO are very weak and not statistically significant (Polyakov *et al.* 2003a, Schmith and Hansen 2003). In the SAT series from the end of 20th century a very strong, positive trend of both AO and NAO and SAT has been noted. However, when the trend was removed from one of the series for the period 1980-2002, the correlations between AO/NAO and SAT were shown to have no statistical significance (Styszyńska 2005). This means that correlation of these series may be attributed to the long term trend and not to a common variance. The positive trend in the AO/NAO of recent years is no longer evident, although there is still a very strong positive trend in Arctic SAT and an even stronger negative trend in the ice cover (see 'the Arctic climate paradox', e.g. Overland and Wang 2005, Graversen 2006, Maslanik *et al.* 2007). Such picture casts doubt on AO/NAO as being the main or even one of the main factors which control the changes in the Arctic climate.

1.3. The role of oceanic circulation

Karcher *et al.* (2003) noted that in 1989-1994 and after 1999 the Atlantic Water carrying Norwegian, West Spitsbergen and North Cape Currents to the Arctic was warmer than normal. Styszyńska (2005) concluded that the principal reason for climate change in 1982-2002 in the ASA is simply the variable amount of heat imported by oceanic circulation. The impact of warm Atlantic Water is evidently prolonged and its activity influences air temperature, atmospheric circulation and ice development.

Changes of winter (JFMA) sea surface temperature (SST) in the Faroe-Shetland Channel inform on the heat resources transported to the Arctic with oceanic circulation. Analysis has shown that the SST variability there is influenced by the processes occurring in the Gulf Stream delta (Styszyńska 2005). The record of these processes is registered by SST variations in the northern part of the Gulf Stream delta. The delta of Gulf Stream covers the sea area SE of Newfoundland, the region towards S and E of the Grand Banks (~35-40°N, 45-55°W). In the delta bifurcation of warm and of highly saline water transported with the Gulf Stream occurs and three streams are formed (Barysevskaya 1979). The main part of the Gulf Stream water is directed SSE, towards the NE of the Sargasso Sea. The second branch in the form of weakly organized but vast streams is directed E. The third branch is directed N-NE and forms the North Atlantic Current. The volume of water transported into the Gulf Stream delta is variable, as is also the volume of water transported by particular branches of the current in the delta (Baranov 1979). When the volume of water transported in the S branch of the delta decreases, that transported along the N and E branches increases. The axis of the delta (together with the Gulf Stream joining it from the W) is displaced northward (Baryševskaya and Sinkevič 1979). The best indication of this northwards shift is an increase in the water temperature in the northern part of the Gulf Stream delta (Baryšvskaya 1983). The increase in the volume of water transported N and E results in an increase in the temperature of the water, which later forms the North Atlantic Current (the North Atlantic Drift Current; Rossby 1996). This water later feeds the Norwegian Current (Haugan *et al.* 1991, McCartney and Mauritzen 2001).

The reason why the volume of water transported in particular streams of the Gulf Stream delta varies has yet to be explained. Preliminary research into the S branch of the delta, which directs large quantities of water into the Sargasso Sea (Baryševskaya and Sinkevič 1979) suggest that atmospheric circulation and seasonal variability do not play any significant role in this. Any increase in the Gulf Stream flow before it enters the delta is followed (with a 3-4 month delay) by a decrease of flow in the S branch of the delta and by an increased flow in those streams which direct water to the E and N (Baryševskaya and Sinkevič 1979). A positive correlation between the shifting of the Gulf Stream whether to the Nor S and the NAO phases was found (Joyce *et al.* (2000). Thus, the variation of NAO phases when coordinated with the changes in the Labrador Current can control the shifting of the Gulf Stream. It may be also supposed that shifting of the Gulf Stream towards north or south may control the NAO phases and changes in NAO phases – the activity of the Labrador Current (Marsz 2008) Thus, in the course of the entire sequence of events, the amount of heat which reaches the Norwegian Current, thence to the Arctic Water is controlled by the processes present in the sub-tropical zone in the western part of the North Atlantic.

The aim of this work is to explain to what extent changes in the SAT of the whole Arctic are determined by oceanic processes observed in the delta of the Gulf Stream. This will allow to state: 1) to which extent the changes in the thermal regime of the Arctic are autonomous, 2) to which extent the variations are forced by the activity of external elements (originating outside the Arctic), 3) to which extent the processes of climatic changes observed in the Arctic reflect the natural processes as a consequence of internal variability in the Earth's overall climatic system and 4) the extent to which they reflect those processes which are made by humans.

2. Source Data

The analysis must be carried out for a long period with a long series of reliable data in order to explain all the above mentioned problems. The number of meteorological stations in the Arctic providing long time data changed (both in time and location) and is limited (Przybylak 2007). That is why it was decided to make use of series of annual temperature anomalies estimated for the zone of highest latitudes. Special attention was given to two series of annual SAT anomalies which are often used to compare the results of model simulation with observed courses. These data have been compiled by the GISS (NASA Goddard Institute for Space Studies) and by Lugina *et al.* (2006) for the CDIAC (Carbon Dioxide Information Analysis Center).

The GISS has supplied a series of Zonal-mean annual dTs[1] for 1880-2007 in the data set describing the area from 64°N to 90°N. The calculated annual temperature anomalies in this zone are based entirely on data from stations included in GHCN (Global Historical Climatology Network; Peterson *et al.* 1998). The methods of creating this data set and keeping control over its quality are described in papers by Hansen *et al.* (1999, 2001). The SAT anomalies in this data set are determined in relation to the mean values from the 30-year period 1951-1980. The data set of anomalies in SAT by Lugina *et al.* (2006) covers the period 1881-2005, anomalies are defined in relation to averages in 25 years (1951-1975). To calculate SAT anomalies this set uses data only from meteorological stations; data for the zone 60-90°N[2] were used. The Lugina *et al.* (2006) data set for the zone of highest latitudes makes use of a significantly larger number of stations than that of the GISS.

Although the SAT anomalies in these data sets were calculated for different periods and the southern borders for the highest latitudes were different, both data sets in its common part (1881-2005) describe the same variable (correlation coefficient $r = 0.98$, $p<<0.000$). A comparison of these two sets on a scatter plot shows that there are no values which are to be regarded as outliers. Thus, when taking into consideration the characteristics of the course of temperature variability at the highest latitudes zone the differences between the data sets may be disregarded. As the GISS data set is several years longer, it was decided to use this in further analysis. The comparison of the course of annual air temperature (from different periods) at certain Arctic stations with the series of anomalies included in the GISS data set suggest that there are quite high, and, certainly, in each case, significant, positive correlations. Later, in this paper the values of air temperature anomalies from this data set will be referred to as 'air temperature anomalies in the Arctic' or in short – 'Arctic temperature'.

In the few cases in which detailed problems were solved the SAT data from weather stations were also used. These data sets were obtained from the Nordklim (Tuomenvirta *et al.* 2001), GHCN-monthly v.2. (Peterson *et al*. 1998), RIHMI-WDC (Russian Research Institute of Hydromoteorogical

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[1] Data source: http://data.giss.nasa.gov/tabledata/ZonAnn.Ts.txt

[2] Data source: http://cdiac.esd.prnl.gov/trends/temp/lugina/lugina.html

Information – World Data Center – Obninsk), AARII (Arctic and Antarctic Research Institute, Saint Petersburg, Russia) and the SAT station data set[3] from Overland *et al.* (2004a).

