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Climatic conditions at Arctowski Station (King George Island, West Antarctica) in 2013–2017 against the background of regional changes

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Abstract: Meteorological conditions at Arctowski Station during 2013–2017 were presented against the background of regional climate changes, especially air temperature decline. Air temperature, relative air humidity, air pressure, solar radiation, wind speed and direction, snow cover and precipitation were collected with an automatic weather station and manual measurements and were further analysed. The obtained results were compared with data from previous years and with data from other stations located on King George Island. Our observations confirm that the vicinity of Arctowski Station experienced a decrease in air temperature during summer, which supports the hypothesis of regional cooling.

Key words: Antarctica, South Shetlands, Admiralty Bay, meteorological measurements, climate change.

Introduction

In the second half of the XX century, the Antarctic Peninsula region exhibited very rapid regional warming (Kejna 1999; Turner *et al*. 2005; Stastna 2010; Kejna *et al*. 2013a), which resulted in significant landscape changes, especially glacier mass loss and retreat. Since the end of the XX century, local cooling effects have been observed in this area (Carasco 2013; Turner *et al*. 2016; Oliva *et al*. 2017). According to Oliva *et al*. (2017), mean annual air temperature in decade 2006–2015 at South Shetland Islands (stations Bellingshausen, Marsh and King Sejong in Maxwell Bay) is *ca*. 0.5°C, lower than during the 1996–2005 decade, and is almost the same or slightly higher than in 1986–1995. Similar situation is observed at the northern most part of Antarctic Peninsula at stations O'Higgins and Esperanza (Oliva *et al*. 2017). According to Turner *et al*. (2016), the change in temperature trend was a consequence of the increase in annual mean sea ice concentration around the northern part of the Weddell Sea and northern part of the Antarctic Peninsula, which was also observed in 1998–2014 and was the result of increased cyclonic conditions in the Drake Passage and the north-western Weddell Sea.

As mentioned above, warming caused significant changes in glacier sizes and their front positions, both in the Antarctic Peninsula and South Shetland Islands (Cook *et al*. 2005; Ruckamp *et al*. 2011; Davies *et al*. 2012; Fieber *et al*. 2018). For example, during 1956–2012, glacier mass loss varied from 0.005 GT (Urbanek Glacier, King George Island) to 0.750 GT (Stadium Glacier, Elephant Island; Fieber *et al*. 2018). Sobota *et al*. (2015) pointed out that the Ecology and Sphinx Glacier System (King George Island) lost 41% of its area between 1979 and 2012. However, there were differences in the rates of glacier mass loss and retreat in particular decades. The fastest mass loss occurred in the last two decades of the XX century and then steadily decreased in the second decade of the XXI century (Kejna *et al*. 1998; Davies *et al*. 2012; Pętlicki *et al*. 2017; Pudełko *et al*. 2018). The rate of decrease in all glaciers at western shore of Admiralty Bay changed from a maximum of 0.097 km^2/year during 1989–2001 to a minimum of 0.026 km^2/year during 2011–2018 for land-terminating glaciers and from a maximum of 0.140 km^2/year during 2001–2007 to a minimum of 0.034 km^2/year in 2011–2018 for tidewater glaciers (Pudełko *et al*. 2018). This slowdown seems to be a result of temperature decrease (Oliva *et al*. 2017; Pętlicki *et al*. 2017).

Most of the above research was based on data from stations located on the Antarctic Peninsula and western part of King George Island (mainly Bellingshausen Station), and they lacked observations from the Admiralty Bay area, which is located in the central part of King George Island. Therefore, the main goal of this paper is to verify whether the meteorological conditions, especially air temperature, at the western shore of Admiralty Bay followed the recent cooling that is observed in the region (Turner *et al*. 2016; Oliva *et al*. 2017; Pętlicki *et al*. 2017). To answer this question, meteorological data from the Henryk Arctowski Polish Antarctic Station from 2013–2017, which was the only continuous 5-year long data set recorded in the XXI century at that location, were investigated. The second goal is to analyse the meteorological conditions in the vicinity of Arctowski Station during 2013–2017 and compare the results with previous works that were conducted in Arctowski Station, especially during the period 1977–1998 (Kejna and Laska 1999; Marsz and Styszyńska 2000; Kejna 2008; Angiel *et al*. 2010; Kejna *et al*. 2013b), and with available meteorological data from the period 2013–2017 collected at other scientific stations located at King George Island (GSOD 2018).

Study area

King George Island is located in the South Shetlands Archipelago, approximately 120 km north of the Antarctic Peninsula, and has a total area of 1250 km^2 (Fig. 1; Simoes *et al*. 1999). More than 90% of the island is covered by glaciers, which descend towards land or sea as glacier tongues or icefalls at the margin (Simoes *et al*. 1999; Rückamp and Blindow 2012). The highest part of the glacier cap has an elevation of up to 700 m a.s.l. in central part of the island, north of Martel Inlet, and western part of the island on the Arctowski Icefield (Braun *et al*. 2001; Rückamp and Blindow 2012). According to ground-penetrating radar studies conducted in the west and north-west parts of the island, the maximum ice cap thickens is approximately 420 m (Blindow *et al*. 2010; Rückamp and Blindow 2012). Notably, the glaciers located on the western shore of Admiralty Bay are land based with a well-developed hydrological system characterized by sudden and rapid outflows of water from the glaciers (Rachlewicz 1997; Sziło and Bialik 2017; Szopińska *et al*. 2018).

Arctowski Station is situated on the western shore of Admiralty Bay on a low sea terrace, which is surrounded by terrain to the south and west at elevations from 60 to 170 m a.s.l. (Pudełko 2002). The location of the island at low latitudes (62°10'S) determines the potential influx of solar radiation. At King George Island, the mean length of the day in December and June is 19.5 h and 5.1 h, respectively (Styszyńska 2000a; Kejna *et al*. 2013a). The altitude of the sun changes from an angle of elevation of 51° in midsummer to 4° in

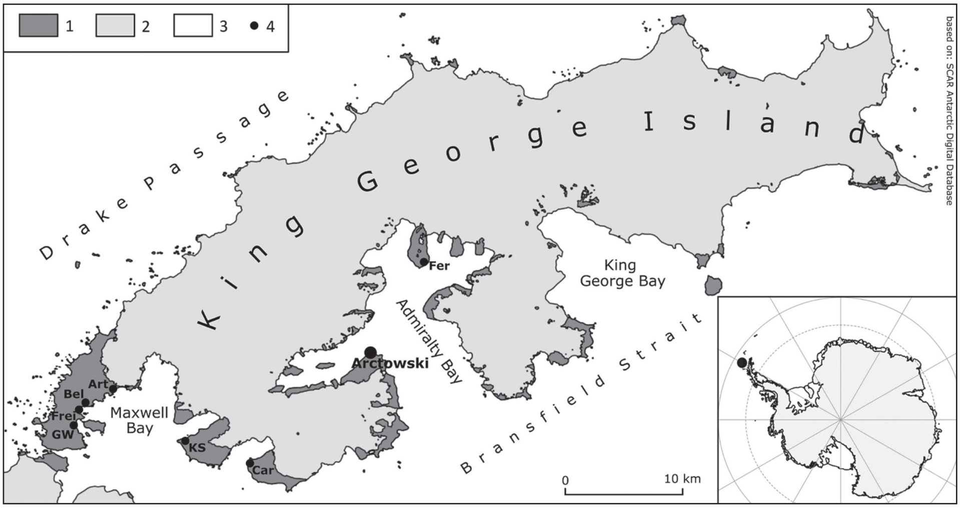

Fig. 1. Location of the study area. 1 – unglacified land; 2 – ice caps and glaciers; 3 – sea; 4 – year round scientific stations (Art – Artigas, Bel – Bellingshausen, Car – Carlini, Frei – Eduardo Frei, Fer – Ferraz, KS – King Sejong, GW – Great Wall).

midwinter. Due to the high cloudiness, the amount of solar radiation that reaches the surface is low and is reflected by the glacier surface and snow cover that remains most of the year (Kejna *et al*. 2013a). Notably, a very important factor that shaped the weather and climate on King George Island is the sea surrounding the island on all sides. The sea water temperature and sea ice extent in the Antarctic Peninsula region strongly affect the local climate (Marsz and Styszyńska 2000; Turner *et al*. 2013; Kejna *et al*. 2013a). The northern part of the Antarctic Peninsula region and Drake Passage have high cyclonicity (Simmonds *et al*. 2003). According to Kejna (1993), during 1986–1989, the weather on King George Island was shaped by low pressure on almost 70% of the days. The predominant direction of advection of air masses is west (Kejna 1999; Marsz 2000a).

