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The origin of coreless winters in the South Shetlands area (Antarctica)

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ABSTRACT: The occurrence of coreless winters in the South Shetland Islands region is related to increase in the intensity of cyclonic circulation and to the presence of massive and rapid advection of warm air northerly and westerly. Coreless winter developments depend on large-scale oceanic processes – the presence of positive anomalies in sea surface temperature (SST) in the Bellingshausen Sea over the range 080°–092°W and the retreat of sea ice extent southwards. When negative anomalies of SST in the same region are observed and the sea ice extent advances northwards, a winter with clearly marked cold core is experienced at the *Arctowski* Station on the South Shetlands.

Key words: Antarctica, *Arctowski* Station, coreless winter, air temperature, climate.

Introduction

As noted by numerous previous authors, the records of mean monthly air temperatures in Antarctica (especially in the region of the South Shetland Islands and northern parts of the Antarctic Peninsula) a very variable from year to year. These are especially pronounced in the winter months. Such winters are called “kernlose winters” by Wexler (1958), Wendler and Kodama (1993) or coreless winters (for example Van Loon 1967, King and Turner 1997) *i.e.* winters which do not have a cold core. Winters during which the air temperature, after a significant drop in autumn, remains at much the same, modest level for the following two to four months occur every other or third year. Sometimes the autumn fall in temperature is followed by a winter during which one or two months have a significantly higher temperature and which are again followed by another slight decrease in temperature. However, during winters which have a clearly-marked cold core, the seasonal decrease in air temperature is appreciable, the minimum being in July or August. As

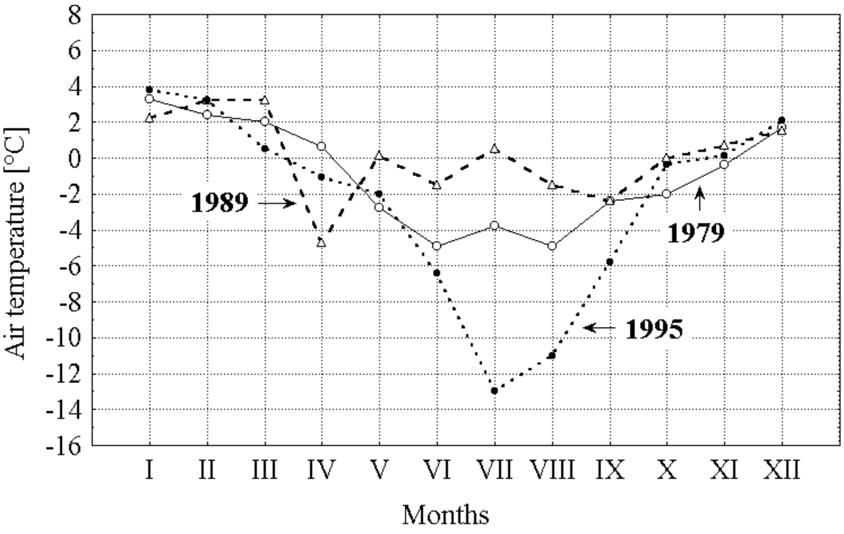

Fig.1. A plot of monthly mean air temperature at the *Arctowski* Station in years 1979 – winter with a cold core weakly marked, 1989 – extreme coreless winter, 1995 – winter with a clearly marked core.

the occurrence of coreless winters has a significant influence on the climatic conditions of the South Shetlands, it is important to understand how they originate.

The annual mean air temperature at the Polish *Arctowski* Station on King George Island (62°10'S, 058°28'W) from the period 1978–1998 is –1.6°C. Over a 21-year long period, records of air temperature show that the lowest monthly mean temperatures are in July (–6.6°C) extremes of 0.5°C and –13.2°C. In the period 1978–1998, the minimum monthly mean air temperature at *Arctowski* Station was, for April (–4.7°C – 1989), for May (–8.5°C – 1992), for June (seven cases), for July (nine cases), for August (two cases), and for September (–7.6°) – 1998). Plots of monthly mean air temperatures for three selected years at this station are shown (Fig. 1).

The occurrence of a coreless winter is usually atributed to the influence of air circulation factors (among others, Wexler 1958, Rubinštein 1962, Rubinštein and Sohrina 1969, Dolgin 1976, Dolganov 1986, Wendler and Kodama 1993, King and Turner 1997). However, Van Loon (1967), Lettau (1971) and Schwerdtfeger (1970, 1984) claim that they are probably related to specific features of the radiation balance, *i.e.* the presence of deep inversions during polar nights, during which larger amounts of long-wave radiation emanate from upper and medium layers of the troposphere, these being warmer than that the layer close to the ground. This results in the increase in temperature. As the occurrence of coreless winter at the high plateau of the Antarctic ice-dome may be influenced, to some extent, by the specific winter radiation balance in which emission the flux of long-wave radiation is relatively small and the long-wave radiation flux reaching the surface from the upper, warmer and moist layers of atmosphere is relatively large (Schwerdtfeger 1984), then, in the case of regions which are located at lower altitudes, the possible influence of advections must also be admitted. Furthermore, even in respect of coreless winters in central parts of Antarctica, one requires to explain why, from where and as a result of which processes, the warmer, moist air masses may be found above the surface layer of air; also, way this long-wave radiation which reaches the ground layer and is so intense that it results in such a long-lasting increase in air temperature. Indeed, perhaps surprisingly, the monthly mean air temperature during this process may increase by as much as 20°C .

The advective character of coreless winters is also demonstrated by the fact that (even over continental Antarctica) they are markedly regional in their distribution; they never occur simultaneously over the whole continent (Rubinštein and Sohrina 1969). If the coreless winters are related to the frequent occurrence of advection of warm (warmer) air masses and, in turn, to more intensive cyclonic circulation over that region, the question then arises: why is it that, in some years, the intensification of air advection of warm air occurs in winter whereas, in others, it does not? The author consideres that the explanation probably lies in the nature of the local climate. Certainly, analysis of the influence of climate-forming factors in this region suggests strongly that the winter changes in the character of the atmospheric circulation originate from the interaction between the ocean and the atmosphere in that region, the local geographical being a dominant factor there.

Monthly mean temperature in July can be assumed as the factor indicating the presence or absence of coreless winters. The subdivision into winters with "cold core" and "coreless" is not made, as all cases of monthly mean temperatures in July from the observational period 1982–1997 at the *Arctowski* Station have been subjects of the analysis and the above mentioned period provides necessary reliable data regarding SST and sea ice cover.

The data concerning SST have been taken from Optimal Interpolation (IO) monthly mean sea surface temperature NCEP – National Center for Environmental Prediction (Reynolds and Smith 1994, 1995) and cover the period from November 1981 to August 1997 whereas the data concerning the ice extent are compiled by Jacka and refer to the period 1973–1997 (these data are available on the Antarctic Cooperative Research Center and Australian Antarctic Division Climate Data Sets Web site, www.antcrc.utas.edu.au/~jacka/climate.html). As a result, an analytic data set which has common elements covers 16 or 15 months (depending on the month) has been erected and the analysis has been carried out on this. Unfortunately for the period preceding year, 1982, there have been no reliable data concerning monthly mean SST.

