Climatic change on King George Island in the years 1948–2011

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Abstract: The climatic change on King George Island (KGI) in the South Shetland Islands, Antarctica, in the years of 1948–2011 are presented. In the reference period, a statistically significant increase in the air temperature (0.19°C/10 years, 1.2°C in the analysed period) occurred along with a decrease in atmospheric pressure (-0.36 hPa/10 years, 2.3 hPa). In winter time, the warming up is more than twice as large as in summer. This leads to decrease in the amplitude of the annual cycle of air temperature. On KGI, there is also a warming trend of daily maximum and daily minimum air temperature. The evidently faster increase in daily minimum results in a decrease of the diurnal temperature range. The largest changes of air pressure took place in the summertime (-0.58 hPa/10 years) and winter (-0.34 hPa/10 years). The Semiannual Oscillation pattern of air pressure was disturbed. Climate changes on KGI are correlated with changing surface temperatures of the ocean and the concentration of sea ice. The precipitation on KGI is characterised by substantial variability year to year. In the analysed period, no statistically significant trend in atmospheric precipitation can be observed. The climate change on KGI results in substantial and rapid changes in the environment, which poses a great threat to the local ecosystem.

Key words: Antarctic, South Shetland Islands, climate, air temperature, air pressure, precipitation, sea surface temperature, sea-ice.

Introduction

In recent decades, there have been substantial changes in the area of the Antarctic Peninsula, both in the Southern Ocean – changes of surface water temperature and sea ice (Abdukhov *et al.* 2006) and on the land – progressive deglaciation and ice-shelf disintegration (Vaughan and Doake 1996; Kejna *et al.* 1998; Birkenmajer 2002; Cook *et al.* 2005; Rückamp *et al.* 2011).

King George Island (KGI), also referred to as Ostrov Vaterloo and Isla 25 de Mayo, is situated in the Antarctic Peninsula region, characterised by some greatest variations of climatic conditions in the southern hemisphere (Smith *et al.* 1996; Jacobs and Comiso 1997; Kejna 1999b, 2003, 2008; van den Broeke 2000a; Doran *et al.* 2002; Domack *et al.* 2003; Vaughan *et al.* 2003; Ferron *et al.* 2004; Lagun *et al.* 2006; Chapman and Walsh 2007; Monaghan *et al.* 2008; Steig 2009; Stastna 2010). The variations result from the feedback between sea surface temperature, sea ice and atmosphere (Weatherly *et al.* 1991; King 1994; van den Broeke 2000b; Marsz 2011). The aim of this study is to analyse the trends of climate changes in the KGI area.

Data and methods

King George Island has been discovered in 1819 by William Smith. It is the largest of the South Shetland Islands with the surface area of about 1,310 km^2, 90 per cent of which is permanently glaciated (Fig. 1). There are ice caps with numerous glacial tongues and the snowline reaches 140–210 m a.s.l. (Birkenmajer 2002). The ice-free areas are either nunataks or coastal oases (Marsz and Rakusa-Suszczewski 1987; Marsz 2000), and the largest ice-free areas, namely the Fildes Peninsula, the Keller Peninsula, the Point Thomas and Three Brother's Hill, are situated in the southern part of the Island, where the climate is more favourable.

A number of research stations have been established on KGI. The oldest of them being the British research station called *Base G* or *Admiralty Bay* (AB), see Fig. 1. It was located in the area of Admiralty Bay, on the Keller Peninsula, and operated during 1948–1960. In the following years, no meteorological observations were carried out on KGI. Nevertheless, between 1944 and 1967, the *Deception* (DEC) scientific station operated on the nearby Deception Island, 120 km away from KGI. After a volcanic eruption on Deception Island the station was moved to Fildes Peninsula on KGI and renamed to *Eduardo Frei*, or *Marsh* Station (FRE since 1969). In 1968, a Russian station – *Bellingshausen* Station (BEL) was established on the Fildes Peninsula and it maintains the longest and most homogeneous data series, started in March 1968. In 1977, on the west shore of Admiralty Bay, at the foot of Point Thomas hill, the Polish station named after *Henryk Arctowski* (HA) was built; however, meteorological observations on that station were not performed continuously. In 1983, the site of the former British AB was taken by newly built *Comandante Ferraz* Station (FER) of Brazil. In 1985, three more stations were established: the Argentinean *Jubany* Station (JUB, in 2012 was renamed to *Carlini*), the Chinese *Great Wall* Station (GW) and the Uruguayan *Artigas* Station (ART). Three years later, in 1988, South Koreans built *King Sejong* Station (KS). Apart from permanent bases, there is a number of seasonal stations, such as the American *Peter Lenie* Station (*Copacabana*), the Peruvian
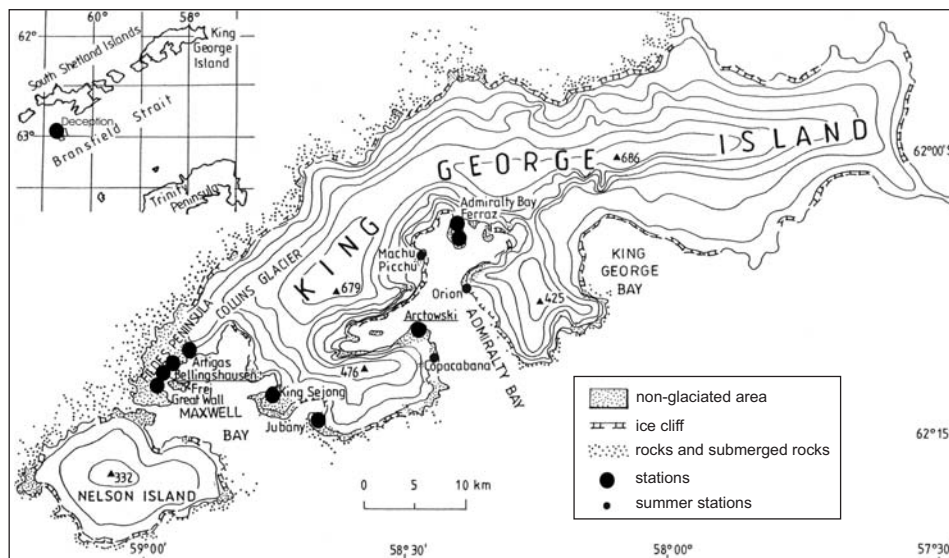
Fig. 1. Location of meteorological stations on King George Island and Deception Island. This map was prepared according to map *South Shetland Islands British Antarctic Territory*, 1968, sheet W6258, 1:200000, D.O.S. 610, London.

Machu Picchu Station and others. All stations maintain meteorological observations, yet their scope, instruments and measurement methods used are different (Kejna 1999b; Ferron *et al.* 2004); refer to Table 1.

In this article, data from READER (Reference Antarctic Data for Environmental Research) database were used, created as part of a project of the Scientific Committee on Antarctic Research (http://www.antarctica.ac.uk/met/READER/) and described by Turner *et al.* (2004), along with data from a database of the Russian Arctic and Antarctic Research Institute in Sankt Petersburg (http://www.aari.aq). Unfortunately, there are discrepancies between the two databases. For the BEL, the air temperature data was verified and adjusted by Marshall and Lagun (2001) and they are identical as the data stored in both READER and AARI databases. Differences of more or less 0.2°C occur between the databases in regards to more contemporary data. Here, the AARI database was used for the BEL station. More details concerning the data sources can be found in Table 1.

When analysing variations in air temperature in the area of the Antarctic Peninsula a combined data series from DEC and BEL stations is often used (Jones and Limbert 1987), also in other studies, *e.g.* Marshall and Lagun (2001). Jones and Limbert (1987) calculated the average difference of air temperature between DEC and BEL at 0.3°C. They used the difference by combining the two series of observations. However, other studies (Kejna 2008) demonstrated that the relationships between the two stations change throughout the year, increasing in the winter season. Therefore, this article includes a new analysis of the series of observations

Table 1

Meteorological stations on King George Island and Deception Island.