Methods

Meteorological measurements were conducted at Arctowski Station from the start of operations in February 1977 to 2001, with a few one-year breaks (Angiel *et al*. 2010). In December 2005, an automatic weather station (AWS) was installed and operated until the end of 2012 (oral information), but the results were never published except for 2006 and 2012 (Angiel *et al*. 2010; Kejna *et al*. 2013b). In addition, during that period of time, some short-term meteorological measurements were carried out (Kejna 2008). In December 2012, a new AWS (manufactured by Campbell) was installed, and since then, the AWS has been working continuously (Fig. 2).

Fig. 2. Weather station at Arctowski Station. **A** – site of the measurements; **B** – Hellmann's rain gauge; **C** – automatic weather station set up in December 2012.

Since the start of the station operations, all meteorological measurements have been carried out in a meteorological garden (62°09’33.5”S, 58°28’05.8”W, 2 m a.g.l.; Fig. 2) in a flat, watery area called Jasnorzewski Garden, which is 150 m from the main station building. The AWS has measured the following parameters: air temperature, relative air humidity, atmospheric air pressure, wind speed and wind direction and global solar radiation. Detailed characteristics of particular elements and devices are presented in Table 1. Precipitation and snow cover are measured manually by an observer once a day using Hellmann’s rain gauge and snow depth ruler. In January 2017, automatic tipping bucket rain gauges were also installed. All devises have calibration certificates. Temperature and humidity sensors are placed in an anti-radiation cover. The air pressure has not been reduced to the sea level; that enable to compare it with the work of Marsz 2000b. Mean hourly data were used to calculate mean values for days, months, and years. Unprocessed data were used to present absolute maximum and minimum values. The results were compared with data from other stations located in the western part of King George Island at Maxwell Bay, particularly Bellingshausen (15 m a.s.l.), Carlini (20 m a.s.l.), Great Wall (15 m a.s.l.), King Sejong (15 m a.s.l.), and Eduardo Frei (20 m a.s.l.; Fig. 1). Data were downloaded from the National Oceanographic and Atmospheric Administration Global Surface Summary of the Day database (GSOD 2018).

Results and interpretation

Solar radiation. — Shortwave total solar radiation is a sum of direct and dispersed radiation measurements from a horizontal surface. The results are presented as the sum of solar radiation per time unit (hour, day, month and year) and as intensity of solar radiation. In general, the daily and annual course afflux of solar radiation depends on the altitude of the Sun above the horizon and is modified by cloudiness (Styszyńska 2000c; Kejna *et al*. 2013a). During the period of 2013–2017, the mean multi-annual sum of total solar radiation was 2932.6 MJ/m^2 and reached the lowest value in 2014 and the highest in 2016 (Table 2). A similar value was measured by Kejna *et al*. (2013b) in 2012, which was 2985.3 MJ/m^2. According to Styszyńska (2000c), the mean multi-annual sum of total solar radiation during 1977–1998 was 3134.3 MJ/m^2, which is quite high compared to that during 2012–2017. However, during 1977–1998, the time series of solar radiation was only partly measured and mostly estimated based on a method proposed by the author (Styszyńska 2000c). During 2013–2017, the highest (higher than 400 MJ/m^2) monthly sum was recorded from November to January. During those months, the highest daily sums of solar radiation were recorded. They were higher than 30 MJ/m^2. The lowest monthly sum of solar radiation (< 100 MJ/m^2) was recorded from May to August, with a minimum in June. From May to July, daily sums of solar radiation were usually < 1 MJ/m^2 (Table 3). The highest intensity of solar radiation occurred at approximately noon.

Table 1

Characteristics of the automatic weather station and elements measured in 2013–2017.

Meteorological element / device	Unit	Manufactured	Type	Accuracy	High [m a.g.l.]	Period of measurements
Data logger	–	Campbell	CR1000 CR3000	–	1.0 m 1.0 m	Jan 2013–Jan 2017 Jan 2017–currently
Air temperature	°C	Vaisala	HMP155	±0.2°C (-40°C to 20°C)	2.0 m	Jan 2013–currently
Relative humidity	%	Vaisala	HMP155	±1.3% RH (-40°C to 20°C)	2.0 m	Jan 2013–currently
Wind speed	m/s	Gill Instruments	WindSonic	±2% at 12 m/s	2.5 m 10.0 m	Jan 2013–Jan 2017 Jan 2017–currently
Wind direction	°	Gill Instruments	WindSonic	±2° at 12 m/s	2.5 m 10.0 m	Jan 2013–Jan 2017 Jan 2017–currently
Wind speed	m/s	Vector Instruments	A100R	±0.1 m/s at 0–10 m/s 1% between 10–55 m/s 2% above 55 m/s	2.0 m	Jan 2017–currently
Wind speed	m/s	Young	05103	±0.3 m/s or 1% of reading	2.5 m	Jan 2013–Dec 2016
Wind direction	°	Young	05103	±3°	10.0 m	Jan 2013–Dec 2016
Air pressure	hPa	Setra	278	800–1100 hPa ±1.5 hPa (-40°C to 60°C)	1.0 m	Jan 2013–currently
Solar radiation	W/m^2	Apogee Instruments Kipp&Zonen	CS300 CNR4	(360 to 1120 nm) ±5–10% for daily sums	2.5 m 1.5 m	Jan 2013–Jan 2017 Jan 2017–currently
Precipitation	mm	A-Ster	A-Ster Hellmann	0.1 mm	1 m 1 m	Jan 2017–currently Mar 2016–currently

Table 2

Sum of solar radiation at Arctowski Station in 2013–2017.

Year\ month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum of solar radiation [MJ/m^2]
2012*	476.7	415.2	257.7	89.0	25.1	10.4	22.2	75.3	234.1	343.5	468.4	567.8	2985.3
2013	412.4	381.0	253.2	110.3	29.5	12.1	22.3	94.0	254.8	306.9	498.6	564.5	2939.7
2014	506.8	300.0	230.9	111.2	31.8	14.2	26.0	89.8	202.9	328.3	443.0	561.0	2845.9
2015	481.8	325.7	244.7	116.1	34.2	9.2	28.8	98.3	221.5	362.1	472.3	546.2	2941.0
2016	526.1	376.1	210.7	103.9	41.7	14.2	29.6	95.5	215.8	367.1	476.4	536.3	2993.3
2017	463.6	298.8	249.9	100.8	32.8	13.6	22.6	79.0	211.8	349.7	516.3	604.5	2943.3
2013–2017	478.2	336.3	237.9	108.5	34.0	12.7	25.8	91.3	221.4	342.8	481.3	562.5	2932.6
1977–1998**	492.0	377.7	239.4	98.5	35.8	13.9	29.0	101.2	266.2	407.7	509.8	564.1	3134.30

* after Kejna *et al.* (2013b); ** after Marsz and Styszyńska (2000)

Table 3

Climate characteristics for Arctowski Station, King George Island in 2013–2017.