The sea area whose location can be defined as 090–080°W, 50–67°S (Styszyńska 1997, 1999; Smith *et al.* 1996, Marsz and Styszyńska 2000) *i.e.* covering the Bellingshausen Sea and the regions of the Pacific located to the north of this seems to have particular influence on the character of the atmospheric circulation in the region of the South Shetland Islands. Because the sea ice cover and the SST clearly control the flow of heat from the ocean to the atmosphere so the elements of the large-scale hydrologic regime of that area have a most important influence on the climate in the adjacent sea area.

The relationship of the air temperature in July at the *Arctowski* Station to the extent of the ice cover and with the SST within the energy-active zone of the Bellingshausen Sea

Correlation of the trends of mean temperatures in July at the *Arctowski* Station with the data concerning the sea ice extent in July at 080°W, *i.e.* roughly at the eastern border of the Bellingshausen Sea indicate a fairly strong linear correlation between these values (see Fig. 2). The temperature in July at the *Arctowski* Station (ARCt07) may be regarded as a function of ice extent at a given meridian in that month (ICEφ07):

$$\mathrm{ARCt07} = -123.904 + 1.814 \cdot \mathrm{ICE}\varphi07, \qquad [1]$$

where: ICEφ07 – ice extent in July – latitude (°S) at the meridian 080°W.

This correlation proves to be significant ($n = 20$, $R = 0.71$, $p < 0.000$) and accounts for at least 50% of the changes in the air temperature in July at the *Arctowski* Station (c. 51%). This implies an extension of the ice extent in July northward to 080°W is concomitant with a decrease in air temperature on King George Island. This is simple explain: an increase in the ice extent means that the

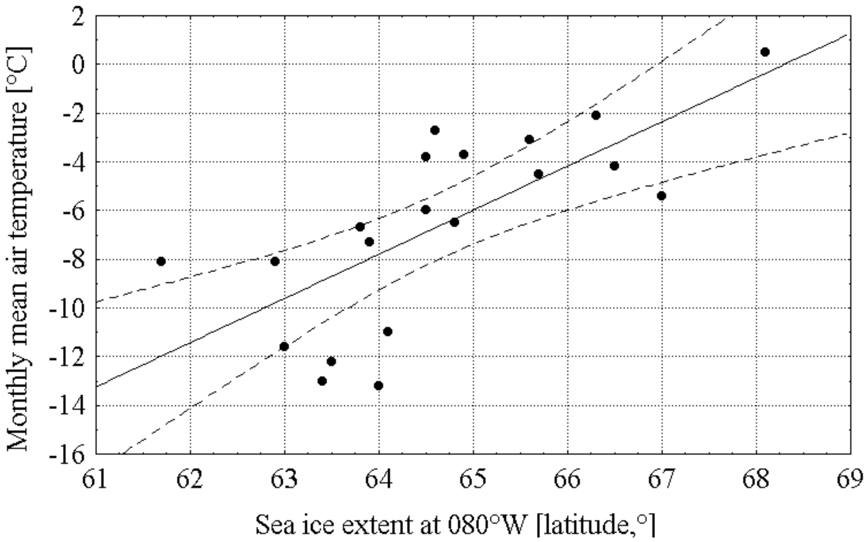

Fig. 2. Correlation between sea-ice extent [j°] at 080°W in July and monthly mean air temperature [°C] in the same month at the *Arctowski* Station.

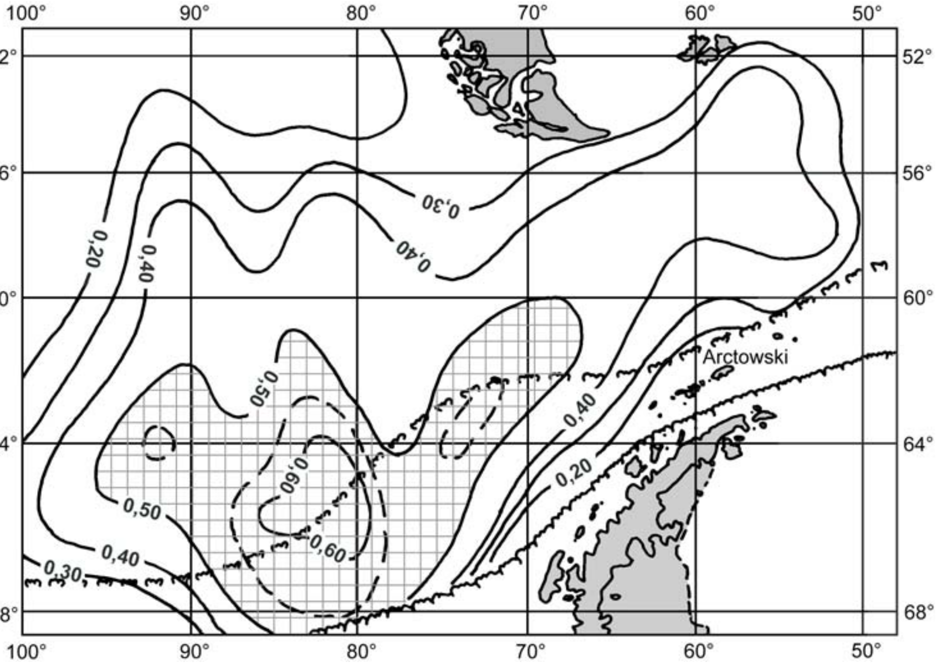

Fig. 3. Spatial correlation between sea surface temperature (SST) in July and mean air temperatures in July at the *Arctowski* Station. Mean (dashed line) and minimum (solid line) sea-ice extent in July (1972–1994). Checked hatching – statistically, represent values are significant at the 95% confidence level.

area of intensive fluxes of sensible and latent heat from the sea is limited, restricting in this way the on-flow of energy, which would later elevate in air temperature, thereby stimulating the cyclogenesis processes (*i.e.* depression formation).

Similarly, an analysis of the variations of mean temperatures at the *Arctowski* Station and the SST in July at latitudes 65°–55°S and on the 080°W meridian indicate an obvious correlation between these values. The strongest linear correlation ($r = 0.57$, determination coefficient $d = 0.33$, $p < 0.020$) was determined between the SST in a 2° × 2° grid and the central point of that grid at latitude 64°S (see Fig. 3). North of this the correlation becomes progressively weaker and north of 55°S the values of correlation coefficients become, statistically, non-significant ($p > 0.05$). This implies that an increase in the SST to c. 63–67°S in July is followed by an increase in air temperature at the *Arctowski* Station.

The higher temperature of the ocean surface indicates to the presence of a greater heat resource in the sea water. When relatively cool air flows over a warmer water surface, the difference between the water and air temperatures becomes greater and heat exchange between the upper layers of the ocean and the atmosphere becomes more intensive. An increase in the SST at high latitudes, in the vicinity of the ice cover extent, permits an enhanced exchange of heat between (the upper layers of) the ocean and the atmosphere. This process takes place, as elsewhere, owing to a rapid deepening of a depression, whereby supplying much energy per unit of time.

Without question, the overall correlation between the temperature of the ocean surface and the air temperature at the *Arctowski* Station is non-linear. To make the problem arithmetically simpler, it can be described with the help of a multiple regression equation (thereby preserving a sufficient accuracy level):

$$\mathrm{ARCt07} = -147.22 + 2.02 \cdot \mathrm{ICE\varphi 07} + 3.07 \cdot \mathrm{SST07[80,60]}, \qquad [2]$$

where:

– ICEφ07 – same as above,

– SST07[80,60] – the monthly mean sea surface temperature in July in a 2° × 2° grid and the central point of that grid is found with co-ordinates 080°W and 60°S (the central part of the region, where the SST is related with air temperature at the *Arctowski* Station).