Station	Symbol	Latitude	Longitude	Elevation m a.s.l.	Period of measured	Source of data
King George Island						
Admiralty Bay	AB	62°03'S	58°25'W	7	1948–1960	1, 4
H. Arctowski	HA	62°10'S	58°28'W	2	1977–2000, 2006–	5
Artigas	ART	62°11'S	58°51'W	12	1986–	6
Bellingshausen	BEL	62°12'S	58°54'W	15	1968–	1, 2
Ferraz	FER	62°03'S	58°25'W	20	1986–2012	1, 3
Frei (Marsh)	FRE	62°12'S	58°54'W	20	1969–	1, 2
Great Wall	GW	62°13'S	58°57'W	15	1985–	1
Jubany	JUB	62°14'S	58°41'W	20	1985–	1
King Sejong	KS	62°13'S	58°45'W	15	1988–	1
Deception Island						
Deception	DEC	63°00'S	60°42'W	8	1959–1967	1

1 – READER (REference Antarctic Data for Environmental Research) – a project of the Scientific Committee on Antarctic Research, http://www.scar.org (Turner *et al.* 2004); 2 – National Antarctic Data Center of Arctic and Antarctic Research Institute (Sankt Petesburg, Russia); 3 – Brazilian Antarctic Program, http://www.cptec.inpe.br/antartica; 4 – Spravocnik po klimatu Antarktidy (1974, 1977); 5 – Rocznik Meteorologiczny "Arctowski" (1978–1989); 6 – Caracteristicas climatological de la Bahia Colins.

which yielded an air temperature and atmospheric pressure data series for the years 1948–2011.

In this study, the air temperature data from the following stations was used: AB (1948–1960), DEC (1948–1967), BEL (1968–2011) and FER (1986–2010), see Fig. 2. It was assumed that FER continued the measurements started at AB, as the two sites are just about 200 m apart. At the first stage, the correlation between air temperature at BEL and FER stations was determined. In the years of 1986–2010, the average difference of temperature between the two stations was -0.5°C. The differences were higher in the warmer half of the year (November -1.0°C, December -0.9°C) than in winter (June 0.2°C, July 0.0°C). The thermal relationship between the two stations varies during the year, therefore a transition coefficient had to be found for each individual month. There is a high correlation between the patterns of air temperature observed at both stations. The Pearson's linear correlation coefficient (r) for the mean annual temperature was 0.966, and in individual months it ranged from 0.643 in November to 0.987 in September. For each month, a regression equation was made for the two stations and the equations provided a basis for the calculation of the likely temperatures at BEL in the years of 1948–1960.

In 1961–1967, no meteorological data was collected on KGI. The nearest operating station was Deception (DEC). There are minor differences between the individual monthly air temperatures at AB and at DEC, however they range from 0.0°C in February and January to 0.9°C in September. The linear correlation between the
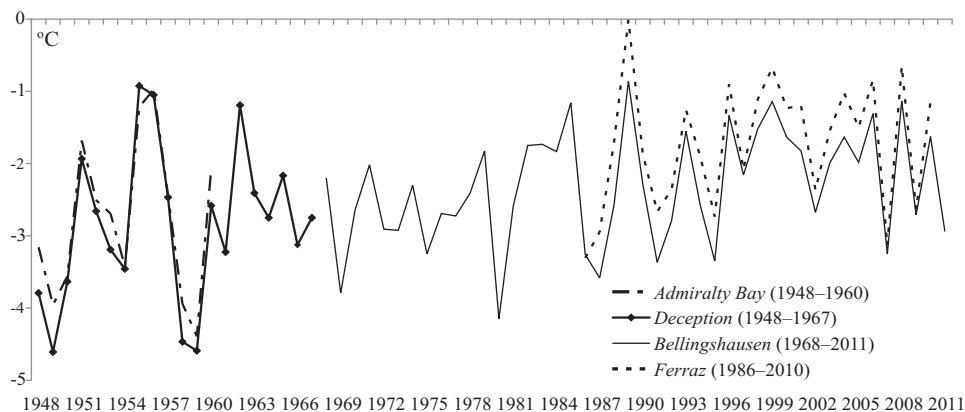
Fig. 2. Course of air temperature at the *Admiralty Bay*, *Bellingshausen*, *Deception* and *Ferraz* stations during 1948–2011.

courses of air temperature at those two stations is 0.978. Based on the regression equations for each month, the temperatures at AB in the years of 1961–1967 were calculated and then the same data was used to determine the temperatures at BEL, using the correlations found between BEL and FER. To that end, the series of air temperature data for BEL was extended backwards, however the series differs from the data obtained from Jones and Limbert (1987). The values obtained in the analysis are higher than those in the Jones and Limbert's series, particularly as far as the winter season is concerned (by 0.9°C in August), but in the summer the differences are smaller (December – none, January – 0.1°C, February – 0.3°C).

The variability of atmospheric pressure on KGI was analysed on the basis of the data series for 1948–2011. To that end, the data from AB station (1948–1960) was used and then the significant values were modified by subtracting between 1.0 and 1.2 hPa, depending on the month (*i.e.* the difference of pressure between BEL and FER stations in the years of 1994–2010). Afterwards, the relationship of pressure values between AB and DEC was determined. On average, the pressure at AB is 0.3 hPa lower, and there is a strong correlation between the pressure patterns at AB and DEC (for annual values of Pearson linear coefficient r = 0.993). Based on this assumption, the mean values were calculated for AB in 1961–1967, and then using the known correlation between BEL and FER, the values of atmospheric pressure at BEL in the same period were obtained.

Furthermore, this article also relies on monthly gridded data (with 1 degree latitude and longitude resolution) from Met Office Hadley Centre, for the sea surface temperature (SST) in 1948–2010 and the sea ice concentration figures for 1973–2010. SSTs are reconstructed using a two-stage reduced space optimal interpolation procedure, followed by superposition of quality-improved gridded observations onto the reconstructions to restore local detail. The sea ice fields are made more homogeneous by compensating satellite microwave-based sea ice concentrations (Rayner *et al.* 2003).

On the basis of the data monthly mean, values of SST and sea ice concentration were determined for individual seasons and for the whole year. Also, the Pearson's linear correlation coefficient (r) was calculated for the relationship between air temperature in the area of KGI and the SST and sea ice concentration values. As a result, areas around the Antarctic Peninsula were identified where variations in thermal properties of water and concentration of sea ice are coincident or opposite to the changes of air temperature.

Factors affecting the climate on King George Island

KGI is situated in the sub-polar latitudes, between 61°50'S (North Foreland) and 62°14'S (Stranger Point), which limits the potential influx of solar radiation. The solar elevation at local noon ranges from *ca* 5°(on 22 June) to 51°(on 22 December), and the daytime lasts from *ca* 4.5 hours to 19.5 hours. Given the considerable cloudiness, much solar radiation is scattered and the amount of solar radiation reaching the surface is low. The annual solar radiation balance is positive, but for a number of months it remains negative, especially as long as the snow cover persists, whose albedo reaches over 80% (Averjanov 1990).

The climatic conditions of KGI and Antarctic Peninsula region largely depend on the temperature of sea water and sea-ice extent in the area of the Antarctic Peninsula (King and Harangozo 1998; Marshall and King 1998; Comiso 2000; Marsz and Styszyńska 2000; Marshall *et al.* 2002; King and Comiso 2003; Morris and Vaughan 2003; Meredith and King 2005; Turner *et al.* 2005).