The SST data were taken from ERSST v.2 data set[4] (Smith and Reynolds 2004), which gives mean monthly values in a 2x2° grid. The accuracy of SST estimation is variable and (according to Smith and Reynolds 2004), for the period of 19th century is not better than ±0.4°C, for the first half of 20th century, ±0.2°C, and period after 1950 at least not lower than ±0.1°C. SST anomalies are calculated with the reference to climatic norms of SST from different periods (Xue *et al.* 2003). Their values in a given grid and in a given time are not the same. This depends on the period for which these values were averaged. That is why this paper made use of only 'raw' monthly values of SST. In a given grid variability in records of SST anomalies and records of 'raw' values of SST is identical.

The source of sea ice cover data is the NSIDC (National Snow and Ice Data Center). The sets characterizing ice cover of the Arctic are not continuous and data are of variable quality. The satellite data have been recorded since 1972; however, data sets which are good and equally reliable for all months of the year started only in 1978. They present results which are slightly different, depending on the algorithms used for estimating sea ice area. Furthermore, particular sets have a different time resolution and different spatial organization, which makes a direct comparison of results impossible. In this respect, the most important data sets used are NSIDC: Sea Ice Index (SII; Fetterer and Knowles 2002/2004) and Daily and Monthly Total Sea Ice Extent and Total Ice-Cover Area from GSFC: Bootstrap Algorithm – Monthly Summaries (Dedrick *et al.* 2001).

The older data sets for the period 1900-1996 are Russian and cover only about 77% of the Arctic Ocean area within its formal border, together with marginal seas adjacent to the Russian coasts and with the Barents and Greenland Seas (Zakharov 1997, Johannessen *et al.* 2004). In the following parts the footnotes will specify which data sets are referred to.

3. The 'tropical signal' and its relationship to air temperature in the Arctic

Styszyńska (2005) concluded that earlier changes in thermal conditions of water located in the northern part of the Gulf Stream delta relate to variability of heat resources in the water transferred to the Norwegian Current. The SST defines the amount of heat transported to the Gulf Stream delta. This is referred to in this paper as the 'tropical signal'. The value of common variance in both series can be a measure of how the 'tropical signal' and SAT variability in the Arctic are correlated. A simple measure of common variance is the coefficient of determination, which is the second power of the Pearson linear correlation coefficient. The value of the correlation coefficient between SST and the series of anomalies in the annual Arctic SAT may be regarded as a measure of the strength of the 'tropical signal'.

The tropical signal which informs us about the heat resources in waters proximal to the Gulf Stream delta (which are further redistributed in the delta and then only partially reach the Arctic) is very strong. The strongest signal can be found in the series for the region 35-39°N, 57-51°W (Fig. 2). The annual

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[3] Data source: http://www.unaami.noaa.gov/analyses/sat/

[4] Full name of Data Set: NOAA NCDC ERSST version2: Improved extended reconstructed global sea surface temperature data based on COADS data. Data source: http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.ERSST/.VERSION2/

SST in these series is correlated with the series of annual anomalies of Arctic SAT at level 0.60. Over the length of this series (128 years), the values of correlation coefficients are statistically highly significant ($p << 0.000$).

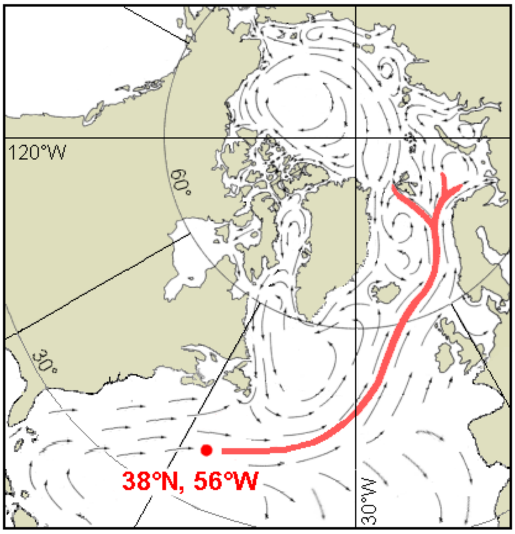

Fig. 2. The location of the grid 38°N, 56°W and the distribution of sea currents in the North Atlantic and Arctic

Ryc. 2. Położenie gridu 38°N i 56°W oraz rozkład prądów morskich na północnym Atlantyku i w Arktyce

In grids located at 38°N, 52-56°W (in the area where the Gulf Stream flows before entering the delta) the strength of the tropical signal reaches its maximum. The mean values for February, August and September reflect the transported heat content for any given year in its finest expression way. This form of mean 'informative value' (which should not be confused with a mean annual SST) results from the annual cycle of changes in the SST and enables us to identify increased or decreased content of heat advection in the waters. The mean SST for February, August and September in a year k is marked as $GL_{(k)}$

$$GL_{(k)} = (SSTFeb_{(k)} + SSTAug_{(k)} + SSTSep_{(k)})/3. \qquad [1]$$

An analysis of the spatial distribution of correlation coefficients indicates that the strongest tropical signal is included in the time series GL at 38°N, 56°W grid ($r = 0.65$).

Styszyńska (2005, 2007) showed that changes in mean winter (JFMA) SST in Faroe-Shetland Channel [62°N, 2°W] and in the Norwegian Current [67°N, 10°E] from year k influence the annual SAT at the stations in the ASA in same year from which the data originate (year k) and also in the following year (k+1). Apparently, this delayed action of SST is associated with a delayed increase of heat resources in waters of the Greenland and Barents Seas, which reduces the extent and concentration of sea ice and increases heat transfer from the ocean to the atmosphere. The delayed influence of variable heat resources in the water on ice and on SAT in the ASA is especially well-marked in November and December of the following year (k+1). As a result, the index being the mean value of winter temperature (JFMA) in waters in Faroe-Shetland Channel from the preceding year (k-1) and the present year (k) shows the strongest correlation with the SAT in the year k.

The time gap before part of tropical waters directed to the N branch of the Gulf Stream delta current reaches (after many transformations) the Faroe-Shetland Channel and as the Atlantic Water, to the Arctic is significant. Before reaching the Arctic, these waters lose different amounts of heat on their way. Part of this heat, transported via atmospheric circulation, reaches the Arctic (most often the ASA) resulting in some, difficult to be assessed in a quantitive way, influence on the SAT.

This signal moves very quickly but its operation is spread in time. This signal cannot be attached to any concrete month, season or year or to any specified sea area. Also the same water (together with its heat resources) carried with the system of oceanic circulation to the Arctic has delayed influence which is much spread in time. Thus, the rate of heat signal propagation (which later indicates some correlations with SAT in the Arctic) cannot be defined clearly. It may be assumed that the time of that propagation is not shorter than 3 years.