This correlation is statistically significant ($n = 15$, $R = 0.84$, $F(2,12) = 14.0$, $p < 0.001$) and thereby explains about 65% of the air temperature variability at the *Arctowski* Station. A scatterplot of predicted values drawn with the help of this formula and the observed values is illustrated in Fig. 4.

A more detailed analysis suggests that the air temperature in July is not only influenced by the SST in the region 65°–55°S (a) but also by the value of meridional gradients of the SST in both that region and also the area situated between 65° to 48°S (b). As the distance between the central points of grids (Δφ) is known and

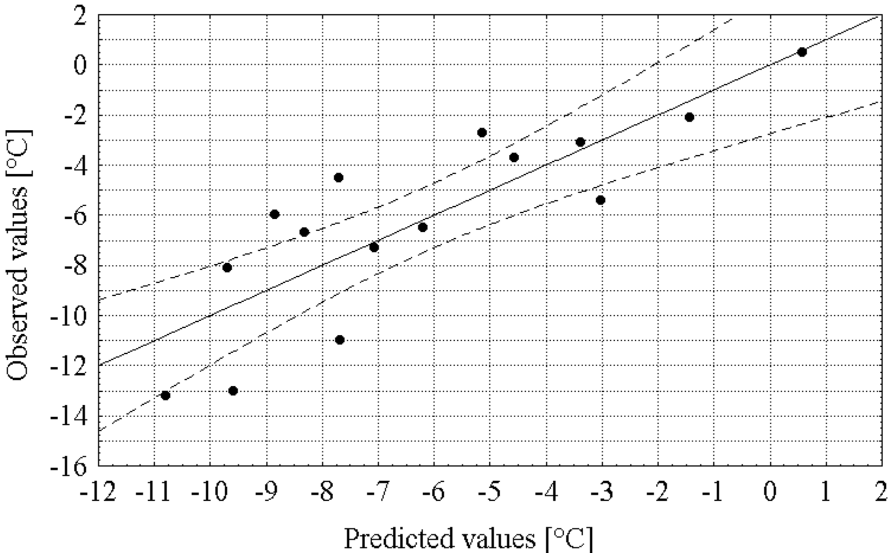

Fig. 4. Monthly mean air temperature [°C] in July at the *Arctowski* Station estimated from equation [2] and observed values [°C].

constant, we need use only the meridional differences in the SST in grids instead of the value of the gradient defined as ΔSST/Δj. These values will marked as dSST07a (dSST07a = SST07[80,56] – SST07[80,64]) and dSST07b (dSST07b = SST07[80,48] – SST07[80,60]).

The relation between the July air temperature at the *Arctowski* Station and the value dSST07a may clearly be observed both in the course of time in Fig. 5. The variability of the water temperature in 07[80,60] grid, that which is southernmost (see Fig. 6), which explains 80% of the variability of dSST07a values, has a large influence on the value of dSST07a:

$$\mathrm{dSST07a} = 5.205 - 0.585 \cdot \mathrm{SST07[80,64]}. \qquad [3]$$

Also, statistically, this correlation is highly correlated ($R = 0.90$, $F(1,13) = 61.0$, $p < 0.000$).

As can be seen from Fig. 5, the lower the meridional gradient of sea surface temperature in the region 65°–55°S in July, the higher the air temperature at the *Arctowski* Station. In respect of the correlation described earlier, this relationship is clear (a higher water temperature at 64°S). However, the value of dSST07a is also relatively strongly correlated with ICEφ07, whereas the value of dSST07b shows a weaker correlation. That is why, in the multiple regression equation, the coefficients of partial correlation are higher and the correlation itself reaches higher level of significance if instead of dSST07a the value of ARCt07 = *f*(ICEφ07, dSST07b) has been specified:

$$\mathrm{ARCt07} = -144.31 + 2.32 \cdot \mathrm{ICE}\varphi07 - 2.62 \cdot \mathrm{dSST07b}. \qquad [4]$$

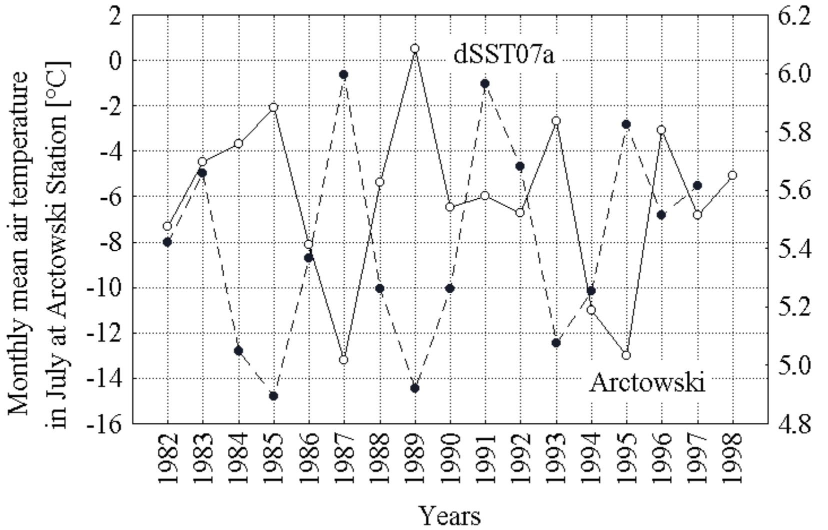

Fig. 5. The course of monthly mean air temperature in July at the *Arctowski* Station in the following years and values dSST07a (SST07[80,56] – SST07[80,64]) being a measure of meridional gradient of SST between 65° and 55°S at 080°W in July.

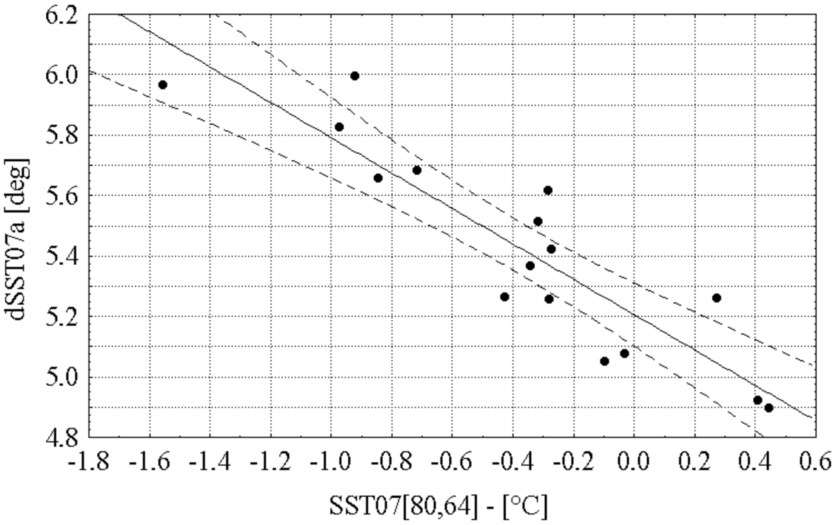

Fig. 6. The value of dSST07a (meridional gradient of SST in the zone 65°–55°S at 080°W in July) as a function of SST in July at the south boundary of that area [65°–63°S] – in grid 2°x2° [80,64].