Climate characteristic		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Air temperature [°C]	Maximum	12.2	11.2	11.6	10.3	10.7	4.7	5.7	6.5	7.5	7.7	8.6	7.2	12.2
	Maximum daily mean	6.7	6.1	5.9	5.5	5.9	2.6	1.5	2.2	3.8	3.8	4.8	3.9	6.7
	Mean	1.2	1.6	1.2	-0.4	-2.1	-4.5	-4.8	-6.1	-3.9	-1.6	-0.9	0.3	-1.7
	Minimum daily mean	-2.7	-4.0	.5.3	-12.7	-10.7	-17.8	-16.2	-17.3	-16.7	-9.4	-6.9	-3.3	-17.8
	Minimum	-4.1	-6.2	-8.5	-15.1	-14.8	-19.4	-20.1	-21.4	-19.5	-12.0	-8.9	-6.5	-21.4
	Absolute amplitude	16.3	17.4	20.1	25.5	25.4	24.1	25.8	27.9	27.0	19.6	17.5	13.6	33.6
	Mean daily amplitude	11.7	13.6	14.7	18.3	19.8	19.4	21.1	24.2	21.2	15.1	13.6	9.7	16.9
	Standard deviation	2.0	2.4	2.6	3.6	4.3	4.7	4.9	5.1	5.0	3.0	2.5	1.6	4.4
	Mean share of days with mean daily temperature > 0 °C [%]	73.9	76.2	72.5	47.7	34.2	16.8	15.6	11.1	22.4	32.2	34.3	57.5	41.2
	Mean share of days with mean daily temperature < 0 °C [%]	26.1	23.8	27.5	52.3	65.8	83.2	84.4	88.9	77.6	67.8	65.7	42.5	58.8
Vapour pressure [hPa]	Maximum	9.3	8.9	10.4	9.0	8.8	7.0	7.2	6.8	7.3	7.5	8.1	8.0	10.4
	Mean daily maximum	6.1	6.4	6.3	5.7	5.3	4.6	4.6	4.1	4.8	5.2	5.3	5.7	5.3
	Mean	5.3	5.5	5.4	4.7	4.3	3.7	3.5	3.2	3.8	4.4	4.5	4.9	4.4
	Mean daily minimum	4.6	4.7	4.4	3.8	3.4	2.8	2.6	2.4	2.8	3.5	3.7	4.2	3.5
	Minimum	2.9	2.7	2.6	1.3	1.2	1.1	0.8	0.9	1.0	1.0	1.5	2.6	0.8
Air humidity [%]	Mean daily maximum	88.0	89.5	89.4	88.5	89.2	89.0	88.1	87.3	87.8	89.2	88.2	88.4	88.5
	Mean	78.3	79.7	79.2	77.5	79.1	79.2	77.0	76.8	77.1.	78.9	76.9	77.8	78.1
	Mean daily minimum	67.0	66.5	65.7	64.0	65.2	66.6	62.2	63.7	63.0	64.7	63.2	64.9	64.7
	Minimum	47.3	41.2	36.3	20.2	27.8	41.4	21.0	16.1	21.4	16.2	36.0	47.2	16.1

Table 3 continued

Climate characteristic		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Air pressure [hPa]	Maximum	1012.6	1014.5	1020.3	1020.7	1023.1	1019.6	1026.9	1031.5	1028.3	1018.3	1015.2	1013.3	1031.5
	Mean monthly maximum	1007.0	1010.5	1012.7	1014.3	1015.5	1011.3	1019.5	1020.4	1018.6	1013.2	1006.3	1004.8	1026.1
	Mean	990.0	990.2	992.3	991.7	993.8	988.8	990.3	991.9	991.0	988.2	984.2	986.1	989.9
	Mean monthly minimum	972.2	967.3	966.7	968.8	964.8	957.7	954.4	954.6	960.8	957.9	957.1	964.6	946.3
	Minimum	960.0	954.8	958.1	960.2	954.9	945.2	946.6	934.5	950.0	949.1	952.9	957.7	934.5
	Maximum daily change	23.0	20.8	29.7	29.9	35.8	30.0	40.5	33.2	35.8	28.3	29.9	25.1	40.5
	Mean daily change	7.20	8.80	10.5	10.4	10.4	10.4	12.3	11.1	11.9	10.7	9.5	7.4	10.1
	Minimum daily change	1.0	1.0	1.1	2.1	1.8	1.0	1.8	1.6	1.1	1.7	2.0	1.0	1.0
Wind speed [m/s]	Maximum	36.9	31.8	46.7	35.7	36.2	38.3	38.8	38.0	43.5	44.2	35.7	30.0	46.7
	Mean monthly maximum	13.8	15.9	18.3	18.8	17.4	17.6	19.2	17.5	21.4	19.0	17.3	13.5	21.4
	Mean	4.8	5.2	5.5	6.2	5.9	5.7	6.2	5.7	6.7	6.1	5.5	4.6	5.7
	Mean daily wind course [km]	17.4	18.7	19.8	22.1	21.3	20.6	22.4	20.6	24.3	21.9	20.0	16.6	20.5
	Mean number of days with maximum wind speed > 10 m/s	21.4	21.4	26.8	28.8	27.8	26.0	27.2	26.4	27.6	28.6	26.0	21.6	309.6
	Mean number of days with maximum wind speed > 20 m/s	4.2	6.0	11.6	10.4	8.0	9.8	14.2	9.8	15.2	12.6	8.4	3.0	113.2
	Mean number of days with maximum wind speed > 30 m/s	0.4	0.2	2.2	2.6	1.6	2.4	2.6	3.0	6.0	3.2	2.2	0.0	26.4
Solar radiation [MJ/m^2]	Mean daily sum	15.1	12.5	7.7	3.7	1.1	0.41	0.8	3.0	7.7	10.8	15.9	17.9	8.1
	Maximum monthly sum	526.1	381.0	253.2	116.1	41.7	14.2	29.6	98.3	254.8	367.1	516.3	604.5	2993.3
	Minimum monthly sum	412.4	298.8	210.7	100.8	29.5	9.2	22.3	79.0	202.9	306.9	443.0	536.3	2845.9

The mean maximum values of solar radiation at that time were > 250 W/m^2 (Fig. 3). The absolute maximum values of solar radiation were > 1000 W/m^2 and were recorded between 9:00 and 17:00 (UTC-03:00).

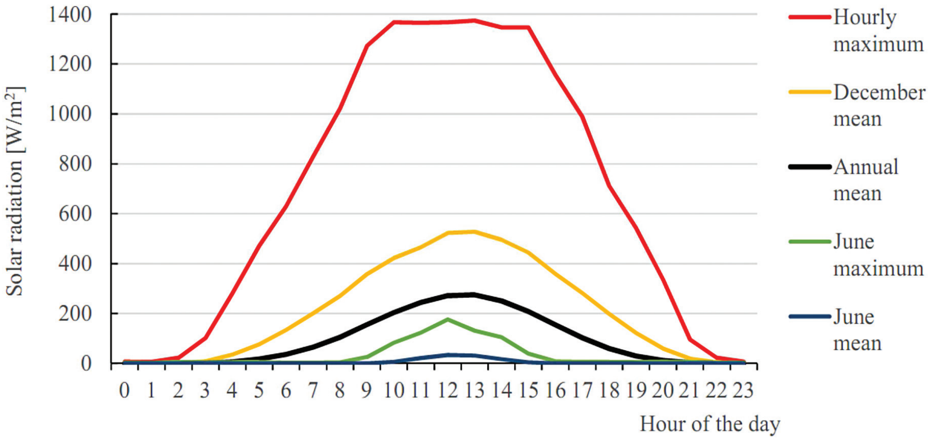

Fig. 3. Course of long-term average hourly solar radiation and absolute hourly maximum values at Arctowski Station during 2013–2017 (UTC-03:00).