An index was defined informing both on the relative heat content imported via the Gulf Stream delta to the North Atlantic Current (and next with the Norwegian West Spitsbergen and North Cape Currents into the Arctic) and on the heat transferred later by these waters to the atmosphere. This index, here defined as DG_{3L}, will be calculated for a year k as the balanced value[5] of three consecutive GL values – from a present year (k; the year in which the SAT anomalies were noted), from the preceding year (k-1) and the two years previous to this (k-2):

$$DG_{3L(k)} = ((0.43 \cdot GL_{(k)} + (0.32 \cdot GL_{(k-1)}) + (0.25 \cdot GL_{(k-2)})). \qquad [2]$$

During the 128-year series (1880-2007) the linear correlation coefficient between the DG_{3L} index and the series of annual SAT anomalies in the region 64-90°N (GISS; Hansen *et al.* 1999, 2001) is 0.73 ($p<<0.000$). The variability of the tropical signal explains 53.8% variations in SAT in the Arctic region. The correlation of the index with annual SAT anomalies in the region 60-90°N (Lugina *et al.* 2006) in a 125-year series (1881-2004) is nearly the same ($r=0.72$) and is statistically equally significant ($p<<0.000$, $r^2=0.51$).

When the course of the DG_{3L} values compared with the course of Arctic SAT anomalies is presented in Fig. 3. A scatter plot of DG_{3L} values in relation to SAT anomalies is shown in Fig.4. In Fig. 4 were marked 5 outliers. The estimation of the regression parameters (without elimination of the outliers) indicates that the change in DG_{3L} by 1°C in any given year k is followed by a change in Arctic SAT anomalies in the same year by 1.604(±0.132)°C.

In the course of Arctic SAT anomalies ($A_{64-90°N}$) and DG_{3L} (Fig. 3) a far reaching correlation may be observed. This correlation is clearly marked in the run of long-term component. By contrast the correlations of short-term runs are far less obvious and only in a few may corresponding fluctuations be identified. The weakest agreement between the short term runs was noted in 1880-1917. It may be caused by a low quality of data. The course of SST in this period is more reliable than the course of the SAT anomalies. Owing to the paucity of meteorological stations present in the Arctic at that time and their extremely uneven distribution, the calculated SAT anomalies for the highest latitudes are significantly less reliable.

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[5] A 3-element triangular filter (s=3/4) was used here. Its coefficient values were adjusted to non-standard series. The value of the index itself although by default expressed in temperature units, does not denote temperature in a physical sense, but defines the variability of the tropical signal. The coefficient of correlation between the annual SST at 38°N, 56°W grid and the DG_{3L} is 0.85 ($p<0.000$; $n=128$).

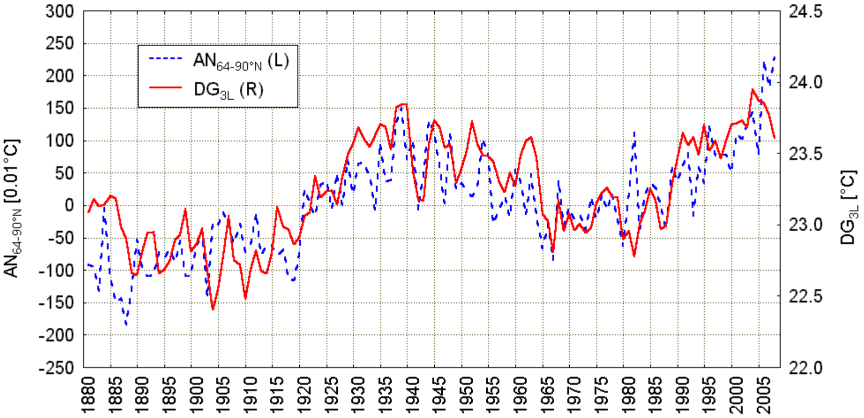

Fig. 3. Annual SAT anomalies in the Arctic (AN$_{64\text{-}90°N}$) and the values of the 'tropical signal' characterizing the heat content in the water before the Gulf Stream delta (DG$_{3L}$; 38°N, 56°W; see the text)

Ryc. 3. Przebieg rocznych anomalii SAT w Arktyce (AN$_{64\text{-}90°N}$) i wartości „sygnału tropikalnego", charakteryzującego zasoby ciepła w wodach przed deltą Golfsztromu (DG$_{3L}$; 38°N, 56°W; patrz tekst)

The location of the minimum and maximum values in the course of DG$_{3L}$ suggests five chapters in the course of the tropical signal:

1) the period 1880-1909 when DG$_{3L}$ values were low and characterized by a significant interannual variability; a statistically-significant falling trend is obvious (-0.015(±0.004)°C·year^{-1}; p<0.000). In this period the lowest recorded value in the course of DG$_{3L}$ (22.4°C, year 1903) was noted.
2) the period 1909-1939 when DG$_{3L}$ increased rapidly; the following increases were consequently higher than the observed decreases. The course was marked by a very strong and statistically very significant positive trend (0.042(±0.002)°C·year^{-1}; p<<0.000).
3) the period 1939-1966marked by decreases in relation to fluctuations of DG$_{3L.}$ In this period the following local maximum and minimum values became progressively lower. The most dramatic fall in DG$_{3L}$ was noted in the last 5 years of this period (1961-1966). The falling trend was weak (-0.012 ((±0.005)°C·year^{-1}) but still significant (p<0.02).
4) the period 1966-1981 when the mean values of (±0.002)°C·year^{-1}; p<<0.000)) were low, the range of interannual fluctuations was clearly limited and there was no obvious trend in the course of DG$_{3L}$ (around zero trend +0.002(±0.008)°C·year^{-1}; p<0.850).
5) the period 1981-2007 when another significant increase in the DG$_{3L}$ values was noted, especially dramatic in 1991-1993. The absolute maximum value in the course of DG$_{3L}$ was recorded in 2003 (23.95°C). After 2003 a decrease in the DG$_{3L}$ was observed in the following four years (2004-2007). The rising trend in the entire period 1981-2007 is strong (+0.034(±0.004)°C and is statistically highly significant.

Corresponding periods of changes in the Arctic SAT match these five periods of changes in the tropical signal. The cold period of 1880-1919 corresponds to the first period of changes in DG$_{3L.}$ The end of this period of 'cold' air temperature is clearly delayed in relation to the changes in the tropical signal, possibly by as much as 5-9 years. In the first period of changes in DG$_{3L}$, correlations between annual SAT and DG$_{3L}$ are negative and statistically not significant (r=–0.30, p<0.109).