Based on the data from Met Office Hadley Centre from the years of 1948–2010 (Rayner *et al.* 2003), it has been noted that in the area of the Antarctic Peninsula the mean SST decreases southwards with the lowest values at the coast of Antarctic, where it falls to the freezing point. At the same time, an asymmetry with regard to the Antarctic Peninsula is noticeable. East of the peninsula, at the Weddell Sea the temperature is lower, which is due to the permanent sea ice cover and currents bringing very chilled Antarctic waters, formed at the mainland coast, into the sea basin. The SST is higher in the less ice-conditioned Bellingshausen Sea. During the year, there are slight fluctuations of the SST, in the range of a few degrees. The lowest SST can be observed in August, when it falls to the freezing point for sea water (*ca* -1.8°C) over large areas. The mean 0°C isotherm of the water runs from the polar circle on the Bellingshausen Sea, approximately 400 km north of KGI, to 56°S on the Weddell Sea (Fig. 3). The highest values of SST occur towards the end of summer, *i.e.* in February. At that time SSTs below zero persist over the entire area of the Weddell Sea and at the coast of West Antarctica. At the western coast of the Antarctic Peninsula, the SST is above zero, and in the area of KGI it exceeds 1°C. In the course of temperature, 2- and 6-year periodicity can be observed (Kejna 2008). White and Peterson (1998) distinguished a 4-year periodicity
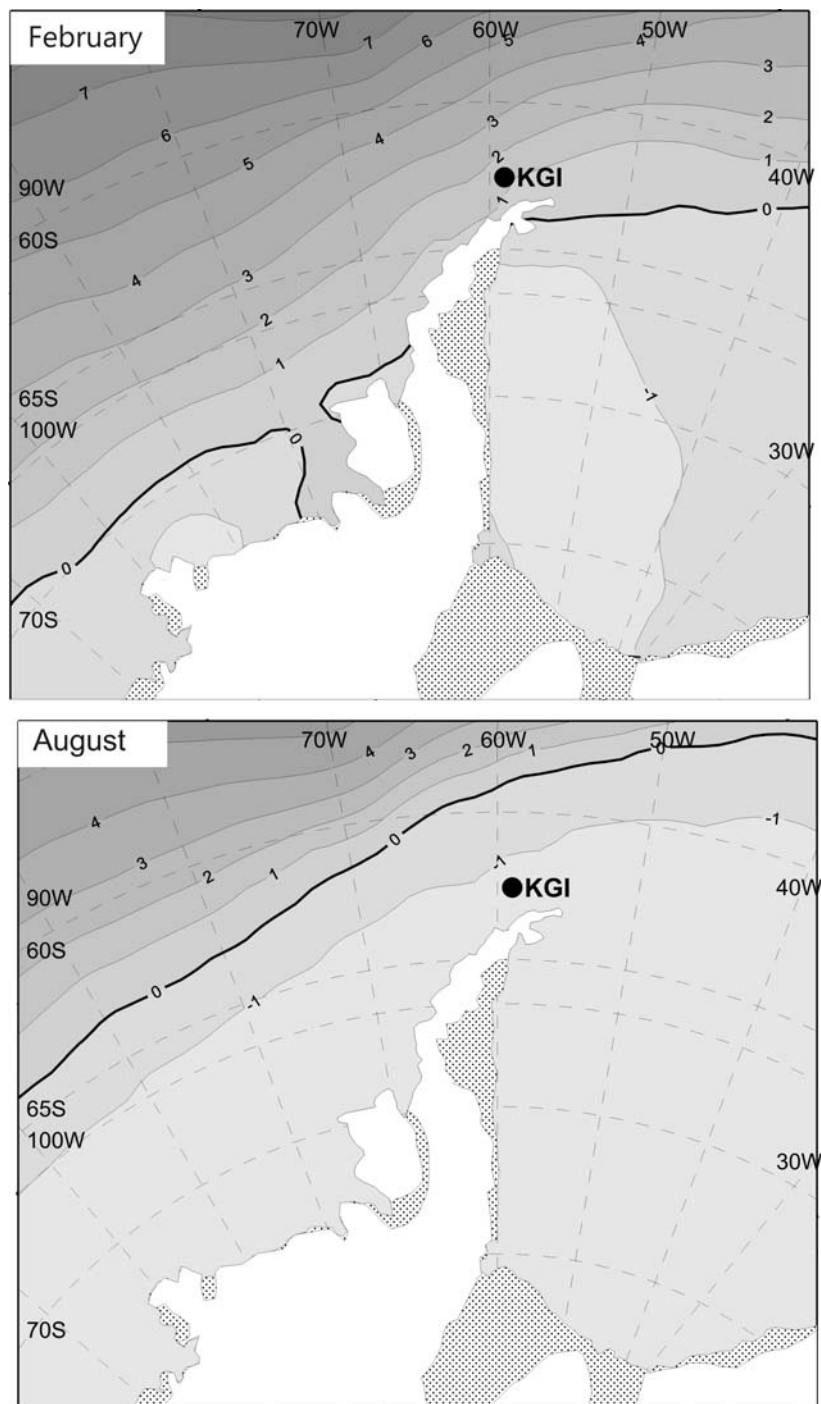
Fig. 3. Mean sea surface temperature (in °C) in February and August in the King George Island (KGI) region during 1948–2010. Data according to Met Office Hadley Centre (Rayner *et al.* 2003).

of SST, related to the oscillations within El Niño-Southern Oscillation and the Antarctic Circumpolar Wave.

The influence of the ocean on the atmosphere is reduced by sea ice. KGI is situated within the limits of the range of sea ice surrounding Antarctica (Zwally *et al.* 2002; Marsz 2011). Based on the data from Met Office Hadley Centre (Rayner *et al.* 2003), it has been found that the longest range of influence of the sea ice occurs in September. In the area of the Antarctic Peninsula, highly concentrated sea ice extends on the Weddell Sea as far as 50°S (Fig. 4). On the west side of the Peninsula, the range and concentration of sea ice are lower. In spring and summer, the sea ice melts fast and covers the smallest area in March. However, even in summer sea ice concentration of 80% or more still persists in the eastern part of the Weddell Sea. At the western coast of the Peninsula, no sea ice occurs in summer, or its concentration is negligible. KGI is sea ice free in summer, whereas in winter the limits of its influence stay a few hundred kilometres north of the KGI.

The air masses formed over the ocean and sea ice also affect the weather and climatic conditions of KGI (Schwerdtfeger 1975; Rogers 1983; Marshall and King 1998; Kejna 1999a, b; Marsz and Styszyńska 2000; Braun *et al.* 2001). The predominant type of air movement in the area of KGI is connected with western atmospheric circulation, constituting 70% (Kejna 1993). Cyclonic centres move from west to east along the Drake Passage. Besides, KGI is often influenced by the low formed on the western side of the Antarctic Peninsula, being the regional centre of atmospheric circulation (Jones and Simmonds 1994; Simmonds *et al.* 2004). On the eastern side of the peninsula, over the permanently ice-conditioned Weddell Sea, a high pressure wedge is often developed, bringing chilled Antarctic air masses from the south (Schwerdtfeger 1984). With substantial atmospheric pressure gradients and high dynamics of the atmosphere, the weather and climatic conditions in the area of KGI are very changeable.

Changes of the atmospheric pressure

The mean atmospheric pressure on KGI is very low and does not exceed the value of about 991 hPa. In the annual course of pressure, its semi-annual oscillation is evident (van Loon 1967). The highest pressure values (BEL) are found in the cool half of the year (994.7 hPa in May) and in summer (991.2 hPa in January). Lower pressure occurs in February (990.1 hPa) and November (987.9 hPa). The pressure courses show some waves, lasting from a few to a dozen or so days, resulting from the movement of cyclonic centres and influence of southern high-pressure centres. The passage of cyclones is accompanied by sudden and dramatic pressure drops below 960 hPa (Marsz and Styszyńska 2000).