The relationship [4] explains about 68% of the variability of the mean monthly July air temperatures at the *Arctowski* Station and, statistically, is strongly significant ($R = 0.85$, $F(2,12) = 15.6$, $p < 0.000$). Significantly, this indicates that the temperature of July at the *Arctowski* Station depends not only on the ice extent in the Bellingshausen Sea and the SST at 56°–61°S (*i.e.* in the vicinity of the edge of the pack ice), but also on the SST in the region of 47°–49°S, which value is a component of the dSST07b element. Owing to the large thermal gradients at the ocean surface in that region, the value of the July air temperature at *Arctowski* Station decreases more than in the case of the lower thermal gradients.

The present relationship can be explained in the following way:

(1) Low values of the dSST07b expression will be observed when the water temperature at 60°S is higher than usual and the temperature of water at 48°S is close to the average. The effects will be the same or closely similar to the meridional changes in the SST between 56° and 64°S (greater heat resources in the ocean close to the ice extent).

(2) Large temperature gradients may be observed in two cases:

  (a) when the water temperature in the subantarctic zone (~60°S) drops below the average *i.e.* the SST are close to mean the SST at 48°S; the effect is the converse of that described in (1), *i.e.* small heat resources in the region ~60°S, low air temperatures at the *Arctowski* Station,

  (b) when the SST at the mid-latitudes (~48°S) increases and the SST at the higher latitudes (~60°S) is constantly low or average, the zone of maximum gradients of SST migrates northwards. Concomitantly, cyclogenesis will increase at the northern boundary of the zone (latitudes 40°–50°S) whereas in the zone 56°–64°S, decrease. As a result, in the region of the South Shetlands intensity of atmospheric circulation will be weaker and in consequence the July air temperature will decrease. It follows that, in July, in winters in which ice extent at the meridian 080°W recedes southwards and when the SST at the latitudes 59°–65°S is higher than usual, an increase in the intensity of atmospheric circulation will be observed.

Air warmed up close to the sea surface rises resulting in an increase in temperature in the lower layer of the troposphere (at least up to 500 hPa level) and the mean density of that layer (1000–500 hPa) reduces. East of the source of heat, the air transported by an intensive westerly flow present at the 750–500 hPa level causes the geopotential level to rise. As a result of this, east of the heat source, a ridge in the long (or Rossby) waves in the upper airflow usually develops. On its western side, a flow southeasterly is initiated.

An increase in the frequency of cyclogenesis over the Bellingshausen Sea results in an increase in the frequency of the warmer air mass advection from the NW sector to the South Shetlands and the north edges of the Antarctic Peninsula and the adjacent sea area (*i.e.* between longitudes 065°–058°W). The increase in the frequency of advection from the N and from NW over the region west of the South Shetlands and the Antarctic Peninsula limits the possibilities for sea ice development in this sea area. This is caused by both the influence of a thermal element (higher air temperatures, restriction of heat absorption from the ocean surface) and by a dynamic factor ("pushing" the edge of the drifting ice southwards, thereby precluding the possibility of their drift northwards). As a result, when the ocean is ice-free, the inflow of cold air from the S and SW sectors (that associated with the movement of the rear parts of depressions) does not result in pronounced cooling over the South Shetlands. Cold air masses which flow over the ice-free ocean are partially transformed and their temperature increases significantly.

Thus, when the ice extent at the 080° W meridian is relatively southerly and the SST at 59°S latitudes is higher than usual, there is an increase in the frequency of warm advection from the NW and W over the South Shetlands. Concomitantly, it is impossible for the non-transformed cA air masses (Antarctic-continental air) to reach the South Shetlands. Both these phenomena lead to an increase in monthly mean temperature in July which is significantly above the average *i.e.* a coreless winter develops.

Predisposition of hydrological conditions of the Bellingshausen Sea relating to the occurrence of a coreless winter

Defining the conditions which are necessary for the coreless winter to develop is outlined above, is not easy, i.e. it becomes necessary to determine which elements influence the particular hydrological condition of the Bellingshausen Sea in July.

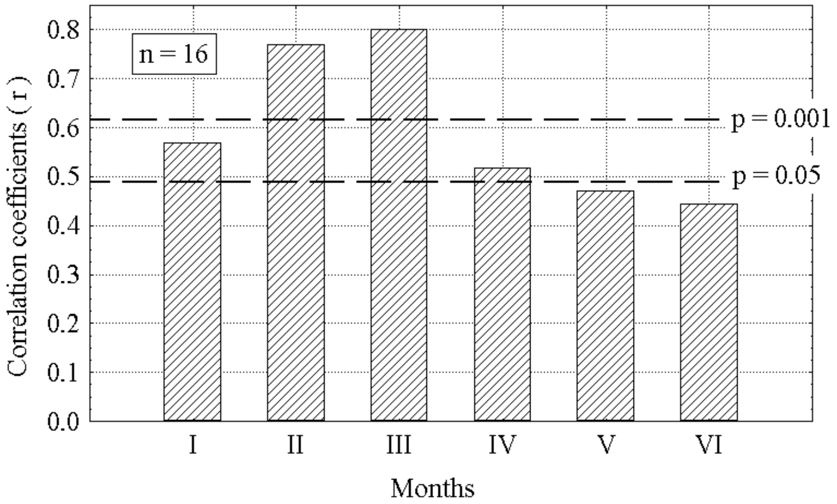

Fig. 7. Coefficients of linear correlation between SST in July in [80,64] grid and SST in the preceding months (January – June) in [80,60] grid the same meridian (4° N).

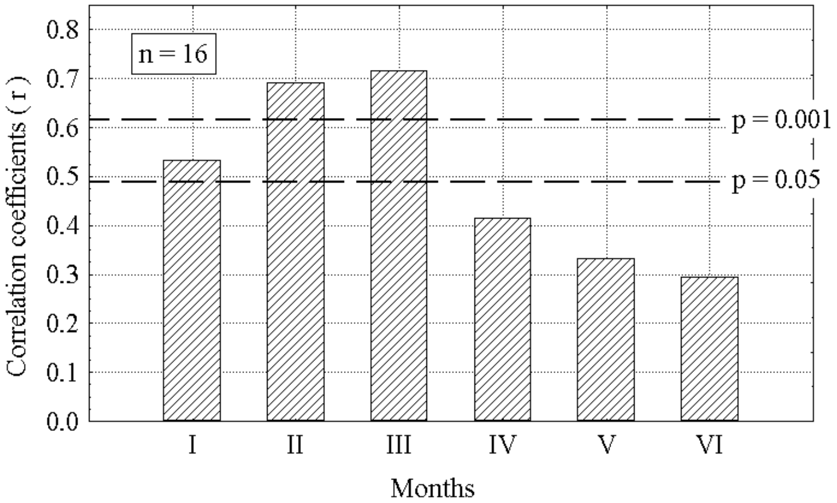

Fig. 8. Coefficients of linear correlation between SST in July in [80,64] grid and SST in the preceding months (January – June) in [86,60] grid (located 6°W and 4°N with reference to the grid for which the calculations are carried out)

Analysis of asynchronic correlation points to a strong correlation between the SST in July and the SST at the end of the summer warming season (February, March; Styszyńska, 1998, 1999). A plot of the SSTs noted between January and June and those water temperatures in July in 080°W, 64°S grid is given (Fig. 7, 8). The correlations with the SST in January, February and March prove to be strong and probably significant ($p < 0.05$) or significant ($p < 0.01$), whereas the correlations in April, May and June are generally weak and, statistically, insignificant ($p > 0.05$). Figs 7 and 8 show the distribution of coefficients of correlation between the mean SST in July at 080°W and 64°S grid and the SST in some other grids. Note that, at the latitude 60°S, the strongest correlations occur between SST in March and, in the zone 56°S, February.