Air temperature. — The multi-annual mean air temperature during 2013–2017 was -1.7°C (Tables 4 and 5), which is only approximately 0.1°C lower than the annual mean air temperature during 1977–1998 (Marsz 2000c). The annual mean temperature varied from -2.3°C in 2015 to -0.9°C in 2016. The mean annual air temperatures at Arctowski and Carlini stations are higher than those at other stations located on King George Island (Table 4 and Fig. 4). At Arctowski Station, the highest recorded temperature during the time of measurements was 12.2°C (1st January 2016) and was 4.5°C lower than the maximum temperature during 1977–1998, which was 16.7°C (January 1979; Marsz 2000d). The lowest recorded temperature was -21.4°C (22nd August 2016) and was 11.0°C higher than the minimum temperature during 1977–1998, which was -32.2°C (July 1986; Marsz 2000d). The annual air temperature amplitude (difference between the annual absolute maximum and minimum) during 2013–2017 varied from 27.1°C to 33.6°C. The mean for that period was 30°C and was 19°C lower than the mean during 1977–1998. The highest and lowest daily air temperature amplitudes were usually recorded during winter and summer, respectively (Table 3).

The warmest month during the analysed period was February (mean monthly air temperature 1.5°C), and the coldest month was August (-6.1°C; Table 5 and Figs. 5–6), while in 1977–1998, January was the warmest month, and July was the coldest month. There is an evident difference between the mean monthly air temperature during 1977–1998 and 2013–2017. The mean monthly air temperature from November to February during 2013–2017 was lower than that during 1977–1998, while from April to July, the mean monthly air temperature during 2013–2017 was higher than or equal to that during 1977–1998 (Table 5 and Fig. 6). A similar situation was observed at Bellingshausen Station for the period 1968–2012 and 2012–2015 (Pętlicki *et al*. 2017). According to Oliva *et al*. (2017), mean annual summer air temperature (December to February) at Bellingshausen, Marsh, and King Sejong Stations (Maxwell Bay) in decade 2006–2015 was 0.3°C lower than in period 1986–2015.

A mean daily air temperature of > 0°C predominated from December to March, while < 0°C predominated from April to November (Table 3). In addition, the lowest air temperature during the day occurred mostly before sunrise, and the highest air temperature was observed between 15:00 and 18:00 (UTC-03:00; Fig. 7).

Table 4

Long-term statistics of annual air temperature at Arctowski Station and annual mean air temperature on King George Island during 2013–2017; all in °C.

	Arctowski						Bel	Car	Frei	GW	KS
Year	Mean	SD	Median	Maximum	Minimum	Amplitude	Mean				
2013	-2.2	4.8	-0.8	11.1	-19.6	30.7	-2.6	-1.7	-2.7	-2.1	-2.1
2014	-1.9	3.7	-1.1	8.3	-18.8	27.1	-2.3	-1.7	-2.5	-1.8	-1.9
2015	-2.3	5.0	-0.8	10.6	-18.6	29.2	-2.8	-2.3	-3.0	-2.7	-2.3
2016	-0.9	4.0	0.0	12.2	-21.4	33.6	-1.6	-0.7	-1.7	-1.2	-0.9
2017	-1.4	4.6	-0.4	9.3	-20.1	29.4	-1.7	-1.4	-2.1	-2.8	-1.7
2013–2017	-1.7	4.4	-0.6	12.2	-21.4	30.0	-2.2	-1.5	-2.4	-2.1	-1.8
1977–1998*	-1.6	–	–	16.7	-32.3	49.0	–	–	–	–	–

Bel – Bellingshausen, Car – Carlini, Frei – Eduardo Frei, GW – Great Wall, Sej – King Sejong; data source GSOD 2018; SD – Standard deviation; * after Marsz and Styszyńska (2000)

Table 5

Mean monthly air temperature during 2013–2017 and multi-annual mean monthly air temperature for 2013–2017 and 1977–1998 at Arctowski Station; all in °C.

Year/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
2013	1.0	1.7	1.5	1.9	-3.7	-3.8	-6.2	-7.8	-4.0	-2.1	-1.2	-0.8	-2.2
2014	0.7	0.4	-0.5	-0.5	-2.4	-4.5	-2.5	-5.2	-4.1	-2.0	-1.9	0.0	-1.9
2015	1.5	1.9	1.3	0.5	-2.2	-7.2	-7.4	-5.5	-7.6	-1.8	-1.1	0.6	-2.3
2016	1.2	1.3	1.9	-2.7	-0.5	-1.2	-3.9	-6.7	-0.1	-0.2	-0.1	0.6	-0.9
2017	1.6	2.4	1.8	-1.2	-1.7	-5.7	-3.9	-5.1	-3.6	-2.4	-0.1	1.3	-1.4
2013–2017	1.2	1.6	1.2	-0.4	-2.1	-4.5	-4.8	-6.1	-3.9	-1.7	-0.9	0.3	-1.7
1977–1998*	2.5	2.3	1.2	-1.1	-3.3	-5.0	-6.6	-5.6	-3.7	-2.0	-0.2	1.5	-1.6

* after Marsz and Styszyńska (2000)

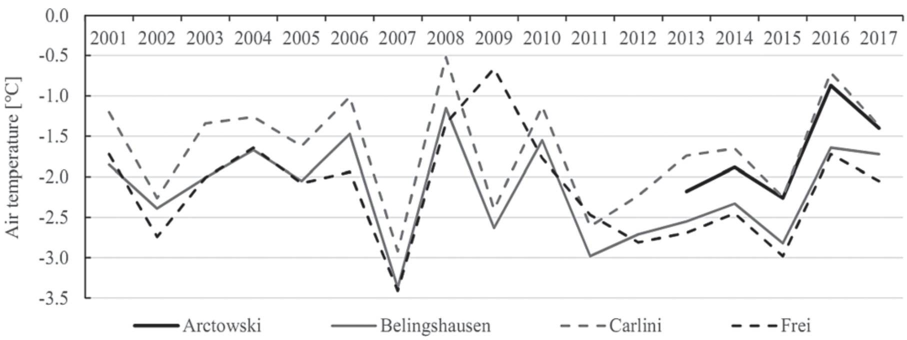

Fig. 4. Mean annual air temperature on King George Island during 2013–2017.

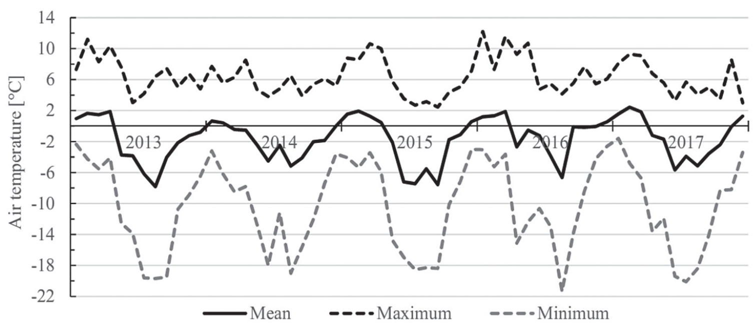

Fig. 5. Monthly course of mean, absolute maximum and absolute minimum air temperatures at Arctowski Station during 2013–2017.