The mean atmospheric pressure at BEL in the years of 1948–2010 was 991.6 hPa and its characteristic feature was the year-to-year variability (Fig. 5). The low-
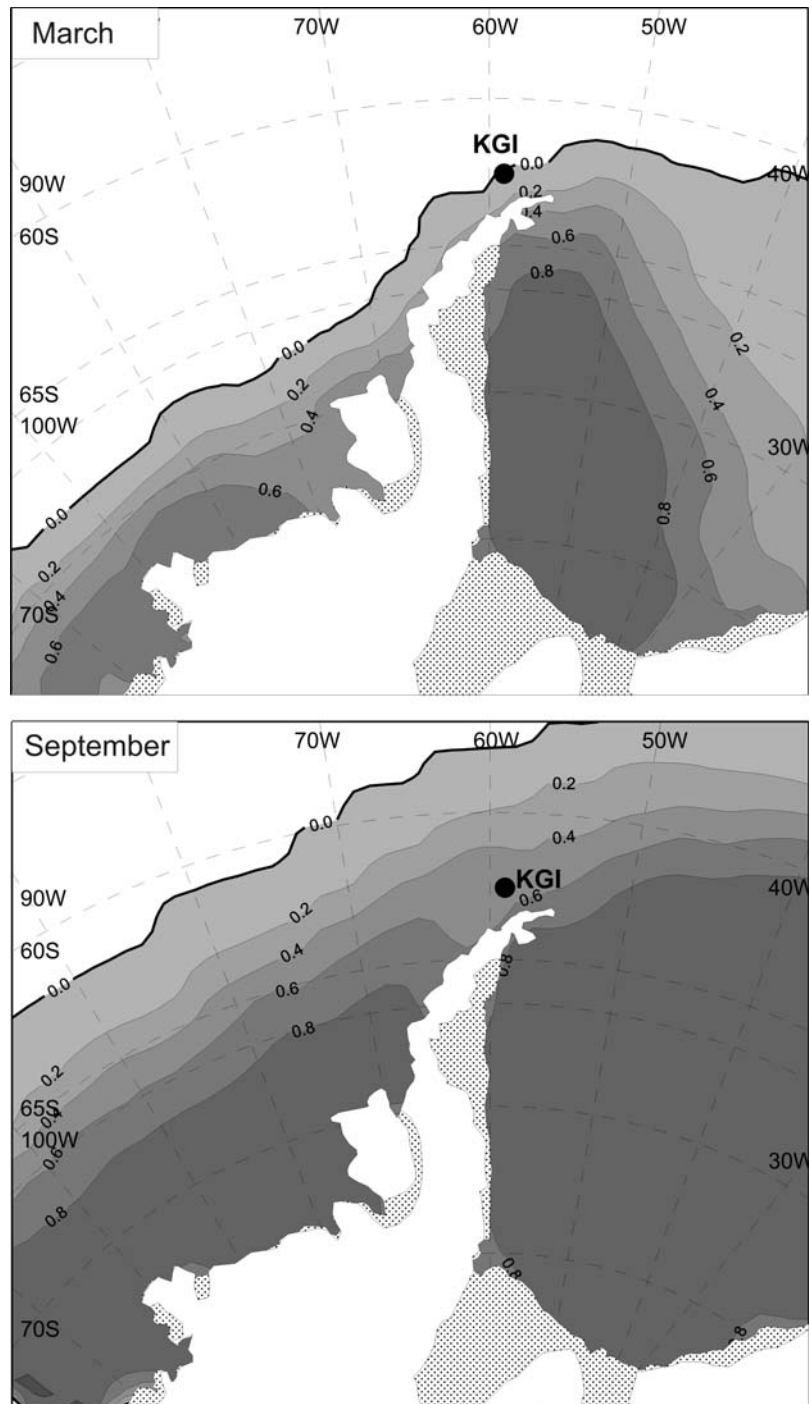
Fig. 4. Mean concentration of sea-ice in March and September in the King George Island region during 1973–2010, expressed in 0–1 scale. Data according to Met Office Hadley Centre (Rayner *et al.* 2003).
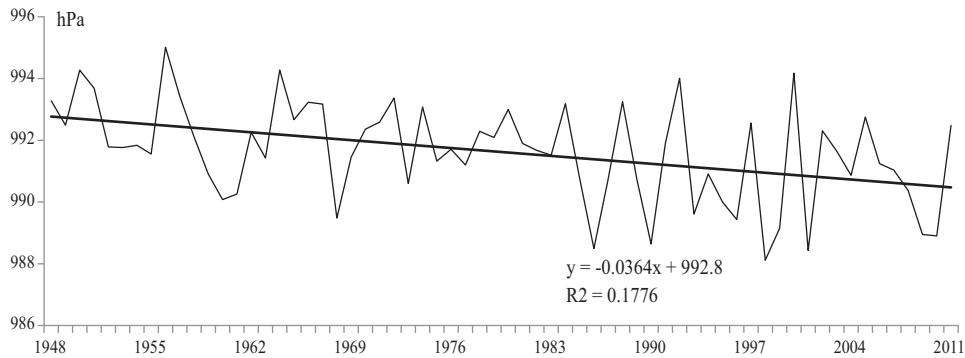
Fig. 5. Year-to-year course of air pressure at the *Bellingshausen* Station region during 1948–2011.
Explanations in the text.

est values were determined for the years 1998 (988.1 hPa), 2001 (988.4 hPa), 1986 (988.5 hPa), 2010 (988.9 hPa) and 2009 (989.0 hPa), whereas the highest were in 1956 (995.0), 1950 and 1964 (994.3 hPa). In the period of reference, a statistically significant ($p < 0.05$) decreasing trend in the atmospheric pressure can be seen, reaching -0.36 hPa/10 years ($p = 0.0005$). The pressure drops about 2.3 hPa as compared to the initial value at the beginning of measurement.

The largest changes took place in the summertime (-0.58 hPa/10 years) and winter (-0.34 hPa/10 years). The Semiannual Oscillation pattern of air pressure was disturbed. In the years of 1981–2011, as compared to 1948–1980, the winter maximum on KGI decreased, with higher values occuring in May (Fig. 6). The secondary summer maximum is also hardly noticeable. The pressure dropped in spring (*i.e.* in November) and in summer (December and January).
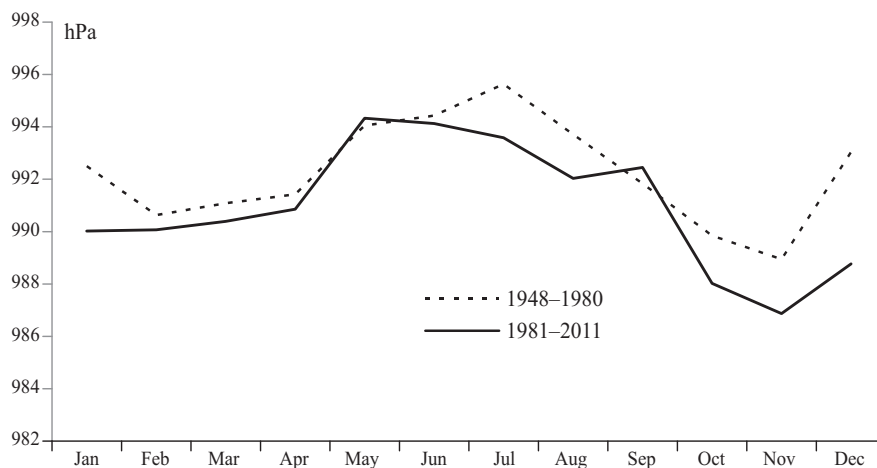

Fig. 6. Annual courses of air pressure at the *Bellingshausen* Station region during 1948–1980 and 1981–2011.