Such distributions of correlation coefficients over time may be interpreted in the following way. During the periods with high Sun altitudes and long days (i.e. summer: December, January and February) the increase in both diffuse and direct solar radiation which reaches the surface of the ocean results in an increase in heat resources within the upper (active) layer. Also, when compared to the winter season the absorption of heat from the surface of the ocean in the summer season is significantly reduced. This is attributed to a decrease in the differences between air and water temperatures and to a decrease in the frequency of very strong winds. When compared to summer thermocline the thickness of water layer increases. A positive thermal anomaly results when the temperatures of water at the end of winter are higher than their mean climatic temperature. When the water is colder, the negative anomaly of water temperature weakens. At the lower latitudes in February and at the higher ones, March, the SST reaches its maximum value. The anomaly of the SST is not so pronounced, normally not more than one degree. The cause of such situation is a permanent overall cloudiness.

However, if in the summer season low total cloudiness is observed several times and if the winds over that area are weaker at the same time, the anomalies of SST will be extremely high (owing to the cocsiderable contribution of direct radiation which reaches the surface of the ocean and limitations of the capacity of the water to absorb that heat). This may exceed 1°C. A decrease in cloudiness, accompanied by winds of lower force and speed over that region of the ocean, is related to the formation of anticyclones.

During April and May when the Sun's altitude decreases quickly and days become shorter, atmospheric processes due to heat absorption from the surface of the ocean lead to great differences of temperature in that part of the active layer close to the surface. The wind area, strongly differentiated spatially and associated with wind-generated waves appear to be the chief causes of the differences in heat resources. Occasionally, in June and commonly in July, when the differences between the temperatures of water and air are considerable, convection becomes more intensive. Heat which reaches the surface comes from the deeper layers. When the depth to the summer thermocline was larger, then the higher temperature of water will be observed at the beginning of the intensification of the convection.

It follows from this that, when the SST is high in February – March (*i.e.* at the end of the summer warming) it is also higher than average in July. The converse is also true. Thus, the coefficients of correlation between the temperatures in July and February – March are markedly positive. In their research on positive anomalies of the SST (Weatherly *et al.* 1991, Harangozo 1994) took no account of the solar radiation which reaches the surface of the ocean. Their explanation that positive SST anomalies are simply due to higher summer temperatures of the air over the ocean is clearly inadequate. Other factors must also be involved.

An advection factor can be regarded as another reason for the occurrence of positive anomalies to sea temperature. Advection of warmer water to this region is influenced by the Antarctic Circumpolar Current and by the inflow of surface waters from the north (Košlyakov and Sažina 1995, Radikevič and Romanov 1996) which compensate for the descent of the cool waters at the edge of sea ice, or along the coast of the Antarctic Peninsula. The advection due to the Circumpolar Current is probably more important for that region than the decrease in cloudiness and decrease in wind force and speed. When warmer water flows in from the west to this region in summer, it is highly probable that, in a situation when the heat absorption from the water is limited during summer, the water will retain that increased heat until winter, in this case, at least till July. The positive correlation between the SST from February – March and the temperature in July may also be observed then.

These correlations allow us to predict the July temperature with considerable reliability. The following formula is used to compare the SST in the 080°W 64°S [80,64] grid in July (the most significant month for changes in air temperature at the *Arctowski* Station) with the SST in this ocean area over the period February – March:

$$\mathrm{SST07[80,64]} = -0.104 + 0.71 \cdot \mathrm{SST03[80,64]} - 0.25 \cdot \mathrm{SST03[86,52]}, \qquad [5]$$

where $R = 0.91$, $F(2,13) = 31.3$, $p < 0.000$, SEe (standard error of estimation) = 0.24.

This formula, which has only two independent variables from March, explains 80% of the variability of SST in July in the [80,64] grid. Fig. 9 shows the scatterplots of points representing sea temperature in the [80,64] grid based on this

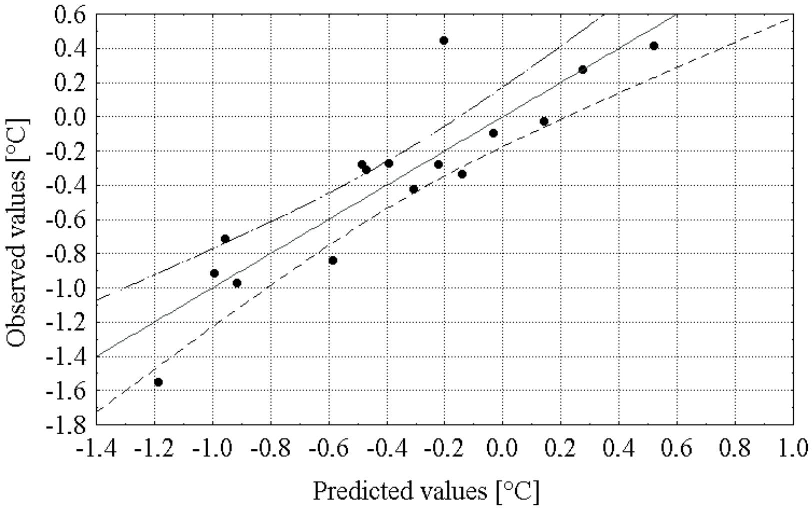

Fig. 9. SST in July in [80,64] grid estimated from equation [5] and the SST in July observed in the same grid.

formula and the observed SST. It should be noted that the other independent variable in that formula originates from the region situated farther west and at lower latitudes. This may be considered to include the influence of the advection of water masses together with the Circumpolar Current.

The northern limit of the sea-ice in July is another factor which has a significant influence on the atmospheric circulation over the South Shetlands in winter. However, this is difficult to quantify. Generally, ice formation commences when the flow of heat from the surface of the ocean to the atmosphere becomes greater than that originating from deep ocean levels; heat deficiency is compensated by the water's latent heat of fusion. If ice formation is due only to heat flow from the deep ocean, the greater will be heat resource in water above the summer thermocline and the later will the deficiency be observed – the differences between the air and sea temperatures and wind force are average.

Therefore, the changes in the ice limit in July in the Bellingshausen Sea may be regarded as a function of the thermal state of its water at the end of the summer warming season. The correlation between the thermal state of this sea region 47°–65°S, 092°–080°W indicates that such a situation is best explained by the multiple regression equation:

$$\mathrm{ICE\varphi07} = 69.98 + 1.25 \cdot \mathrm{SST02}[86,64] - 2.78 \cdot \mathrm{SST03}[80,52] + 1.83 \cdot \mathrm{SST02}[92,52], \qquad [6]$$

where $R = 0.83$, $F(3,11) = 7.8$, $p < 0.005$, $SEe = 0.9$.

The variability of the SST in February and March in the three grids detailed above accounts for c. 59% of the observed variation of the ice extent at the 080°W meridian. Fig. 10 is a scatterplot of the calculated points of ice extent based on this formula.