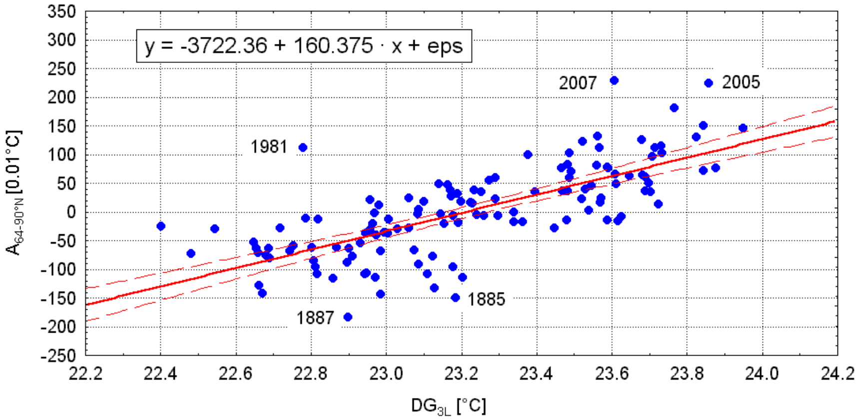

Fig. 4. The annual SAT anomalies in the Arctic (y; $AN_{64-90oN}$) as the linear function of the tropical signal DG_{3L}. The outliers (years) have been marked

Ryc. 4. Roczne anomalie SAT w Arktyce (y; $AN_{64-90^{\circ}N}$) jako funkcja liniowa sygnału tropikalnego (DG_{3L}). Oznaczono przypadki (lata) odstające

In the second period of changes in DG_{3L}, the correlations between DG_{3L} and SAT become strong and clear and they took place with only a 3-year delay. The correlation coefficient between these values is very high (r=0.83) and statistically very significant. The culmination of the DG_{3L} values relating to 1937-1939 almost entirely matches the culmination of the course of SAT anomalies (1937, 1938) but, subsequently in 1940-1941 there was a rapid drop in both DG_{3L} and SAT anomalies. In 1943 and 1944 the values increased again (Fig. 3).

The period of decreases in the SAT anomalies corresponds to the next period of falls in DG_{3L} (1939-1966), the correlation coefficient being relatively high (r=0.59) and statistically significant ($p<0.001$). In the 1966-1981 cooling period correlations between DG_{3L} and SAT become almost zero (r=0.09, p=0.750) although the plot shows a clear concordance of both courses. The explanation lies in the outlier, observed in 1981, the last year of that period during which a very strong positive anomaly in SAT corresponds to a sharp drop of DG_{3L}. This is the only case after 1909, when such considerable phase reversal of both courses occurred. However, if this case is disregarded, the picture is quite different – correlations again become strong and statistically significant (r = 0.64, $p<0.01$, n=15).

In the last period of present warming (1981-2007) the correlations with SAT anomalies become strong and statistically significant (r=0.56, $p<0.002$). The rapid increase in DG_{3L} in 1987-1991 corresponds to a rapid increase in the Arctic SAT observed in 1992-1995 (Przybylak 2002). The years 1981, 2005 and 2007 seem to be outliers in the scatter plot – SAT anomalies are higher in these years, and appear higher than it would theoretically result from the value of the tropical signal. However, by disregarding these cases, the correlation coefficient between DG_{3L} and the Arctic SAT anomalies increased to 0.74 (n=24, $p<0.000$), becoming equally as strong as the coefficient during the early phase of the first warming (1880-1909).

In the following periods of increases and decreases in the strength of the tropical signal changes in the Arctic SAT faithfully follow the changes in DG_{3L}. The first period was the exception but he general character of correlations between the DG_{3L} and SAT persisted – both values being lower than the mean. Such a close and statistically significant correlation suggests that the processes of the Arctic SAT changes are controlled by the variable amount of heat transported in waters by oceanic circulation. The earlier increase in heat resources in waters before the Gulf Stream delta was related to the warming of the Arctic observed in the 1930s, whereas cooling of the Arctic in the 1960s and '70s corresponds to the decrease in heat content. The last rapid warming of the Arctic, which started in the 1980s, is also related to the increase in the heat resources of waters before the Gulf Stream delta. Analyzing such courses of SAT and DG_{3L}, it is justified to state that both phases of warming of the Arctic in the 20th century have the same origin.

4. The mechanism of correlations between the 'tropical signal' and the Arctic SAT anomalies

The ‘tropical signal’ carries information on heat resources in waters that will later be transported into the Arctic. It was found that the heat resources in waters influence sea ice melting (Marsz 2007a). Subsequent changes in the sea ice concentration and cover are followed by a chain of processes resulting in climatic changes. Unfortunately, complete documentation of these correlations for the whole analyzed period (1880-2007) is not possible, as reliable data concerning the sea ice data are of too short duration.

The analyses of correlations between the time series DG_{3L} and the sea ice cover, as originating from different data sets and different periods, give consistent results regarding the occurrence of the strong and delayed correlations between DG_{3L} and sea ice properties. These relationship are so close that they merit a more detailed consideration.

The strongest correlations between DG_{3L} and sea ice extent are marked with a one year lag when the time serie DG_{3L} is one year earlier than the serie of sea ice extent[6]. This means 1-4 years delay in reaction of Arctic sea ice for changes in the heat resources of water in the Gulf Stream delta. Correlations between DG_{3L} and mean annual ice cover in the Arctic and that in September are compiled from the NSIDC data (Table 1). These correlations cover the period 1978-2007 (29 years).

The compilation of correlation coefficients shows clearly that the mean annual sea ice extent (SIE) in the whole region of the Arctic is very strongly correlated with earlier changes in DG_{3L}, whereas the SIE during the minimum ice formation (September) is less weaker. A similar picture emerges for the changes of SIE in the Arctic Proper. In respect of the American Arctic, the correlation between DG_{3L} and the SIE have the same positive or negative signs but they are weak and statistically not significant. They are similar to the correlations with SIE in September. The waters from the Gulf Stream delta transported with North Atlantic, Norwegian, West Spitsbergen and North Cape currents reach the Arctic Proper. The American Arctic is isolated from the direct inflow of these waters. If this fact is taken into consideration, then this type of distribution of correlation coefficients becomes clear. Also, this regionally asymmetrical distribution of correlation coefficients explains that neither the changes in the thermal regime of the Northern Hemisphere nor that of the Arctic (SAT anomalies) with which DG_{3L} is strongly correlated, can have any influence on the SIE in the Arctic. It is clearly the physical

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[6] Data set: gsfc.nasateam.month.extent.1978-2007.n, source: ftp://sidads.colorado.edu/pub/DATASETS/seaice/polar-stereo/trends-climatologies/ice-extent/nasateam/

influence of the heat content in water flowing from the Atlantic which controls the main features of the ice regime of the Arctic.

Table 1 – Tabela 1

The values of the coefficient of correlation (r) between DG_{3L} in the year k-1 and the mean annual and September sea ice extent in the water of the Arctic and its parts in 1978-2007

Wartości współczynników korelacji (r) między DG_{3L} a średnimi rocznymi i wrześniowymi powierzchniami zlodzonymi (extent) na wodach Arktyki i jej częściach (1979-2007)

	Whole region of the Arctic Cała Arktyka		Arctic Proper Arktyka Właściwa		American Arctic Arktyka Amerykańska	
	Mean annual Śr. roczna	September Wrzesień	Mean annual Śr. roczna	September Wrzesień	Mean annual Śr. roczna	September Wrzesień
r	–0,83	–0,74	–0.80	–0.74	–0.54	–0.41
p	0.000	0.000	0.000	0.000	0.002	0.027

The whole region of the Arctic – sea areas other than the Bering, Okhotsk and Japan Seas and the Gulf of St. Lawrence. The Arctic Proper – the Greenland, Barents and Kara Seas and the Arctic Ocean. The American Arctic – sea areas of the Canadian Archipelago, Hudson Bay and Baffin Bay. Classification according to NSIDC; p – level of the statistical significance