Changes of the air temperature

In the years of 1948–2011, the mean temperature of the air on the KGI (BEL series) was -2.5°C (Table 2). At the same time, the temperature was considerably variable and from time to time notably cooler years occur, for example: 1959 (-4.3°C), 1980 (-4.2°C), 1958 (-4.1°C) and 1949 (-3.9°C), or warmer years: 1989 (-0.9°C), 1999 and 2008 (-1.1°C), 1985 (-1.2°C).

Table 2

Mean monthly and annual air temperature (in °C) at *Bellingshausen* Station during 1948–2011.

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1948–1950	1.1	0.5	-0.3	-4.1	-5.4	-6.9	-10.0	-9.0	-5.3	-2.5	-1.9	0.2	-3.6
1951–1960	1.2	1.4	-0.1	-2.0	-4.9	-6.3	-7.9	-6.9	-4.5	-2.8	-1.2	0.0	-2.8
1961–1970	1.3	0.9	-0.2	-2.2	-5.0	-6.6	-6.4	-6.5	-3.4	-2.7	-1.4	0.2	-2.7
1971–1980	1.3	1.3	0.5	-1.8	-3.7	-5.8	-8.0	-8.1	-5.2	-2.4	-1.3	0.3	-2.7
1981–1990	1.4	1.8	0.6	-2.1	-4.1	-5.1	-5.6	-5.5	-4.0	-2.7	-1.1	0.3	-2.2
1991–2000	2.0	1.8	0.5	-0.9	-3.4	-5.1	-6.4	-6.1	-4.9	-2.9	-1.0	0.6	-2.1
2001–2010	1.6	1.7	0.4	-1.7	-2.8	-5.6	-6.2	-5.0	-3.3	-2.5	-1.1	0.3	-2.0
1948–2011	1.4	1.4	0.2	-1.9	-4.0	-5.8	-6.9	-6.5	-4.3	-2.6	-1.2	0.3	-2.5

In the course of air temperature, three periods can be seen: from 1948 to 1963 there were large temperature fluctuations, from 1964 to 1979 the patterns are balanced and after 1980 the temperature tends to vary substantially year to year (Fig. 7). With high oscillation in the reference period, a gradual increase of temperature occurs. The years of 1948–1950 were definitely the coldest (-3.6°C); in the years of 1951–1960 the mean temperature was -2.8°C, and in 1991–2000 and 2001–2010 it went up to -2.0°C (Table 2). In the cold 1950s, the impact of sea ice was much larger than today (King and Harangozo 1998).

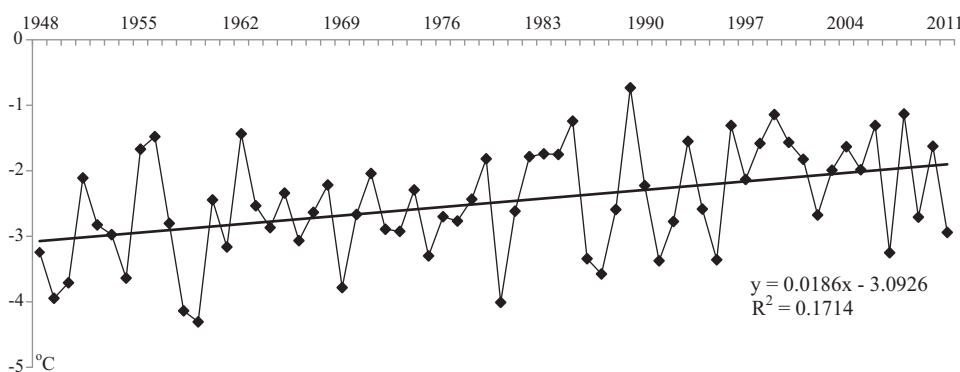$$y = 0.0186x - 3.0926$$
$$R^2 = 0.1714$$

Fig. 7. Year-to-year course of air temperature at the *Bellingshausen* Station region during 1948–2011.

On KGI, a statistically significant temperature increase is observed, reaching 0.19°C/10 years (p = 0.0007). The increase involves all seasons of the year, except spring (summer: 0.11°C/10 years, p = 0.0005; autumn 0.25°C/10 years, p = 0.001 and winter 0.31°C/10 years, p = 0.021). In wintertime, the warming up is more than twice as large as in summer (*e.g.* in August 0.37°C/10 years and in February 0.16°C/10 years). This leads to a flattening of the annual amplitude of air temperature, but it does not provide a statistically significant trend. As a result, the local thermal oceanity of the climate is more evident (Styszyńska and Zblewski 2002).

During 1981–2011, as compared to 1948–1980, air temperature increased in summer, autumn and winter seasons. In spring there is no significant temperature change.

The most noteworthy warming occurred in May (0.45°C/10 years, p = 0.013) and August (0.37°C/10 years, p = 0.033), however in summer the increase was not as large (*e.g.* February 0.16°C/10 years, p = 0.002), see Fig. 8. Marshall *et al.* (2002) also found the most significant temperature increase at BEL in the summertime (1968–2000).

On KGI, there is also a growing trend of averaged daily maximum (T_{max}) and minimum (T_{min}) air temperature (Fig. 9). In the years of 1968–2011 at BEL T_{max} went up by 0.6°C (0.14°C/10 years, p = 0.062), whereas T_{min} rise up by 1.3°C (0.30°C/10 lat, p = 0.009). The biggest changes of T_{max} and T_{min} occurred in August (0.55°C and 0.99°C/10 years, respectively), and May (0.43°C and 0.81°C/10 years). The evidently faster increase in T_{min} results in a decrease of the diurnal temperature range, which in the reference period dropped by 0.7°C (trend -0.18°C/10 years, p = 0.001).

Response of air temperature on King George Island to the sea surface temperature and sea-ice

The air temperature on KGI is connected with changes in the SST and the sea ice concentration in the Antarctic Peninsula region. An analysis of the SST data collected in the years of 1941–2010 has revealed that at moderate latitudes there is a slight, yet statistically significant, increase of the SST. The most notable changes have taken place in the north of the Bellingshausen Sea, where the SST trend is 0.2–0.3°C/10 years in winter and spring (in summer and autumn the increase is smaller), see Fig. 10. Only at the coastline of the continent, some cooling can be noticed. According to the results of research carried out by Marsz (2005), most of the cooling occurs in cold season (May–August).