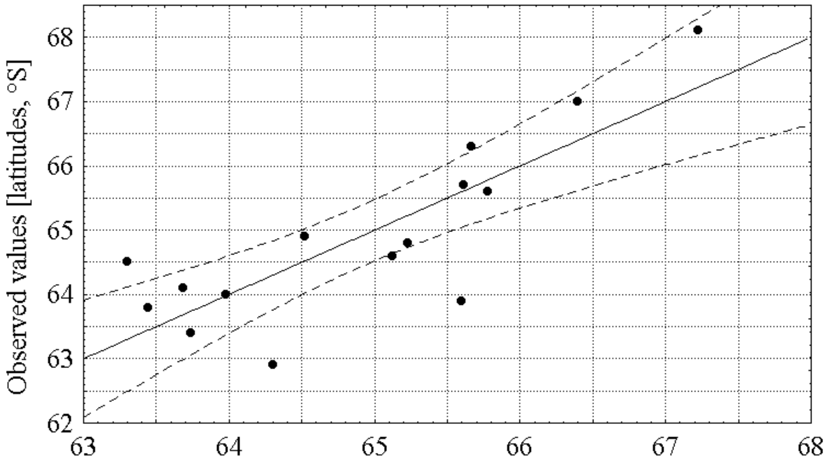

Fig. 10. Sea-ice extent in July [ICEφ07] at 080°W meridian estimated from equation [6] and the ice extent actually observed.

Having analysed the variables from this equation, it should be noted that two describe the thermal state of water at 52°S (51°–53°S), i.e. at the northern edge of the Circumpolar Current. This seems to indicate that, in the formation of the sea-ice at the 080°W meridian, the advection processes of the ocean are rather more significant than the summer radiation which reaches the surface of the ocean.

Thus, it is concluded that the thermal conditions of that sea area observed at the end of the summer warming season determines whether any given winter will experience an increase or decrease in the atmospheric circulation over the Bellingshausen Sea (which, in turn, will result in the thermal characteristics of winter at the *Arctowski* Station). From this it follows that the thermal conditions of July at the *Arctowski* Station (and indeed, over the entire Southern Shetlands) may reliably be forecast 3 months in advance.

The hydrology of the Bellingshausen Sea and winter characteristics at the *Arctowski* Station

It is now necessary to try to determine the factors which define the thermal character of July at the *Arctowski* Station. In mathematical terms, the state of the thermal conditions at the Bellingshausen Sea and the sea areas of the Pacific adjacent to it from the north may be define by three asynchronic values. The correlation is as follows:

$$\mathrm{ARCt07} = 67.36 - 4.81 \cdot \mathrm{dSST07c} - 8.65 \cdot \mathrm{SST03}[80,52] + 4.58 \cdot \mathrm{SST02}[92,52], \qquad [7]$$

where: $\mathrm{dSST07c} = \mathrm{SST07}[92,48] - \mathrm{SST07}[92,64]$ (the difference between mean monthly SST in July in grids 48°S and 64°S at 092°W meridian).

The coefficient of multiple regression of that equation $R = 0.88$, $F(3,12) = 13.9$, $p < 0.000$, $SEe = 2.01$, a correlation which explains 72% of variability of July air temperatures at the *Arctowski* Station. It should be noted that two variables of that equation (SST03[80,52] and SST02[92,52]) are the same as those in equation [6] which described the position of the sea-ice limit along the 080°W meridian. Equation [7] thereby describes the concurrent position of ice limit (as a function of the SST, as measured at the end of the summer warming period). The variability of the July air temperatures at the *Arctowski* Station suggests that by controlling the character of atmospheric circulation, the hydrological conditions of the Bellingshausen Sea and the adjacent sea areas have great influence on the changes in the winter thermal conditions of the South Shetlands.

The equation contains two variables which describe the SST from March and February at the 52°S latitude and the July difference in SST between 48° and 64°S at the 092°W meridian. As previously stated, the latter value may be regarded, as a simplified measure of the SST gradient between the subantarctic and temperate zones. The independent components define the preceding state (February – March;

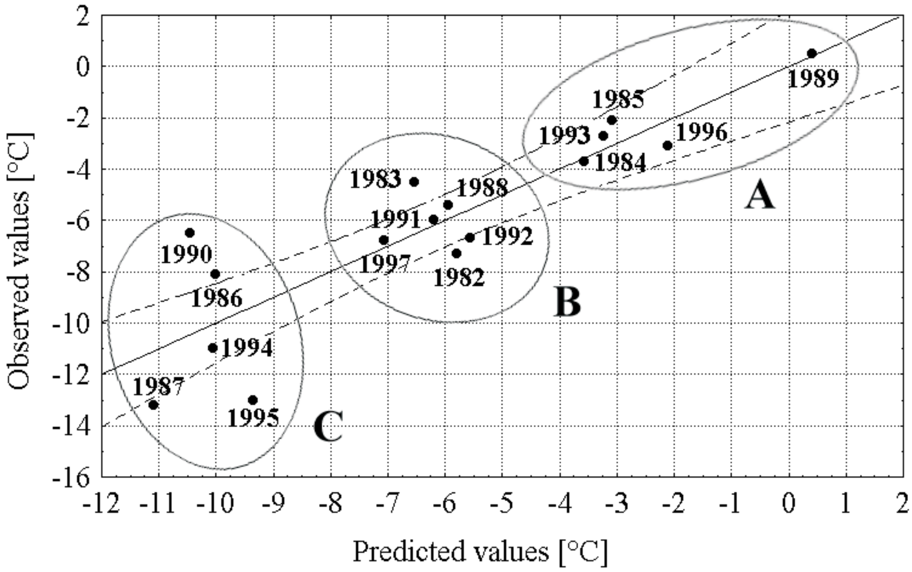

Fig. 11. Monthly mean air temperatures in July estimated with equation [7] and observed at the *Arctowski* Station.

the end of the summer warming period) and the July state of the thermal conditions of that area. This indicates that the changes in winter temperatures at the *Arctowski* Station are not a Markov process.

Fig. 11 shows a scatterplot of the values ARCt07 calculated from equation [7] and observed values. The temperatures in July over the period 1982–1997 clearly form three groups:

(A) Years: 1984, 1985, 1989, 1993, 1996 (5 cases),

(B) Years: 1982, 1983, 1988, 1991, 1992, 1997 (6 cases),

(C) Years: 1986, 1987, 1990, 1994, 1995 (5 cases).

The mean values of temperatures from the whole July in group “A” is –2.2°C (sn = 1.46 deg), in group “B”, –6.1°C (sn = 0.94 deg), and in group “C”, –10.4°C (sn = 2.66 deg). The mean temperatures of the period June – August are as follows: in group “A”, –2.9°C, in “B”, –5.7°C, in “C”, –7.6°C.

Unfortunately a similar analysis of mean monthly pressures in July did not show positive results. The differences between the mean values are minimal (the biggest is 1.54 hPa), i.e. significantly smaller than their standard deviation.