Według NSIDC cała Arktyka to akweny bez mórz Beringa, Ochockiego, Japońskiego i Zatoki Św. Wawrzyńca; Arktyka Właściwa – morza Grenlandzkie, Barentsa i Karskie oraz Ocean Arktyczny (Morze Arktyczne i jego morza marginalne: Łaptiewów, Wschodniosyberyjskie, Czukockie, Beauforta i Lincolna); Arktyka Amerykańska – akweny Archipelagu Kanadyjskiego, Zatoki Hudsona oraz Zatoki (Morza) Baffina; p – poziom istotności statystycznej

The NSIDC series is short but the quality of the data is excellent. To check if the obtained correlation is characteristic not only for the last part of the period analyzed (1978-2007) the Zakharov set[7] covering years 1900-1996 and describing ice cover on the 77% of the Arctic (from the Greenland Sea to the Chukcha Sea) was used (Johanessen i in. 2003, 2004). The quality of this data set is variable; Zakharow (1997) regards the period 1958-1996 as being perfectly reliable. However, that from the mid-1930s to 1958 contains data which are reliable but less accurate, earlier data are even less reliable. The correlation coefficient between DG_{3L} and the mean annual SIE, as recorded by Zakharov in this 97-year long series (1900-1996) amounts to –0.60 ($p<<0.000$). Such a high correlation coefficient for almost a century period indicates that the strong negative correlations between DG_{3L} and SIE are relatively stable in time – i.e. an increase in DG_{3L} causes, with a delayed reaction, a decrease in SIE (Fig. 5).

The most useful synthetic register which details the formation of ice cover in the area of the Northern Hemisphere the Sea Ice Index NSIDC (Fetterer i Knowles 2002/2004) presents monthly data from 1979[8]. This includes the data describing extent of the sea ice cover i.e. the sea area covered with ice of concentration more than 15% and the data regarding sea ice 'net area' (concentration 100%). With regard to any particular years there are statistically significant negative correlations

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[7] Data Source: http://nwpi.kre.karelia.ru/climas/Ice/Ice_nosat/XX_Arctic.htm.

[8] Data Source: http://nsidc.org/data/g02135.html: sets: ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/.

between monthly sea ice extent and the DG_{3L}. The maximum correlation was found in June (r=–0.79, n=29) and in December-June these correlations were higher than 0.7 (Fig. 6). Of course, it is June when the Sun's elevation is at its highest and the radiation to the surface is at its greatest intensity. Strong negative correlations in June mean that, in years with higher values of DG_{3L}, heat accumulation takes place over a large sea area. This water surface of little albedo absorbs much more energy (in relation to for e.g. August). Furthermore, an increase in the ice free area in the winter season (DJFM) means that there is an increased heat flow from the ocean to the atmosphere, and consequently an increase in air temperature.

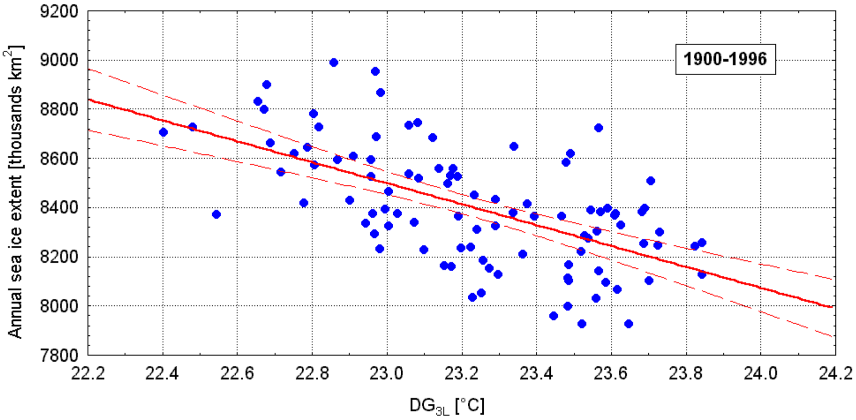

Fig. 5. The correlation between the annual sea ice extent in 77% of the Arctic Ocean (Zakharov data set; 1997) and the value of the tropical signal (DG_{3L}) in 1900-1996

Ryc. 5. Związek średniej rocznej powierzchni lodów na 77% powierzchni Oceanu Arktycznego (zbiór Zakharova; 1997) z wartością sygnału tropikalnego (DG_{3L}) w latach 1900-1996

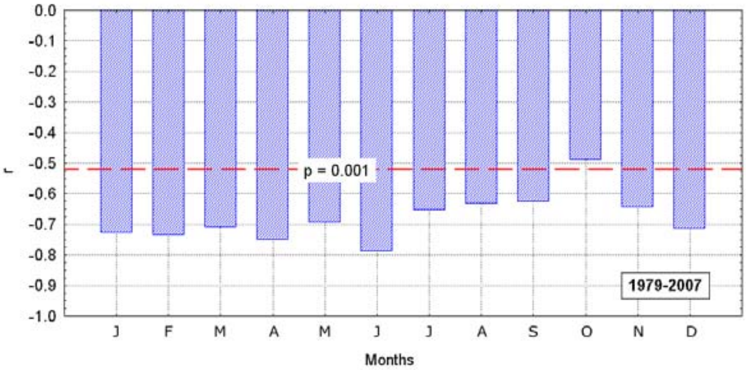

Fig. 6. The distribution of linear correlation coefficients (r) between the value of the tropical signal (DG_{3L}) and the monthly values of the sea ice extent in the Arctic. p – level of the statistical significance

Ryc. 6. Rozkład współczynników korelacji liniowej między wartością sygnału tropikalnego a miesięcznymi wartościami powierzchni zlodzonej w Arktyce [1979-2007]. p – poziom istotności statystycznej

In terms of the sea ice extent and net area the NSIDC set gives a pictures similar to that of the Sea Ice Index. The relationship of the net area to the extent of the sea ice gives approximate information about the mean ice concentration in this area. When calculated in this way there is also a positive correlation between the ‘tropical signal’ (DG_{3L}) and ice concentrations in particular areas. But there is main regional variation and, for the purpose of this paper, only the correlations for the Arctic Ocean and the Barents and Kara Seas are given (Fig. 7).