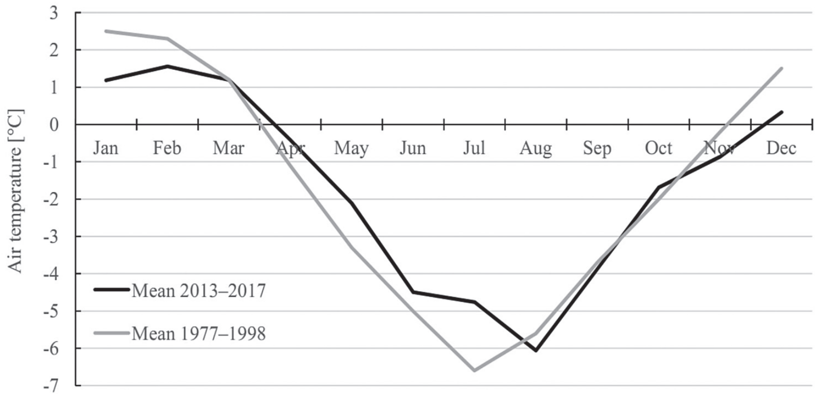

Fig. 6. Yearly course of monthly mean values of air temperature at Arctowski Station during 1977–1998 and 2013–2017.

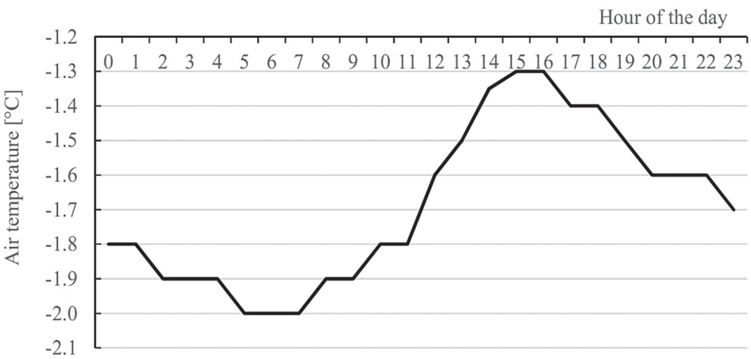

Fig. 7. Diurnal course of mean long-term (2013–2017) hourly values of air temperature at Arctowski Station (UTC-03:00).

Air pressure. — The mean annual air pressure at Arctowski Station during 2013–2017 varied from 987.8 to 992.0 hPa. The multi-annual mean value was 989.9 hPa during 2013–2017 and 991.5 hPa during 1977–1998. In comparison, the multi-annual mean value during 2013–2017 at Bellingshausen Station was 989.7 hPa, and that at Frei Station was 989.4 hPa (Table 6). The mean monthly air pressure values varied from 980.5 hPa (September 2017) to 1003.3 hPa (March 2017). Usually, the highest mean monthly air pressure values occur in the autumn and winter months (March–September), and the lowest values occur in November and December. In particular, during 2013–2017, the mean monthly air pressure varied significantly during the winter and autumn months and was less variable in November, December and January (Fig. 8 and Table 6). The course of mean monthly air pressure in 2013–2017 and 1977–1998 was very similar, but in 2013–2017, it was almost always lower than that in 1977–1998.

This corresponds to observations by Kejna *et al*. (2013), who, based on data from Bellingshausen Station, noticed a decreasing trend in atmospheric pressure. The highest differences in the mean monthly atmospheric pressure values were observed in June (-5.3 hPa) and December (-4.8 hPa; Fig. 8 and Table 6). In 2013–2017, the course of the monthly air pressure values at Arctowski, Frei and Bellingshausen stations were almost the same (GSOD 2018).

The lowest registered air pressure value was 934.5 hPa (16th August 2015), and the lowest mean daily air pressure was 948.3 hPa (15th August 2015). The highest observed air pressure value was 1030.5 hPa, and the highest mean daily air pressure value was 1030.0 hPa (both on 22nd August 2013). In general, the lowest values were observed in August, September and November, and the highest values were observed in May, July and August. In each year, the number of days with particular daily mean pressure values was similar, and approximately 60% of the days had a mean daily air pressure value from 980.0 to 1000.0 hPa. An increase in the days with a mean daily air pressure range of 1000–1010 hPa was noticeable (Fig. 9).

The air pressure on King George Island changed in a relatively short time, even in a few hours. The exemplary daily changes are presented in Fig. 10. From 30th July to 1st August 2017, a cyclone moved from west to east, and its centre passed south of King George Island (ventusky.com 2018). On 31st July 2017, the highest daily air pressure amplitude (40.5 hPa) during 2013–2017 was observed. The predominant daily air pressure change was approximately 5–10 hPa (mean annual 10.1 hPa), and each year, more than 40% of the days received values higher than 10 hPa (Fig. 11). High values of daily air pressure

Table 6

Mean monthly air pressure during 2013–2017 and multi-annual mean monthly air pressure during 2013–2017 and 1977–1998 at Arctowski Station; all in hPa.

Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
2013	988.8	989.2	997.3	988.1	988.5	982.0	987.0	992.8	998.1	985.0	981.0	987.4	988.8
2014	991.7	990.7	985.5	997.5	994.9	995.4	994.5	997.2	998.8	983.4	981.7	983.6	991.2
2015	991.4	988.2	988.7	989.2	990.5	984.9	986.3	985.4	984.6	993.3	984.3	986.7	987.8
2016	989.6	986.8	986.5	988.3	1002.8	992.0	997.2	994.6	993.2	994.3	986.0	992.5	992.0
2017	988.7	995.9	1003.3	995.1	992.2	989.7	986.6	989.5	980.5	984.9	988.1	980.4	989.5
2013–2017	990.0	990.2	992.3	991.7	993.8	988.8	990.3	991.9	991.0	988.2	984.2	986.1	989.9
1977–1998*	991.5	990.5	990.6	992.2	995.7	994.1	993.7	991.6	991.8	988.5	986.7	990.9	991.5

* after Marsz and Styszyńska (2000)

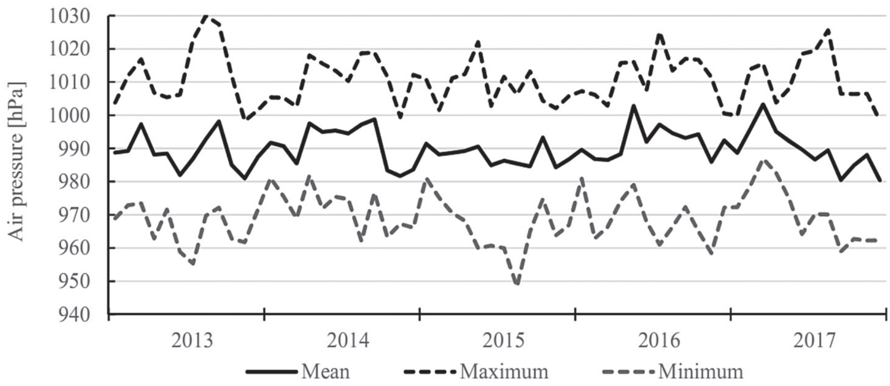

Fig. 8. Monthly course of mean, absolute maximum and absolute minimum air pressure at Arctowski Station during 2013–2017.