Therefore, winters represented by group “A” may be regarded as the “extreme” coreless winters (in 5 cases, the values of mean monthly maximum July temperatures higher than zero occur three times, whereas the other two are –1.4°C and –0.9°C). Group “B” represents winters characterised by a poorly – defined cold core, members of group “C” have a clearly defined cold core. However, this very variable thermal character of the winters is not reflected clearly in variation of the monthly atmospheric pressure.

$$z = -1691.61 + 51.388 \cdot x - 701.563 \cdot y - 0.388 \cdot x^2 + 10.4 \cdot x \cdot y - 12.178 \cdot y^2$$

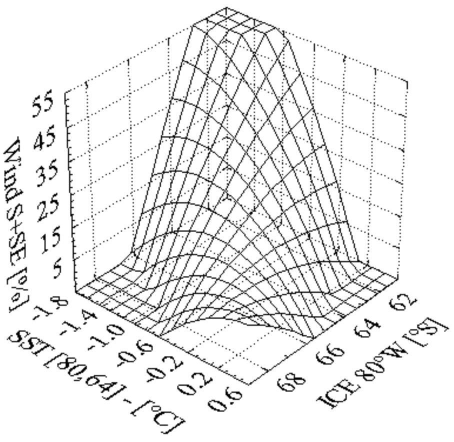

Fig. 12. Sum of frequencies of occurrence of S and SE winds [S + SE, %] at the *Arctowski* Station in July – (z) as a function of SST in July in [80,64] grid – (y) and sea-ice extent in July at 080°W meridian – (x axis).

Finally, it must be emphasised that the classification of winters into "A", "B" and "C" groups has been made, not on the basis of temperatures measured at the *Arctowski* Station but on mean temperatures in July approximated to values which reflect asynchronous hydrologic factors in the Bellingshausen Sea. The scatterplot of the values on the Y-axis on Fig. 12 (the observed values) is less obvious than that on the X-axis (the predicted values). It is concluded that the thermal character of winter, particularly of July, reflects the state of thermal conditions of July and the ice extent in the Bellingshausen Sea and, in turn, reflect their thermal state in the February and March preceding a given July.

The coreless winters and the pattern of wind directions at the *Arctowski* Station

It is clearly important to determine the extent to which the differences in the direction of the air masses which flow towards the South Shetlands relate to those three types of winter specified above. In order to solve this problem, the wind pattern at the *Arctowski* Station in July has been analysed. Clearly, the regional trends of air flow will be distributed by local orographic features. Nevertheless, surface wind flow at the *Arctowski* Station broadly reflects the regional pattern.

Unfortunately, the data concerning the frequencies of the wind directions at the *Arctowski* Station for the analysed period 1982–1996 are incomplete. There are no data from July for the years 1990, 1992, 1993 and 1994; thus only 12 records are available. This set contains four cases of extremely coreless winters (the "A" group), five characterised by a weak core ("B") and only three which have a clearly marked cold core ("C").

Camparisons between the mean air temperatures in July and the frequencies of wind direction observed during 1978–1997 indicate several which are statistically significant. They are the correlations of monthly mean air temperature with:

– frequency percentage of winds from the E ($r = –0.559$, $p < 0.024$),
– frequency percentage of winds from the SE ($r = –0.649$, $p < 0.006$),
– frequency percentage of winds from the W ($r = 0.573$, $p < 0.020$),
– frequency percentage of winds from the NW ($r = 0.753$, $p < 0.001$),
– percentage of calm periods ($r = –0.777$, $p < 0.000$).

A strong positive correlation of frequencies of winds from the SE with the calm periods ($r = 0.759$, $p < 0.001$) and correlation of those from the NW with W ($r = 0.758$, $p < 0.001$) is established. The latter correlations indicate that an increase in the frequency of SE winds is generally accompanied by the increase in calm periods (and *vice versa*) and that an increase in the proportion of W winds by an increase in the proportion of NW winds.

One interpretation of the strong positive correlation of the SE winds with calm periods is this way that the increase in the frequency of SE winds is accompanied by periodical decreases in the intensity of atmospheric circulation over the South Shetlands (as evidenced by more frequent occurrence of anticyclonic situations there). This seems to be a result of the blocking effect of anticyclones which have centres located in the region of the South Shetlands. Accordingly, the region of the *Arctowski* Station may experience sharp radiant falls in air temperature. This explains the strong negative correlation between the mean temperature in July and the frequency of calm periods.

When an anticyclone, the centre of which is located south of the *Arctowski* Station and west of the Antarctic Peninsula, moves eastward slowly, a SE airflow prevails over the South Shetlands. Later, when the centre of this anticyclone translocates to the Antarctic Peninsula or over the Weddell Sea the central parts of the anticyclone lie over the South Shetlands and the weather is calm.

Strong positive correlation of the July air temperatures with the frequencies of W and NW winds is obvious if we take into consideration movement of depressions or the occurrence of parallel isobaric lines in the region of the South Shetlands (with lower pressure south of the South Shetlands). The obtained results follow the direction axes of the advection sectors which have the most significant influence on the thermal conditions at the *Arctowski* Station (Kejna 1999, Marsz and Styszyńska 2000).

Table 1 shows the proportion of wind frequencies which are most significant, *i.e.* those most strongly correlated with the mean air temperature in July and the proportion of calm periods for each of the winter groups specified above. Table 1 clearly reveals the principal differences in the proportion of W, NW, E and SE winds and the proportion of calm periods in the various groups. The coreless win-

Table 1

Percentage of E, SE, N, NW winds in July, percentage of calm periods in the observational period and their sums and the ratio of these sums in given years attributed to "A" group (extremely coreless winters), to "B" (winters with cold core weakly marked) and to "C" (winters with clearly marked cold core) and mean values for each concentration and their standard deviations (sn)

Type	Year	Percentage of winds from				% of calms [C]	Sum W+NW	Sum E+SE+C	(W+NW)/ (E+SE+C)
		E	SE	W	NW				
A	1984	3.1	6.3	19.0	24.0	8.3	43.2	17.7	2.4
	1985	1.6	2.1	25.3	24.0	3.2	49.3	6.9	7.1
	1989	1.2	1.2	29.1	26.2	1.7	55.3	4.1	13.5
	1993	–	–	–	–	–	–	–	–
	1996	4.8	12.9	20.2	20.2	0.0	40.4	17.7	2.3
	Mean	2.7	5.6	23.4	23.7	3.3	47.1	11.6	6.3
	σn	*1.42*	*4.62*	*4.05*	*2.17*	*3.10*	*5.74*	*6.18*	*4.56*
B	1982	4.2	4.0	7.3	6.1	0.0	13.4	8.2	1.6
	1983	17.9	3.0	14.5	16.7	5.6	31.2	26.5	1.2
	1988	8.6	11.9	14.0	16.3	23.0	30.3	45.3	0.7
	1991	15.5	11.7	20.8	11.4	4.0	32.2	31.2	1.0
	1992	–	–	–	–	–	–	–	–
	1997	9.5	10.0	14.3	16.2	13.2	30.5	32.7	0.9
	Mean	11.1	8.1	14.2	13.3	9.2	27.5	28.4	1.1
	σn	*4.94*	*3.84*	*4.27*	*4.11*	*8.14*	*7.09*	*11.49*	*0.32*
C	1986	11.8	14.3	12.3	12.8	26.2	25.1	38.4	0.7
	1987	12.5	8.0	13.4	11.2	20.6	24.6	41.4	0.6
	1990	–	–	–	–	–	–	–	–
	1994	–	–	–	–	–	–	–	–
	1995	19.3	28.3	8.4	1.8	29.7	10.2	77.3	0.1
	Mean	14.5	16.9	11.4	8.6	25.5	20.0	52.4	0.5
	σn	*3.38*	*8.46*	*2.15*	*4.85*	*3.74*	*6.91*	*17.67*	*0.23*

– lack of data concerning the frequency of wind directions in July in a given year.

ters ("A" group) are characterised by clear domination of W and NW winds. In all of those cases, the frequency of winds from these directions is more than twice that of E and SE winds and calm periods. Calm periods represent an insignificant percentage of observations (average about 3%), which indicates to the occurrence of increased atmospheric circulation in these years. In the case of winters characterised by a strongly marked cold core ("C" group) a domination of E and SE winds and calm periods over W and NW winds is observed. Further, the proportion of E and SE winds and calm periods is approximately twice the frequency of W and NW winds. Having only 12 years for the statistical analysis is insufficient to draw any far-reaching conclusions. Nevertheless, the available observational material suggests broadly that both the variability in the predominant directions of advections and the intensity of the atmospheric circulation may relate strongly to the types of winter experienced at the *Arctowski* Station.