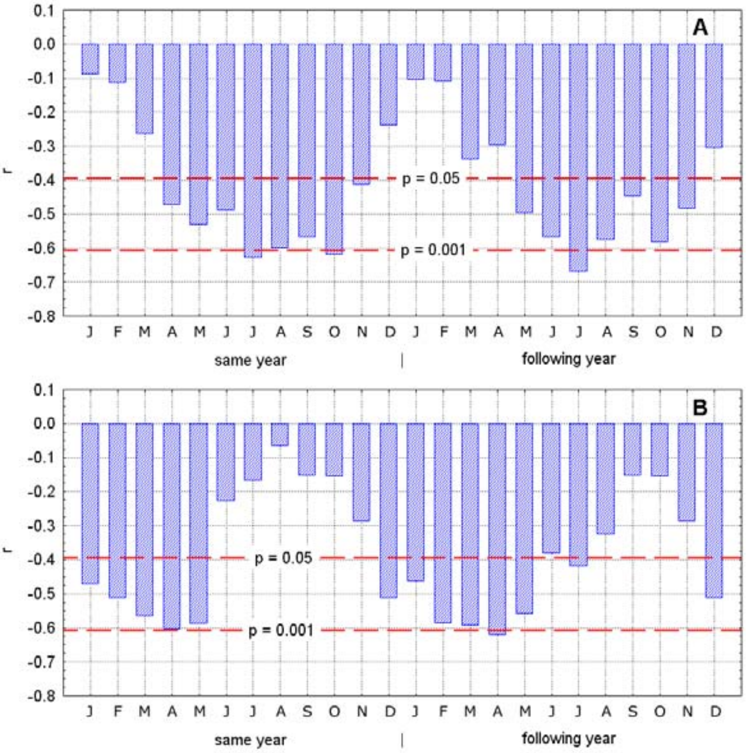

Fig. 7. The distribution of correlation coefficients (r) between the value of the tropical signal (DG_{3L}) and the monthly values of sea ice concentration in the same and in the following year in: A – the Arctic Ocean, B – the Barents and Kara Seas. With respect to both sea areas there is an obvious shift of the maximum strength of these correlations; in the Barents and Kara Seas, the maximum in strength of these correlations falls during the spring months and, in the Arctic Ocean, during summer months and at the beginning of autumn

Ryc. 7. Rozkład współczynników korelacji między wartością sygnału tropikalnego (DG_{3L}) a wartościami miesięcznych koncentracji lodów w tym samym roku i roku następnym na: A – Oceanie Arktycznym, B – morzach Barentsa i Karskim. Zauważalne „rozciągnięcie” oddziaływania w czasie na obu akwenach oraz przesunięcie w czasie maksimum siły związków; na morzach Barentsa i Karskim maksimum siły związku przypada na miesiące wiosenne, na Oceanie Arktycznym na miesiące letnie i początku jesieni

On the surface of the Arctic Ocean (with included the Laptev, East Siberian, Chukcha, Beaufort and Lincoln Seas) the strongest correlations between the ice concentration and DG_{3L} are recorded for summer and autumn months (Fig. 7). This is attributable to the decrease of ice concentration, mainly in the adjacent seas during years in which an increase in DG_{3L} is evident. The stronger correlations

DG_{3L} with the sea ice concentration in the Arctic Ocean in November and December are demonstrable in the year following that in which the DG_{3L} was recorded. It may be interpreted as delayed direct reaction of DG_{3L} but it may also be result of the increased accumulation of solar heat in the sea water during the summer when the ice concentration is lower (indirect control of DG_{3L}). In the Barents and Kara Seas, the strongest positive correlations of ice concentration and DG_{3L} have been noted during winter and spring months, both in the same year when DG_{3L} was recorded and also in the following year. This indicates that an increase in the value of DG_{3L} in a given year causes the decrease in the ice concentration during winter and spring seasons also in the following year (Fig. 7).

Thus, a change in the strength of the tropical signal (DG_{3L}) is reflected both in the changes in the sea ice covered area, as well as in the changes in ice concentration. Changes in the ice extent and concentration are reflected in the values of SAT and they are both synchronic and asynchronic (occurring with delay in relation to changes of sea ice area and concentration). The generally-recognized rule is that the winter (JFM) SIE anomalies correspond to the SAT anomalies, both negative and positive in spring and beginning of summer (AMJ). The summer SAT anomalies are reflected in the SIE anomalies in the following autumn and beginning of winter (Alekseev 2003). A consequence of these correlations is that the tropical signal DG_{3L} shows strong correlations with both monthly and annual SAT records at the Arctic stations. However, there are considerable regional variations; as expected, the strongest are observed in the ASA, the weakest at the stations located in the Pacific sector (Fig. 8). The more distant the coast lines of the Arctic Ocean and its adjacent seas (Siberian, Canadian Arctic, Alaska) the weaker are correlations; this indicates that the observed increases in air temperature on land must be controlled by other mechanisms.

The heat and salt contents in the sea water have the primary role in controlling changes in the area and concentration of sea ice during autumn and at the beginning of winter. When they are lower the flow of a strong heat stream from the ocean to the atmosphere is promoted. This results in an increase of air temperature during the autumn and winter. Ice thickness is influenced by the winter air temperature, as indicated by the number of frost degree-days. The most rapid rate of the ice thickness growth takes place at the early stage of ice formation. When the ice thickness increases, the influence of frost degree-days total in the following months on the ice thickness decreases (a non-linear correlation) which is why the most important role in the sea ice thickness has the course of SAT at the first stage of winter season.

When owing to winter increase in SAT the ice thickness is reduced an earlier decrease in ice concentration and appearance of ice free water is observed . This leads to an increase in heat accumulation in the sea water and a further increase in SAT in the spring season. Because heat accumulation in the sea water in the summer season does not result in any significant increase in SST, the SAT over sea areas does not increase as much. After the summer warming the accumulated heat content is the first to be transferred to the atmosphere. This causes further increases in temperature in the autumn. The activity of the intra-system mechanism accumulates with the activity of the forcing factor (i.e. DG_{3L}) and the first feedback loop is closed in the annual cycle.

The influence of the air temperature on the Atlantic Water presented here is simplified. The authors do not discuss the problem of the increase in heat content in the Intermediate Arctic Water associated with the changes in DG_{3L}. The influence of the stamping out of the pycnocline (halocline; Steele and Boyd 1998) on the reduction of the ice extent and the consequences of this process on changes in the air temperature (Wu *et al.* 2004) are also not discussed.

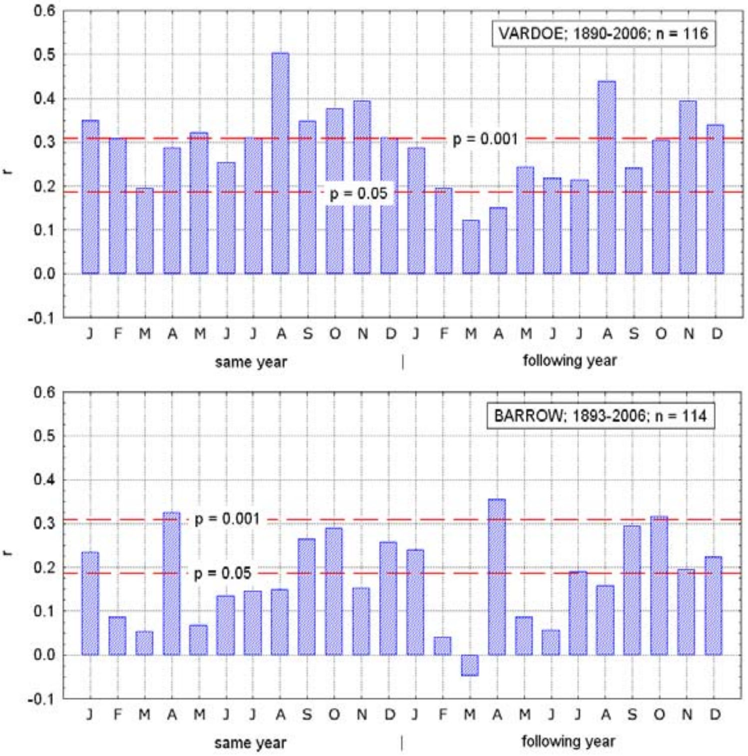

Fig. 8. The correlations between the tropical signal (DG_{3L}) and the monthly temperature in the same and the following year at the stations: A – Vardoe (closely associated with the inflow of Atlantic Water into the Arctic), B – Barrow (the most distant station from the area of inflow of Atlantic Water into the Arctic). p=0.05 and p=0.001 levels of statistical significance

Ryc. 8. Korelacje między sygnałem tropikalnym (DG_{3L}) a miesięczną temperaturą powietrza w tym samym roku i roku następnym na stacjach: A –Vardoe (bezpośrednie pobliże wnikania wód Atlantyckich do Arktyki), B – Barrow (najbardziej oddalona stacja od obszaru wnikania wód atlantyckich do Arktyki). Oznaczone poziomy istotności statystycznej p = 0,05 i p = 0,001

5. Discussion of results

From the data presented here we conclude that climatic changes observed in the Arctic since the end of 19th century are controlled solely by the oceanic circulation currently active in the North Atlantic. Sea-water from here transports a variable heat content into the Arctic. The source of this steering signal is situated in the circle of the anticyclonic oceanic circulation of the North Atlantic – antecedent to and in the region of the Gulf Stream delta.