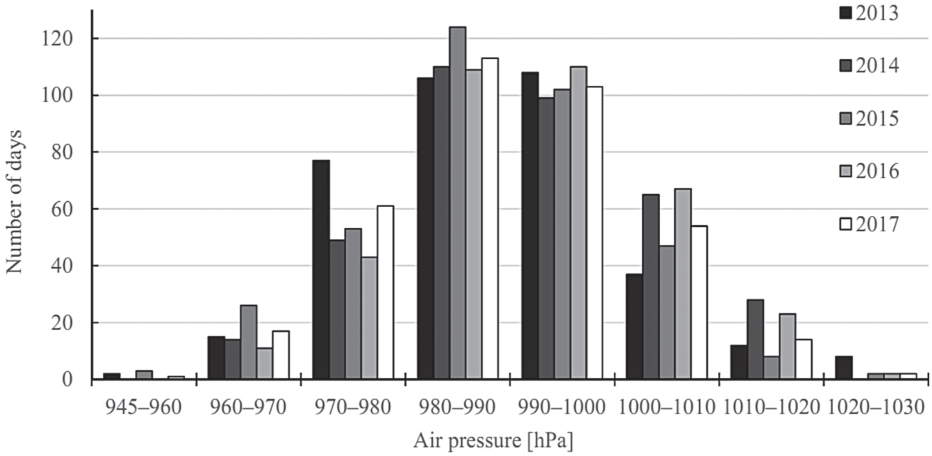

Fig. 9. Number of days with particular values of mean daily air pressure at Arctowski Station during 2013–2017.

change occurred from July to September, and low values occurred from December to February (Table 3).

In general, similar to a previous investigation (Marsz 2000b) mean monthly and annual values of air pressure remained quite stable and were relatively low, whereas air pressure values may change rapidly, even during the day. Those quick changes are caused by very dynamic air circulation in the area of Drake Passage, especially the movement of cyclonic centres and influence of southern high pressure centres (Marsz 2000b; Kejna *et al*. 2013a).

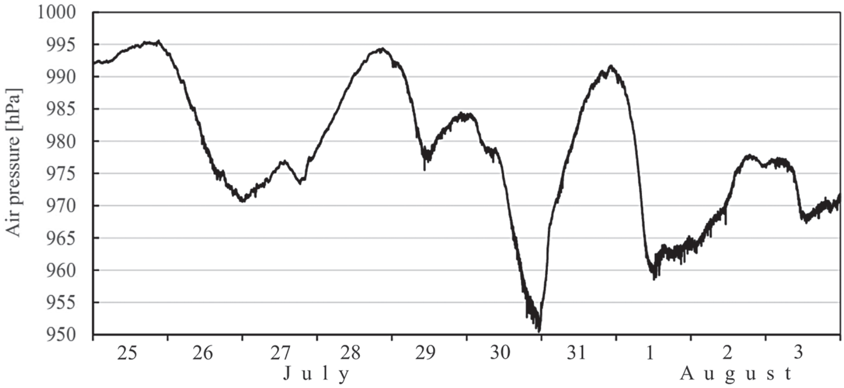

Fig. 10. Course of air pressure (one-minute measurements) at Arctowski Station from 25th July to 3rd August 2017.

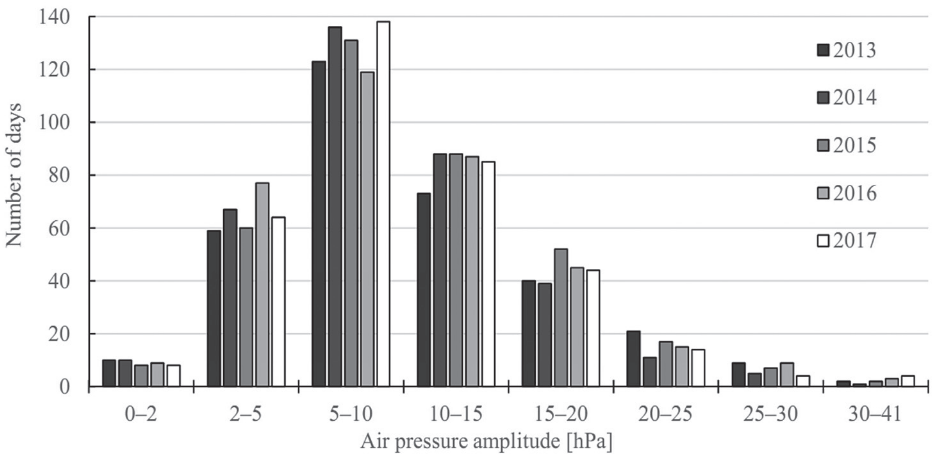

Fig. 11. Number of days with particular values of daily air pressure change at Arctowski Station during 2013–2017.

Air humidity. — To present air humidity, vapour pressure and relative air humidity were analysed. The multi-annual mean vapour pressure during 2013–2017 was 4.4 hPa and was approximately 0.3 hPa lower than that during 1978–1996 (Marsz 2000e; Table 7). In the period of 2013–2017, the minimum value was 3.7 hPa, and the maximum was 5.3 hPa. The multi-annual relative air humidity during 2013–2017 was 78.1%, while that during 1978–1997 was 82.3% (Table 7). The highest values of mean monthly vapour pressure (higher than 5 hPa) occurred from January to March, and the lowest values (lower than 4 hPa) occurred from June to September (Table 3). The mean monthly values of relative air humidity varied from 73.9% (November 2016) to 82.7% (August

2017, Fig. 12). The absolute minimum relative air humidity was 16% on 25th August 2015 (Table 3), and that during 1977–1998 was 21% (July 1989), see Marsz (2000e). Similar to air pressure, air humidity does not show low long-term variability but varies rapidly during short periods of time (Marsz 2000e).

Table 7

Long-term, annual and monthly statistics of relative air humidity (RH) and vapour pressure (e) at Arctowski Station, Antarctica, in the period of 2013–2017.

Year	RH [%]			e [hPa]		
	Mean	Max*	Min*	Mean	Max*	Min*
2012***	83.4	87.4	78.0	-	-	-
2013	77.7	88.2	64.1	4.3	5.2	3.4
2014	78.1	88.1	65.7	4.3	5.1	3.5
2015	77.5	87.9	64.1	4.3	5.2	3.4
2016	76.8	87.8	62.9	4.6	5.5	3.7
2017	80.4	90.7	66.5	4.6	5.6	3.7
2013–2017	78.1	88.5	64.7	4.4	5.6	3.4
1977–1998**	82.3	86.2	78.7	4.7	5.1	4.3

* averages of daily maximum and minimum; ** after Marsz and Styszyńska (2000); *** after Kejna *et al*. (2013b)

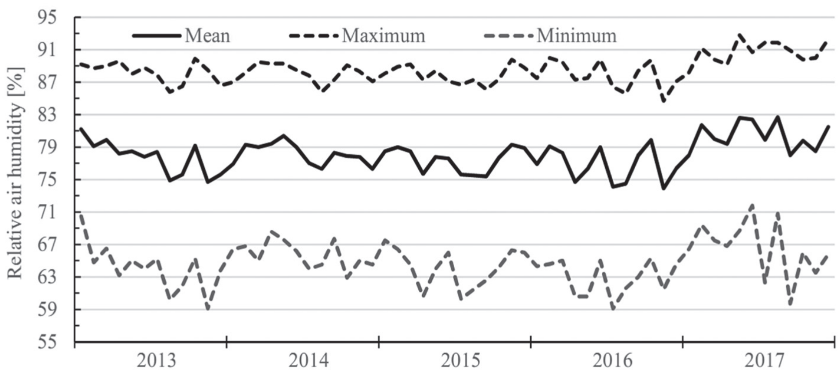

Fig. 12. Monthly course of mean, mean daily maximum and mean daily minimum relative air humidity at Arctowski Station during 2013–2017.