The thermal properties of the waters west and north of the island are fundamental for the thermal conditions on KGI, as that is where most of the air masses come from. The strongest relationship (r > 0.5) occurs in winter (Fig. 11), when
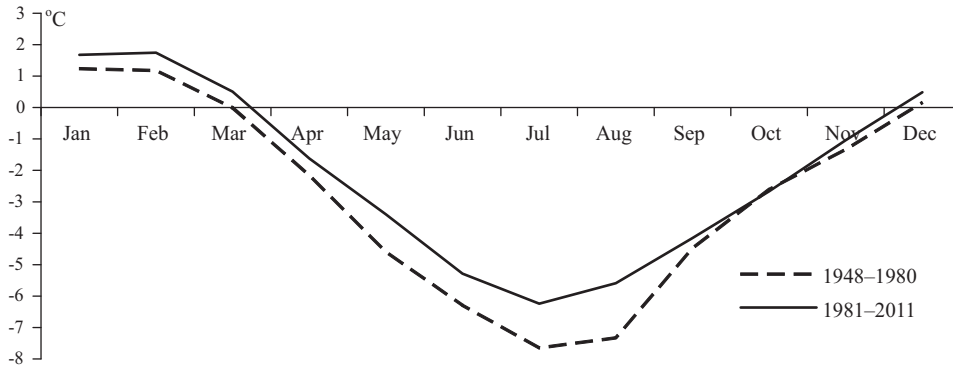
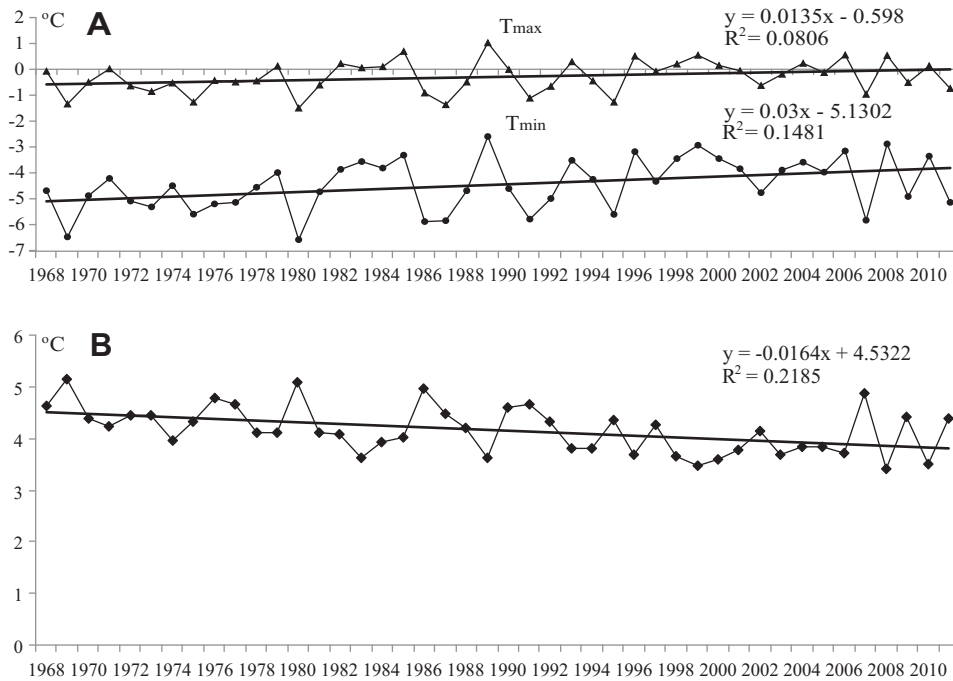Fig. 8. Annual courses of air temperature at *Bellingshausen* Station during 1948–1980 and 1981–2011.

Fig. 9. Year-to-year course of mean daily maximum (T_{max}) and daily minimum (T_{min}) – (A) and daily temperature range (B) at *Bellingshausen* Station during 1968–2011.

thermal contrasts and heat transfers between the water and air are the largest. The influence of the thermal conditions of the ocean on the changes in the atmospheric circulation may 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 (Styszyńska 2004).
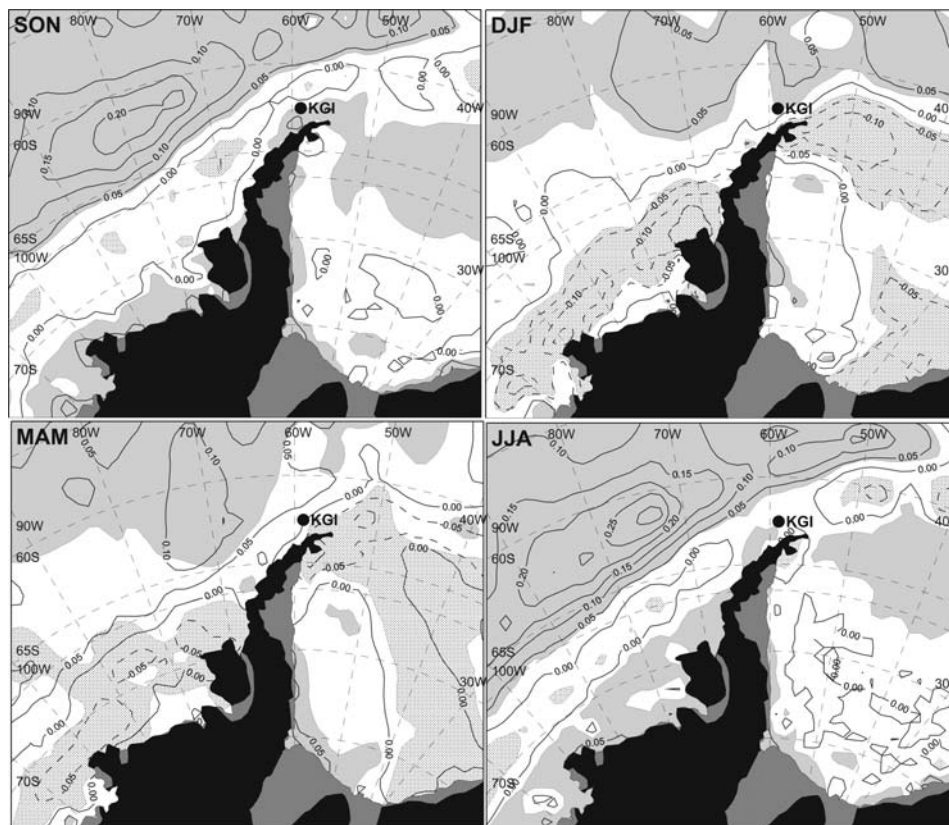
Fig. 10. Trends of sea surface temperature (in °C/10 years) in the Antarctic Peninsula region in the period 1948–2010. Grey area means significant trend at the level 0.05. SON – spring, DJF – summer, MAM – autumn, JJA – winter. Data source is Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) – Rayner *et al.* (2003).

The increase of SST affects the reach and concentration of sea ice. The relationship is disturbed by the sea ice drift connected with the direction of sea currents and the activity of wind. Summertime temperatures are particularly significant here, as the absorbed energy delays forming of the ice cover in autumn, thus influencing the maximum reach of sea ice at the end of winter (Weatherly *et al.* 1991). In the analysed area, both are evidently reduced. The area of the Bellingshausen and the Amundsen Sea is characterised by the highest variability of ice cover in the whole of Antarctic, both during the year and in a year-to-year perspective (Gloersen *et al.* 1992; Parkinson 1992). Changes in the location of sea ice margins in winter on the Bellingshausen Sea (70°) reach 0.9–1.9°, and even 4.5° latitude in summer. During the years 1973–2010, the most changes in the concentration of sea ice have occurred in the area of their maximum reach (Fig. 12). This trend is visible in all seasons of the year, however the largest differences in concentration, reaching 1% per year, can be seen in spring. Summer shows less changes (up to 0.2% per
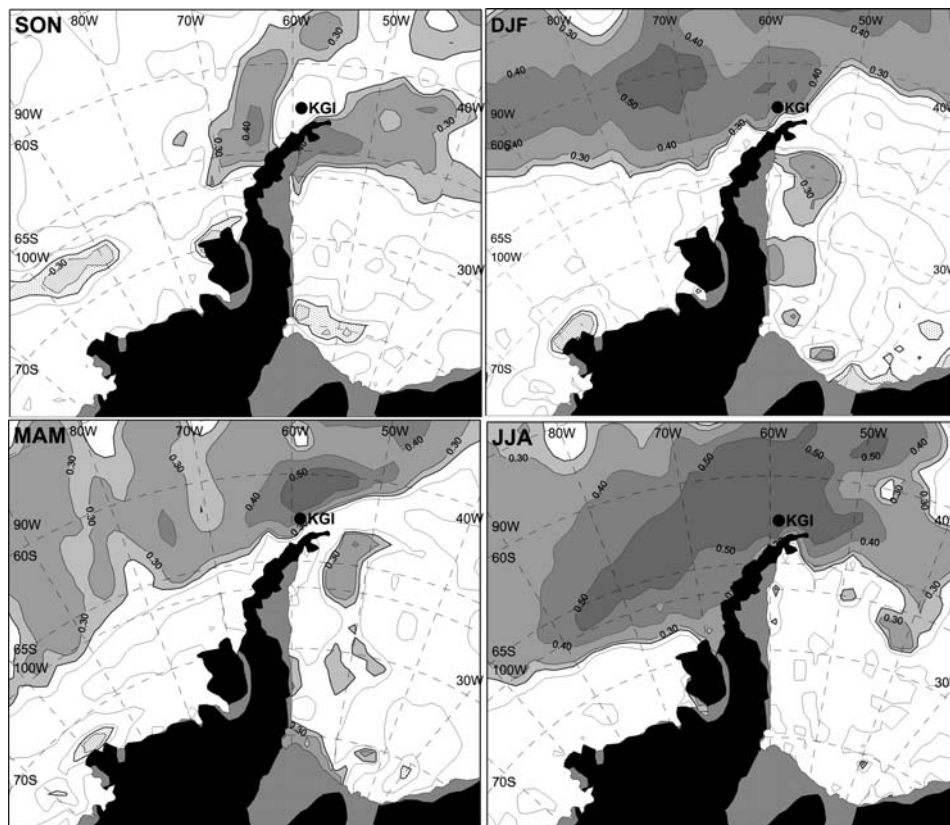
Fig. 11. Pearson correlation index between sea surface temperature and air temperature on the King George Island in the period 1948–2010. Grey area significance at 0.05 level. SON – spring, DJF – summer, MAM – autumn, JJA – winter.