The thermal condition of the water in this region is highly influenced by the thermal condition and location of the centre of the warmest water in the Sargasso Sea, and not, as has previously been supposed, by the Gulf Stream. According to Keigwin (1996) changes in the SST of the Sargasso Sea reflect climatic changes observed on a hemispherical scale. Hemispheric changes of temperature in Holocene, including Medieval Warm Period (or Medieval Climate Optimum) and Little Ice Age are recorded there in the course of SST (Keigwin 1996) as well as earlier phases of climatic changes at least 3000 years back (Keigwin i Boyle 2000). Keigvin and Boyle (2000) concluded that changes in the SST of the Sargasso Sea result from changes in the intensity of thermohaline circulation.

In the course of changes of the SST in the northern part of the Sargasso Sea a roughly- 70-year periodicity may be observed. Schlesinger and Ramankutty (1994) noted the presence of 65-70-year periodicity in the global course of temperature and the natural variability of the SST of the North Atlantic which they concluded to be the result of ocean-atmosphere interaction. Delworth and Mann (2000) determined a c. 70-year periodicity in the course of more than 330-year series of temperature variations; furthermore the presence of such periodicity is amply supported by model simulations. According to these authors this periodicity represents fluctuations in the intensity of thermohaline circulations in the North Atlantic and they are first manifested by changes in the SST. This periodicity is now defined as the AMO (IPCC 2007). The 70-year-or-so periodicity in the course of the tropical signal seems to reflect the AMO.

Dickson *et al.* (1996) showed that the formation of subtropical water in the Sargasso Sea on a multidecadal scale is functionally connected with convection processes in the Greenland and Labrador seas, albeit shifted in phase in relation to each other. These are elements of a general thermohaline circulation and they are dynamic elements of unquestionably natural character. Ergo, the generated tropical signal being derivative from these processes also must have a natural character. This means that observed in 1880-2007 climatic changes in the Arctic were promoted by the transport of variable heat content from the tropics with the oceanic circulation; they also have a natural and non-anthropogenic genesis.

This conclusion is strongly supported by regression analysis. In the multiple regression equation where the dependent variable are Arctic SAT anomalies ($AN_{64\text{-}90°N}$), the independent variables are: the value DG_{3L} and CO_2 concentration in the troposphere representing 'anthropogenic signal'. The equation which expresses this relationship is as follows:

$$AN_{64\text{-}90°N} = -3147.25(\pm 292.36) + 120.36(\pm 13.83) \cdot DG_{3L} + 1.11(\pm 0.20) \cdot CO_2\,, \qquad [\,3\,]$$

where:

$AN_{64\text{-}90°N}$ – annual SAT anomalies in the zone 64-90°N (in 0.01°C),

DG_{3L} – tropical signal (°C),

CO_2 – concentration of CO_2 in the troposphere (ppmv), obtained from measurements at Low Dome (1880-1975)[9] and Mauna Loa (1957-2007)[10].

The variance analysis indicates that DG_{3L} variability explains 55% and CO_2 concentration – 9% of Arctic SAT anomalies variance.

Equation [3] is statistically highly significant (R=0.80, F(2,126)=117.8, SEE=47.9) and explains (adj. R^2) 63.4% of the observed variance of annual Arctic SAT anomalies in 1880-2008. The activity of other, not mentioned in the equation, factors gives 36.6% of not explained remainder variance. A scatter plot of values calculated by eq. [3] in relation to the observed values is presented in Fig. 9.

The parameters of the multiple regression were intentionally estimated without removing outliers. A relatively large standard estimation error (SEE) seems to appear (apart from not removing outliers) because the function has not taken into consideration some independent variable. This variable

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[9] Source: http://cdiac.ornl.gov/ftp/trends/co2/lawdome.combined.dat.

[10] Source: http://cdiac.ornl.gov/ftp/trends/co2/maunaloa.co2.

represents some element which has strong influence on the changes in annual Arctic SAT. It is probable that the estimation of independent variables or/and dependent variable originating from data sets is not very accurate. The most important climatic element which has not been taken into consideration here is the atmospheric circulation over the Arctic (more precisely that process which has a decisive influence on the ice drift). According to modeling carried by Maslowski *et al.* (2000, 2001) interdecadal variability in the character of atmospheric circulation over Arctic seems to lead to very large changes in the distribution and sea ice extent. Certainly, these features of the atmospheric circulation are not well described by NAO or AO indices in the Arctic as a whole. It seems that the general pattern of ice drift in the Arctic (especially in the eastern and central parts) is much better described by an 'Arctic dipole' pattern (Wu *et al.* 2006). However, the series of this circulation formula is much too short (1949-2007) to be usable in this analysis.

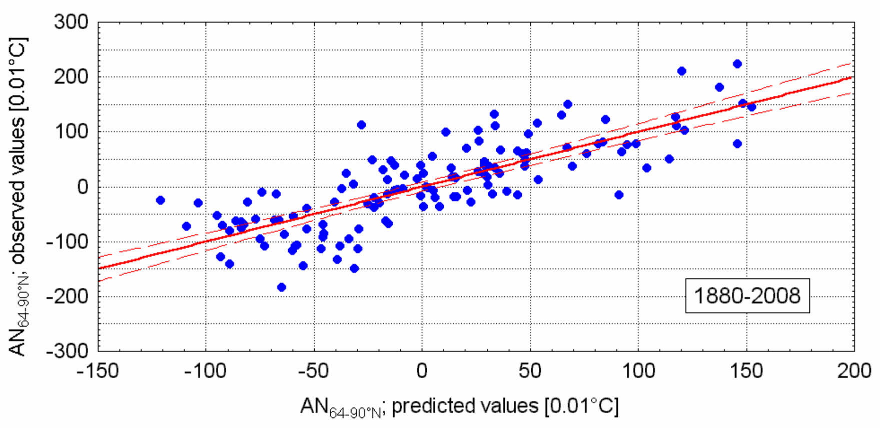

Fig. 9. The annual SAT anomalies in the Arctic ($AN_{64\text{-}90°N}$) predicted with equation [3] in relation to the observed values (R^2=0.60). The parameters of the equation [3] were intentionally estimated together with the outliers

Ryc. 9. Anomalie SAT w Arktyce obliczone za pomocą równania [3] względem obserwowanych (R^2=0.60). Parametry równania [3] zostały oszacowane celowo bez eliminacji przypadków odstających

Explanation of about 60% of variability in changes in the annual Arctic SAT and statistically significant estimation of hierarchy of the influence of particular factors (i.e. tropical signal, CO_2, NAO) on the annual SAT variability in 128-year series indicates unity of all these factors. The main role of tropical signal in this explanation (changes in CO_2 concentration in the troposphere were taken into consideration) provides another argument for the principal role of natural processes which have influence on the changes in SAT in this area.