Wind speed and direction. — In the vicinity of Arctowski Station, wind speed and direction depend mainly on synoptic situations and local terrain conditions (Styszyńska 2000b). During 2013–2016, the wind speed and direction were measured at 2.5 m a.g.l. In 2017, wind gauges at 10 m a.g.l.

and at 2 m a.g.l. were installed. To describe wind conditions in 2013–2017, we used data from 2.5 m a.g.l. for 2013–2016 and from 2.0 m a.g.l. for 2017. During 2013–2017, SW was the predominant wind direction (31.3%), and the multi-annual wind direction was 257°. The last observed wind direction was NE (4.90%) and S (5.12%; Table 8). In 2013–2017, the mean multi-annual wind speed at 2.5 m a.g.l. was 5.7 m/s (Fig. 13 and Table 9). For those five years, the annual mean varied from 5.6 to 6.0 m/s (Table 9). In 2012, the mean annual wind speed was 4.8 m/s (Kejna *et al*. 2013b), and in 1977–1998, it was 6.6 m/s (measured on 10 m a.g.l.; Styszyńska 2000b). Using a simple algorithm that estimates wind speed depending on the height above ground level (WMO 2014; Lorenc 1996), the wind speed at 10 m a.g.l. in 2013–2017 was estimated as 7.0 m/s. This value was similar to that measured in 1977–1998 (Styszyńska 2000b). In general, in the period of 2013–2017, the most frequent wind direction (15.96%) was to the SW, with wind speeds between 5 and 10 m/s (Table 8).

In the annual course, the highest mean monthly values were observed in July, September and October (> 6 m/s), and the lowest values (< 5 m/s) were observed in December and January (Table 3). The highest daily maximum wind speed values (> 40 m/s) were measured in March, September and October. The lowest daily maximum wind speed values were observed from December to February (Table 3). The highest wind speed during 2013–2017 was 46.7 m/s, which was recorded on 28th March 2017.

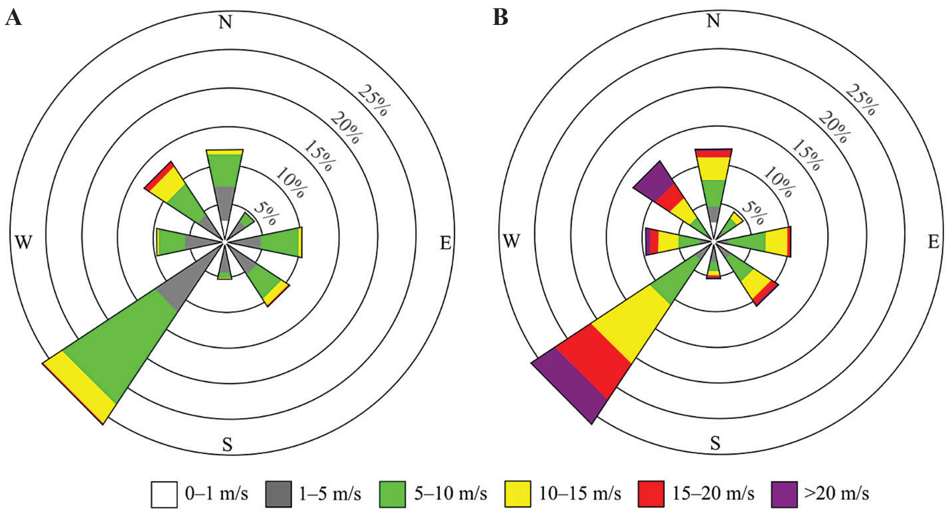

Fig. 13. Frequency of mean hourly (**A**) and maximum (**B**) wind direction and wind speed at Arctowski Station during 2013–2017.

During 2013–2017, 26 days each year had a maximum wind speed > 30 m/s, 113 days had a maximum wind speed > 20 m/s, and 309 days had a maximum wind speed > 10 m/s. On average, 2 days per month had a maximum wind speed > 30 m/s. The most days with a maximum wind speed > 30 m/s were recorded in September, and the least days were recorded from December to February. On average, 9 days per month had a maximum wind speed > 20 m/s, and 26 days per month had a maximum wind speed > 10 m/s (Table 3 and Table 9).

Table 8

Long-term frequency [%] of wind direction and wind speed [m/s] at Arctowski Station during 2013–2017.

		Wind speed						
		0.0–1.0 m/s	1.0–5.0 m/s	5.0–10.0 m/s	10.0–15.0 m/s	15.0–20.0 m/s	> 20.0 m/s	Total [%]
Wind direction	N	2.75	5.14	4.76	0.62	0.03	0.00	13.30
	NE	0.24	3.20	1.44	0.02	0.00	0.00	4.90
	E	0.27	4.73	5.55	0.51	0.00	0.00	11.06
	SE	0.35	4.98	4.21	1.30	0.10	0.00	10.94
	S	0.40	3.88	0.76	0.08	0.00	0.00	5.12
	SW	0.52	11.40	15.96	3.28	0.17	0.00	31.33
	W	0.39	5.12	3.82	0.32	0.00	0.00	9.65
	NW	0.39	4.08	5.37	2.98	0.83	0.05	13.70
	Total	5.31	42.53	41.87	9.11	1.13	0.05	100.00
Year	2013	9.38	14.70	26.08	41.80	6.91	1.13	100.00
	2014	4.52	17.06	26.26	43.22	8.12	0.82	100.00
	2015	3.43	14.42	28.80	42.42	10.09	0.83	100.00
	2016	3.52	14.25	28.19	40.64	11.06	2.35	100.00
	2017	4.02	16.05	27.51	42.14	9.47	0.81	100.00
	2013–2017	4.95	15.30	27.38	42.04	9.14	1.19	100.00

Table 9

Long-term and annual mean wind direction and speed (measured at 10 m a.g.l.) at Arctowski Station during 2013–2017.

Year	Mean wind direction [°]	Mean wind speed [m/s]	Absolute maxi-mum wind speed [m/s]	Number of hours with max wind speed > 25 m/s	Number of days with maximum wind speed		
					> 30 m/s	> 20 m/s	> 10 m/s
2012*	–	4.8	40.2	–	–	–	–
2013	258	5.6	36.9	123	10	80	291
2014	257	5.6	44.2	217	18	105	300
2015	250	5.7	39.2	316	32	132	334
2016	254	6.0	43.5	537	42	137	315
2017	259	5.7	46.7	288	30	112	308
2013–2017	257	5.7	46.7	–	26.4	113.2	309.6
1977–1998**	–	6.6	60.0	–	–	–	–

* after Kejna *et al*. (2013b); ** after Marsz and Styszyńska (2000).

Precipitation and snow cover. — The daily sum of precipitation and snow cover began to be measured in March 2016. Currently, less than two years of data have been recorded. The daily sum of precipitation has been measured using Hellmann's rain gauge (since March 2016) and an automatic rain gauge (since January 2017). The sum of precipitation measured using these two methods were compared, but for analysis of the meteorological conditions at Arctowski Station, the data collected with Hellmann's rain gauge were used. Notably, meteorological conditions, especially strong winds, are very unfavourable for precipitation measurements–snow and rain are blown out of the water gauge or sea water is blown into the water gauge. This issue will be covered by separate research. In addition, the snow melts and freezes again, and new snow cover accumulates on the ice.