Direct statistical correlations between the SST and the extent of sea-ice in the Bellingshausen Sea and the distribution of wind directions at the *Arctowski* Station

Direct statistical correlations between the hydrological elements of the Bellingshausen Sea (as analysed at the beginning of this paper) and the structure of the wind flow at the *Arctowski* Station are also possible. The analysis of the sea-ice extent in July at 080°W meridian and the proportion of NW winds at the *Arctowski* Station in July (15 cases) indicates, statistically, a significant linear correlation ($r = 0.7182$; $NW07[\%] = -187.5 + 3.1 \cdot ICE\varphi07$). This shows that the decrease in ice extent in July (when the ice edge moves southward) from 63°S to 67.5°S is accompanied by an increase in the frequency of NW winds at the *Arctowski* Station from about 8% to 22%. Similarly, statistically significant linear correlations may be observed between the SST in July in the [80,64] grid and the frequency of E and NW winds in the same month.

The relationship of the ice extent and SST with the percentage of winds at the *Arctowski* Station is clearly non-linear (Figs 12, 13 and 14). We obtain correlations which are statistically significant for some of the wind directions when polynomials are replaced by a linear equation. The frequency of east wind (E [%]) at the *Arctowski* Station in July is described by the following formula:

$$E\,[\%] = 145.78 - 2.53 \cdot ICE\varphi07 + 5.78 \cdot dSST07b, \qquad [8]$$

where $R = 0.80$, $d = 0.56$, $F(2,8) = 7.25$, $p < 0.016$, $SEe = 4.4$.

The frequency of west winds (W [%]) at the *Arctowski* Station in July is described by the following formula:

$$W\,[\%] = -183.24 + 3.26 \cdot ICE\varphi07 - 2.89 \cdot dSST07b, \qquad [9]$$

where $R = 0.79$, $d = 0.52$, $F(2,8) = 6.43$, $p < 0.022$, $SEe = 4.7$.

The sum of frequency of W and NW winds ($\Sigma(W, NW)$ [%]) is described by the following equation:

$$\Sigma(W, NW)\,[\%] = -399.07 + 7.05 \cdot ICE\varphi07 - 5.74 \cdot dSST07b, \qquad [10]$$

where $R = 0.82$, $d = 0.59$, $F(2,8) = 8.33$, $p < 0.012$, $SEe = 8{,}8$.

It should be noted that in all these formulae [8, 9 and 10] the same independent variables, i.e. the ice extent at 080°W meridian in July ($ICE\varphi07$) and the differences of SST between 48° and 60°S grids at 080°W meridian (dSST07b = SST07

$$z = -359.348 + 12.123 \cdot x - 784.08 \cdot y - 0.1 \cdot x^2 + 11.864 \cdot x \cdot y - 12.416 \cdot y^2$$

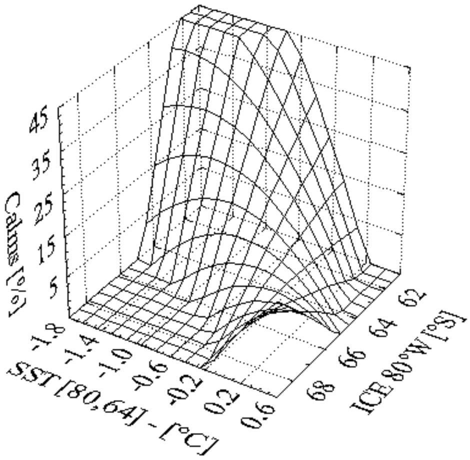

Fig. 13. The frequency of occurrence of calms [C, %] at the *Arctowski* Station in July – (z) as a function of SST in July in [80,64] grid – (y) and sea-ice extent in July at 080°W meridian – (x axis).

$$z = 3132.34 - 97.312 \cdot x + 556.183 \cdot y + 0.764 \cdot x^2 - 8.209 \cdot x \cdot y + 16.604 \cdot y^2$$

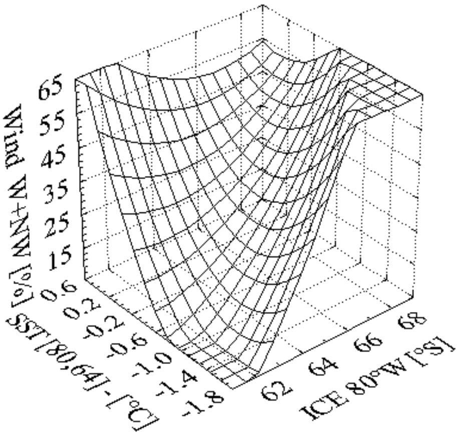

Fig. 14. Sum of frequencies of occurrence of W and NW winds [W + NW, %] at the *Arctowski* Station in July – (z) as a function of SST in July in [80,64] grid – (y) and sea-ice extent in July at 080°W meridian – (x axis).

[80,48] – SST07[80,60]) may be observed. The farther north the ice extent in July and the larger thermal gradient between latitudes 48° and 60°S at 080°W meridian, the higher the resulting percentage of E winds at the *Arctowski* Station. Conversely, when the ice limit migrates southwards along this meridian, and the me-

ridional gradient of SST decreases, the proportion of W winds and the sum of frequency of winds from sector W-NW increases respectively. Figs 12–14 indicate, that the proportion of NW and W winds and frequency of wind from S, SE and calm periods (as a function of ice extent and SST in the area 65°–63°S at 080°W meridian) are complementary values. It may therefore be concluded that at the *Arctowski* Station in July the same set of processes has influenced the frequency of winds from the opposite directions and the occurrence of calm periods.

The frequency of west winds and the sum of the frequency of W and NW winds may therefore be regarded as an indicator of the intensity of the zonal circulation in the southern hemisphere. The frequency of Et winds and calm periods may be regarded as a result of the blockage of the processes of zonal transportation of air masses in winter. The thermal conditions of the surface of the ocean situated west of the South Shetlands quite clearly influence the intensity of the zonal flow in winter.

Conclusion

The author considers that influence of the thermal conditions of the ocean on the changes in the atmospheric circulation over the South Shetlands region may be regarded as proved. By extention, modifications of the atmospheric circulation define the thermal character of the winters in the South Shetlands the following winter being either warm and coreless or one which has a strongly or weakly marked cold core.

To what extent the correlations of the regional hydrological characteristics of the sea areas with the occurrence of coreless winters are also representative of the coast of Antarctica is yet to be determined. However, it may be predicted that owing to the great similarities of the climatic system there to that described above, such correlations may also prove to be similar.

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