We may talk about the anthropogenic nature of the tropical signal variability only then, when it was proved that the variabilities both in the AMO and water redistribution in the Gulf Stream delta resulted from an increase in the concentration of CO_2 in the troposphere. Thus, only then it can be stated that the observed climate changes in the Arctic are forced by the anthropogenic processes. Up to the present moment the AMO variability has not shown to be influenced by changes in the concentration of CO_2 in the troposphere (Gray *et al.* 2004; Latif *et al.* 2004).

6. Conclusions

Our analyses indicate that the adjusted course of DG_{3L} over the whole period has minima in the years 1904 and 1974, which give a 70-year interval. The periodicity in the course of SST in the region of the North Atlantic and the courses of some hydro-climatic elements in the Arctic have been known for a long time and described in number of works (e.g. Schlesinger and Ramankutta 1994; Moron *et al.* 1998; Delworth and Mann 2000; Venegas and Mysak 2000; Polyakov *et al.* 2004, 2005).

The around 70-year periodicity is the mean value of a 60-80-year periodicity of LFO (Low Frequency Oscillation) given by Polyakov *et al.* (2005). In the light of presented correlations of SAT and ice extent in the Arctic with the tropical signal it can be stated that the LFO as defined by Polyakov and Johnson (2000) is not the result of self-driven oscillations generated by Arctic climatic system but is controlled externally by a variable heat flow within Atlantic Water. It is not these processes active in the Arctic which promote a stronger or a weaker ‘suction’ of Atlantic Water into the Arctic Ocean. The increasing or decreasing amounts of heat imported into the Arctic by Atlantic Water are responsible for initiating those processes in the Arctic which later determined whether the LFO is in a positive or negative phase.

If such a 70-year periodicity as identified in the course of DG_{3L} is authentic, one may predict that the climate of the Arctic is just about to reach its warming peak. This should be identifiable in 2009 and (taking into account the roughly 3-year delay for the propagation of the signal) around 2012 in the Arctic. However, one cannot exclude the possibility that the period of variability in the tropical signal is appreciably shorter (Schlesinger and Ramankutty 1994); in which case the climate of the Arctic would already have started to cool. The DG_{3L} records having reached its maximum in 2003 and decreased in 2004-2007 (Fig. 3) support this notion. The latest field research into the changes in the heat content in the water of the West Spitsbergen Current in the Fram Strait (carried out by the Institute of Oceanology of Polish Academy of Science) indicates that water with maximum heat content moved through 78°N in 2004-2005 (Walczowski and Piechura 2006). In 2006 a decrease in heat resources had already been noted and a further fall in the temperature of the Atlantic Water at this profile is also predicted in 2007 (Walczowski and Piechura 2007).

Because the tropical signal even during culmination of its course shows a considerable variability (Fig. 2) and because, to date, only one complete ~70-year cycle has been identified, any assumption regarding a further course of changes in the climate of the Arctic based on the variability of DG_{3l} would be risky. Furthermore, because the summer ice cover has been dramatically reduced in the period 2002-2007 (Serreze *et al.* 2003; Stroeve *et al.* 2005) consideration should be given to the notion that warming mechanisms could have been initiated in the climatic system of this region (Lindsay and Zhang 2005).

The stream of Atlantic Water imported to the Arctic, the heat content of which has earlier been defined by the tropical signal (DG_{3L}) appears to play the main role in direct and indirect control of the processes of changes in Arctic SAT. The Arctic is not an ‘amplification’ of the warming (the so-called 'Arctic Amplification' or 'Polar Amplification') caused by an increase in the concentration of greenhouse gases in the atmosphere. In conditions when a low or very low SAT is identified, it is possible that a huge amount of sensible heat and latent heat from water (close to or below 0°C) is transferred to the atmosphere. This further results in visible increase in SAT. A few conditions must be fulfilled to make this heat transfer to the atmosphere possible. Firstly, there must be a constant supply of heat into this water. Secondly, the water adjacent to the sea ice extent cannot be stratified, as only the lack of pycnocline enables deep convection. Finally, reduction of sea ice cover has to be observed. Such a conclusion supports Zakharov's (1981, 1997) contention regarding the role of sea ice in influencing both climatic changes and stabilization in the Arctic.

The courses of tropical signal as figured in this paper and correlations between DG_{3L} and SAT with the extent and concentration of sea ice cover in the Arctic suggest that is not accidental that the first great warming of the Arctic in the 1920s and '30s, when the CO_2 concentration in the atmosphere was lower than that of the present, started in the Atlantic Arctic and that the highest increases in SAT during that warming period were noted in summer and autumn seasons. Currently (1979-2006), in the same region the strongest and statistically significant trends in the SAT are marked in winter and autumn (Marsz and Styszyńska 2005, Marsz 2007b). Trends in the SAT in spring and summer although generally statistically significant are clearly weaker there. Present warming started in the Atlantic Arctic a few years earlier than over other regions of the Arctic.

The results of analyses presented in this paper suggest that the processes of climatic change in the Arctic take place under the influence of oceanic processes and reflect global rather than local processes in the combined evolution of oceanic climate and atmospheric climate. We consider that, to date, natural processes have played the dominant role. Of course, this does not necessarily mean that some extraneous influence on the further course of this evolution would not be controlled by processes generated by human activity, but this factor has yet to be demonstrated.

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Wpłynęło: 18 października 2008, poprawiono: 10 września 2009.

Streszczenie

Praca wykazuje istnienie silnych związków między temperaturą powierzchni morza (SST) w rejonie delty Golfsztromu a przebiegiem anomalii temperatury powietrza w Arktyce (1880-2007). Związki te wynikają z transportu przez cyrkulację oceaniczną (AMO – Atlantic Multidecadal Oscillation) zmiennych ilości ciepła z rejonu atlantyckich tropików do Arktyki. Głównym mechanizmem regulującym wpływ zasobów ciepła w wodach wnoszonych do Arktyki na temperaturę powietrza jest reakcja lodów morskich, zwiększająca lub ograniczająca strumienie ciepła z oceanu do atmosfery. Geneza wielkiego ocieplenia Arktyki w latach 30-40. XX wieku i współczesnego ocieplenia Arktyki jest taka sama. Oba epizody ocieplenia Arktyki stanowią rezultat działania procesów naturalnych i nie są związane z działaniem efektu cieplarnianego. Zmiany koncentracji CO_2 w atmosferze objaśniają około 9% wariancji SAT w Arktyce.

Słowa kluczowe: Arktyka, delta Golfsztromu, ocieplenie, temperatura powietrza, temperatura powierzchni wody, czynniki naturalne.