year). As a result, the surface area of sea ice on the Amundsen Sea and the Bellingshausen Sea has shrunk. During 1979–1998, the ice receded southwards by 1 degree of latitude (Zwally *et al.* 2002). Warming of the upper 25 m of the water column is equivalent to the energy required to form about 0.3 m of sea ice (Meredith and King 2005).

SST explain the decline in sea ice extent in the Bellingshausen Sea and increase in the air temperature in the region of the Antarctic Peninsula (Marsz 2011). The decreasing concentration of sea ice and its diminishing reach also affect the increase of heat and humidity transferred from the ocean to the atmosphere. The location and trajectories of barometric centres change and so does the atmospheric dynamics, which leads to changes of thermal and precipitation conditions. The decreasing concentration of sea ice is correlated with the increase of air temperature in the KGI region. The connection can be best seen in winter – a strong influence of the ice directly surrounding KGI ($r < -0.6$). In summer and autumn, predominantly
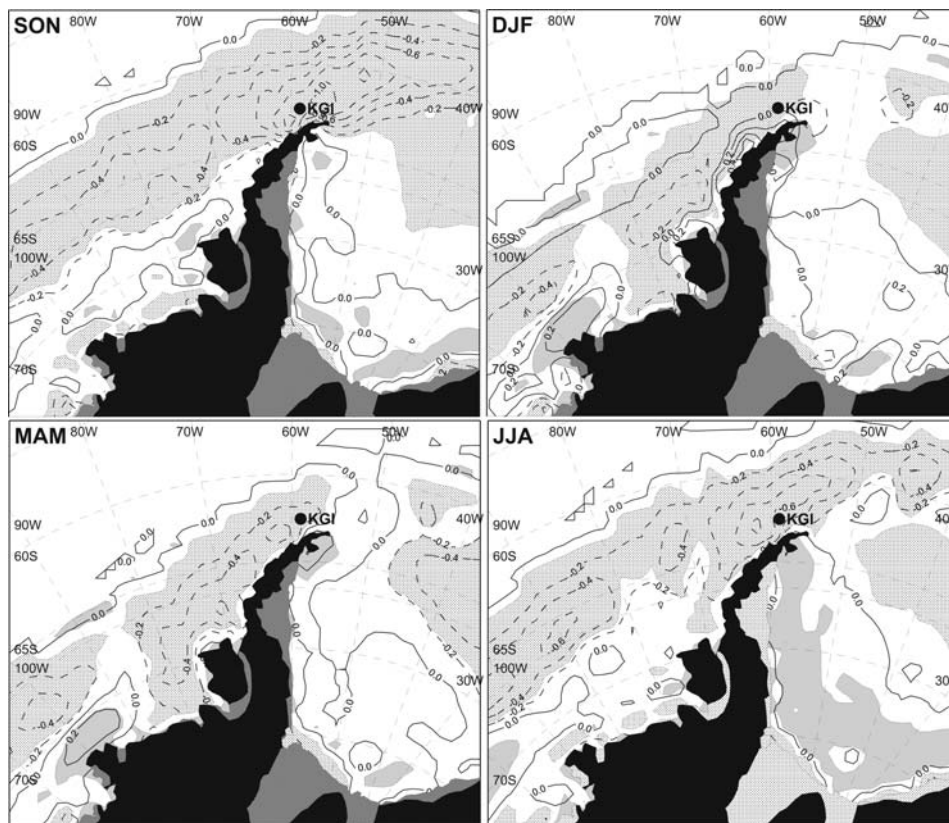
Fig. 12. Trends of sea ice concentration (in %/year) in the Antarctic Peninsula region during 1973–2010. Grey area means significant positive and negative trend at the level 0.05. SON – spring, DJF – summer, MAM – autumn, JJA – winter. Data source is Hadley Centre Sea Ice and Sea Surface Temperature data set (Rayner *et al.* 2003).

as far as the Bellingshausen Sea is concerned (at grid 67°S, 90°W r < -0.8), see Fig 13. In winter, a strong influence of the ice directly surrounding KGI (r < -0.6). The weakest, yet still statistically significant, correlation occurs in autumn. Similarly, for HA station there is a relationship between air temperature and sea ice, whose concentration exceeds 40% at Bransfield Strait (r = -0.86) (Styszyńska 1997). For BEL, the strongest correlation is found in July (r = -0.59) when the sea ice reaches 70°W, and there is a minor connection with the sea ice on the Weddell Sea and in the Drake Passage (Styszyńska 1999). The impact of sea ice in the area of this meridian is also essential for Faraday Station, as it influences its thermal conditions, especially in winter and spring (Jacka 1990; Smith *et al.* 1996; Jacobs and Comiso 1997). The variability of sea ice at 70°W accounts for over 60% of temperature fluctuations at Faraday in July. In summer and autumn, the influence of sea ice is insignificant, as they cover only a small area of the coast of PA (King 1994).
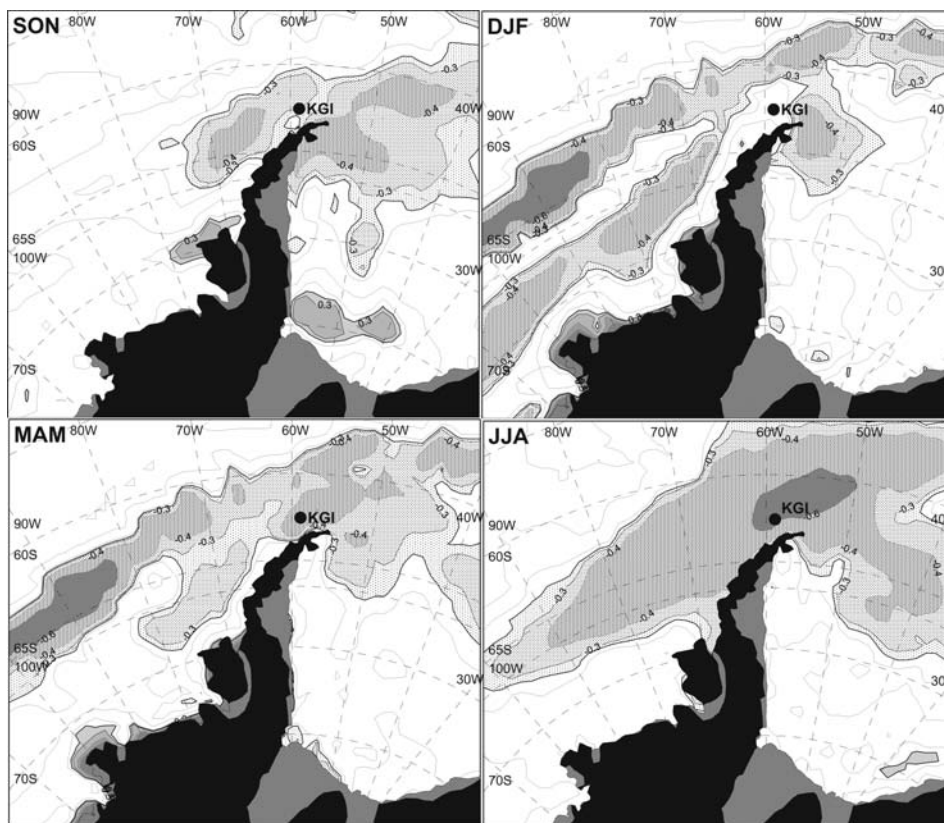
Fig. 13. Pearson correlation index between sea-ice concentration and air temperature on the King George Island during 1973–2010. Grey area significance at 0.05 level. SON – spring, DJF – summer, MAM – autumn, JJA – winter.

Changes of the precipitation

During 1968–2011, the mean sums of precipitation at the BEL was 701.3 mm (Table 3). At the same time wet 1968–1970 (768.4 mm), 1991–2000 (719.5 mm) and dry 1971–1980 and 1981–1990 (with 687.2 mm and 686.0 mm respectively)

Table 3

Mean monthly and annual precipitation at *Bellingshausen* Station in the period 1968–2011.

| Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1968–1970	43.2	71.5	47.6	75.3	69.7	89.3	63.8	79.1	65.5	62.0	65.1	36.5	768.4
1971–1980	41.5	69.7	70.3	69.9	63.5	46.4	50.2	70.9	64.5	49.1	39.7	51.6	687.2
1981–1990	45.3	67.0	84.0	59.1	59.7	47.0	54.1	58.7	57.6	50.1	53.8	49.8	686.0
1991–2000	76.8	61.4	66.3	63.9	49.4	66.9	77.7	63.3	54.2	48.1	47.3	44.2	719.5
2001–2011	62.6	70.0	75.1	63.6	60.8	41.6	59.7	46.6	61.0	63.5	42.4	46.1	693.2
1968–2011	55.8	67.4	72.2	64.9	59.2	52.9	60.6	60.9	59.8	53.6	47.0	47.1	701.3
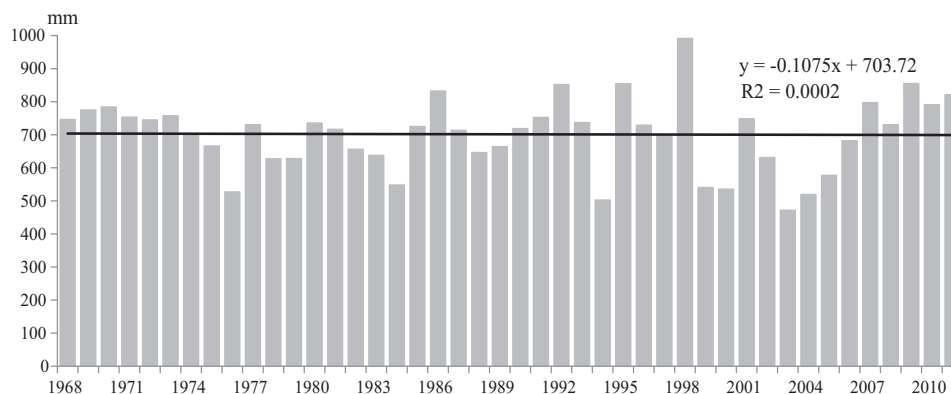
Fig. 14. Year-to-year precipitation at *Bellingshausen* Station during 1968–2011.

periods occurred. The precipitation on KGI is characterised by substantial variability year to year (Kejna and Lagun 2004). During 1968–2011, the annual precipitation total at BEL ranged from 434.2 mm in 1994 to 893.7 mm in 1998.

In the analysed period, no statistically significant trend in atmospheric precipitation can be observed (Fig. 14). Only in January, increasing trend (7.2 mm/10 years) and in August decreasing trend (-8.0 mm/10 years) in the precipitation can be seen. Along the western side of the Antarctic Peninsula (Faraday Station), the number of precipitation events increased. Precipitation on the western side of the Antarctic Peninsula is dependent on synoptic weather system activity. The number of precipitation is associated with changes in the depression tracks across the Bellingshausen Sea, with an increase in the number of depressions approaching from outside the Antarctic rather than from the west (Turner *et al.* 1997).

Summary and concluding remarks

In recent decades, there have been substantial environmental changes in the area of the Antarctic Peninsula, in the Southern Ocean expressed by changes of surface water temperature and the ice condition, and on the land including progressive deglaciation and ice-shelf disintegration. As a result of the feedback between the ocean, cryosphere and atmosphere, significant changes have occurred in the climatic conditions in the area of the Antarctic Peninsula. The thermal conditions of the ocean surface are particularly important, as it is where the air masses over King George Island come from.

The climatic conditions on KGI are characterised by their considerable year-to-year variability, resulting from the interactions between the ocean, sea ice and atmosphere. On the KGI, decreasing trend in the atmospheric pressure

can be seen, reaching -0.36 hPa/10 years (pressure drop about 2.3 hPa during the years 1948–2011). The most pronounced changes took place in the summertime (-0.58 hPa/10 years) and winter (-0.34 hPa/10 years). The Semiannual Oscillation pattern of air pressure was disturbed. The winter maximum decreased with higher values occurring in May, the pressure dropped in spring, *i.e.* in November, and in summer months December and January. The changes of air pressure are connected with the movement of the circumantarctic low pressure trough in the transitional seasons and the expansion of the high over the Antarctic Peninsula in winter (van den Broeke 2000b).

In the years of 1948–2011, a statistically significant increase of air temperature occurred, reaching 1.2°C, *i.e.* 0.19°C/10 years. The warming up affected all seasons, except for spring. Significant changes took place from January to May and in August. In wintertime, the warming up is more than twice as large as in summer. This leads to increased thermal oceanic influence on the climate.

The air temperature on KGI depends from changes in the SST and the reach of sea ice, which not only influences thermal conditions of the air masses lying over, but also modifies the atmospheric circulation. The changes in SST and sea ice concentration also affect the atmospheric circulation in the area. The 500 hPa isobaric surfaces have been brought down over the Amundsen Sea and the Bellingshausen Sea, which is negatively correlated with the air temperature in the area of the Antarctic Peninsula, *e.g.* for *Faraday* Station they account for 40% of temperature variances (Marshall and King 1998). The pressure oscillations between temperate and high latitudes also affect the climate in the area. This mode is referred to as the Southern Hemisphere Annual Mode or Antarctic Oscillation (Thompson and Wallace 2000).

On KGI, there is a negative trend of atmospheric pressure (-0.34 hPa/10 years), which leads to an increased pressure gradient, as compared to temperate latitudes. The high Antarctic Oscillation indices (high differences in pressure) are accompanied by high winds, the north component of the wind increases and, as a consequence, the temperature in the area rises (van den Broeke and van Lipzig 2003). On the other hand, attenuation of western winds results in cooling and *vice versa*.

In the analysed period of 1968–2011, no statistically significant trend in precipitation at *Bellinghshausen* Station can be observed. Only in January, increasing trend, and in August decreasing trend, can be observed. However, further to the south at Faraday Station, the precipitation increased, according to data for the years of 1956–1992. The increase is connected with the diminishing sea ice and the intensification of evaporation, a higher humidity of the air and more dynamic cyclonic activity, especially in the winter season (King and Turner 1997).

On KGI, the climate change results in substantial and rapid changes in the environment, such as deglaciation, which poses a great threat to the local ecosystem (Olech and Masalski 2001; Rakusa-Suszczewski 2003).

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