The total sum of precipitation in 2017 was 491.2 mm, which was similar to the mean annual precipitation during 1977–1998, which was 499.8 mm (Marsz 2000f). During the period from March 2016 to December 2016, the sum of precipitation was 568.6 mm. Considering that this value is a sum for 10 months, it seems quite high. The maximum annual precipitation observed in 1977–1998 was 630.0 mm (Table 10).

The monthly sum of precipitation varied from 10.2 (May 2016) to 177.2 (September 2016). The unusually high sum of precipitation in March and September 2016 (170.1 and 177.2 mm; Table 10) consists mainly of rainfall. In both cases, the high monthly sum is a result of only a few events with high daily rainfall. During 1977–1998, the highest daily sum of precipitation was 149.6 mm (March 1982), and a monthly sum of precipitation greater than 100.0 mm was observed only 7 times (Marsz and Styszyńska 2000).

The daily and monthly amounts of precipitation measured by Hellman's rain gauge and by the automatic rain gauge are different from each other. During 146 out of 333 days, higher precipitation was observed in Hellman's rain gauge, and at 108 days, higher values were observed in the automatic rain gauge. Most of the days (138), the difference between the measurements was less than 1 mm. In the case of the monthly sum of precipitation, the relative error varied from 0.006 to 0.485, with emphasized difficulties connected with precipitation measurements in polar regions. However, for the period of February–December 2017, the relative error for the sum of precipitation was only 0.061 (Table 10).

The monthly and annual amounts of precipitation at the Arctowski, Carlini and Bellingshausen stations differ from each other, but from March 2016 to December 2017, their course is quite similar (Fig. 14). The monthly sum of precipitation at Carlini Station was always the lowest, and at Bellingshausen Station, it was usually the highest. The differences indicate the impact of local factors (*i.e.* elevation, surrounding terrain, distance from the sea) on precipitation. The high sum of precipitation in September 2016 at Arctowski Station was probably the result of such factors. Therefore, the high sum was mainly a consequence of very high precipitation on only two days (together 82.0 mm). In the vicinity of Admiralty Bay, rainfall or snow fall occur very often, but they usually have a small daily sum (Marsz 2000f), see Table 11. From March 2016 to December 2017, 402 days had a daily precipitation ≥ 0.1 mm. In total, 52.7% were days with a precipitation sum of 0.1–1.0 mm, 34.3% were days with a precipitation sum of 1.1–5.0 mm and almost 5.5% were days with daily precipitation > 10.0 mm. There was a large difference between the number of days with precipitation ≥ 0.1 mm in 2016 and 2017, especially in March, May and July (Table 11).

Snow cover thickness and periods with snow cover were very different in 2016 and 2017 (Table 12 and Fig. 15). In winter 2016, snow cover increased and melted a few times. Similar cases were described earlier by Rachlewicz (1997). The longest continuous period with snow cover lasted only 30 days (5th Aug–3rd Sep), and the maximum snow cover thickness at that time was 15 cm. Snow cover thicker than 10 cm was measured only in July and August. In winter 2017, snow cover lasted continuously for 180 days (5 Jun–1 Dec), and at that time, 53 days with snow cover thicker than 10 cm were observed. The flat area located close to the sea shore, where the snow measurements (Fig. 2) are conducted, is very unfavourable to snow accumulation, *i.e.* snow is often blown away into the sea. The terrain that surrounds the station is above sea level, and the snow cover remains longer and is thicker than that at sea level (Gonera and Rachlewicz 1997; Angiel *et al.* 2010).

Table 10

Sum of monthly precipitation at Arctowski Station from March 2016 to December 2017 compared with that from 1977–1998 and the total sum for Carlini and Bellingshausen stations; all in mm.

		2016	2017			1977–1998*			
		Hellmann's rain gauge		Automatic rain gauge	Relative error	Mean	Max	Min	SD
Jan		–	29.4	–	–	34.9	72.7	10.3	15.2
Feb		–	27.0	31.8	0.178	51.3	87.9	11.3	23.7
Mar		170.1	14.3	19.7	0.378	58.3	149.6	18.5	35.0
Apr		38.3	26.8	37.6	0.403	49.3	113.1	15.9	27.4
May		10.2	96.4	86.5	0.103	36.9	115.4	8.4	30.0
Jun		43.6	37.8	23.4	0.381	36.8	98.0	6.8	23.3
Jul		33.4	49.3	36.4	0.262	40.5	87.1	8.7	24.2
Aug		27.4	59.3	58.0	0.022	28.2	47.1	6.3	11.8
Sep		177.2	66.7	67.2	0.007	47.4	105.8	5.8	31.1
Oct		27.1	35.7	18.4	0.485	41.5	83.7	5.1	23.1
Nov		21.3	33.9	34.1	0.006	41.3	145.3	11.4	32.5
Dec		20.0	14.6	20.3	0.390	34.7	82.9	2.8	23.2
Year	Arctowski	568.6	491.2	433.4	0.061	499.8	630.1	365.0	77.4
	Carlini	273.6	344.5	–	–	–	–	–	–
	Bellingshausen	504.4	658.3	–	–	–	–	–	–

* after Marsz and Styszyńska (2000); SD means standard deviation

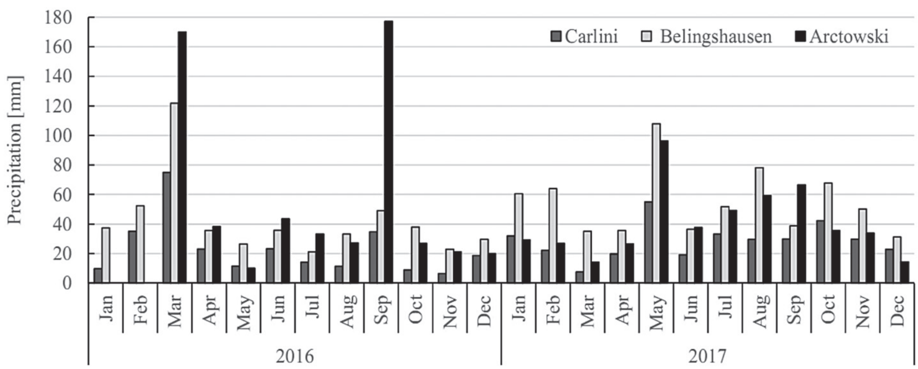

Fig. 14. Monthly sum of precipitation at Arctowski, Bellingshausen and Carlini stations.

Table 11

Maximum daily precipitation and number of days with daily sum of precipitation ≥ 0.1 mm at Arctowski Station for period March 2016 to December 2017, compared with period 1977–1998.

Month	Maximum daily precipitation [mm]			Number of days with daily sum of precipitation ≥ 0.1 mm				
	2016*	2017*	1977–1998**	2016	2017	1977–1998**		
						Mean	Max	Min
Jan	–	6.0	16.9	–	19	15	23	7
Feb	–	7.9	28.3	–	13	16	26	7
Mar	52.3	5.9	65.3	22	10	17	25	6
Apr	26.0	8.8	55.2	15	12	17	25	7
May	5.3	36.2	26.9	7	23	17	26	4
Jun	13.7	8.6	50.5	21	22	16	28	6
Jul	13.9	11.6	41.9	13	26	18	29	7
Aug	8.1	12.9	32.6	19	25	17	26	6
Sep	43.5	13.4	26.7	25	26	19	28	9
Oct	9.7	7.0	36.1	17	18	17	25	7
Nov	4.3	10.2	38.0	15	18	16	27	7
Dec	5.2	2.6	31.0	13	23	14	20	3
Year	52.3	36.2	65.3	167	235	198	256	89

* values measured using Hellmann's rain gauge; ** after Marsz and Styszyńska (2000)

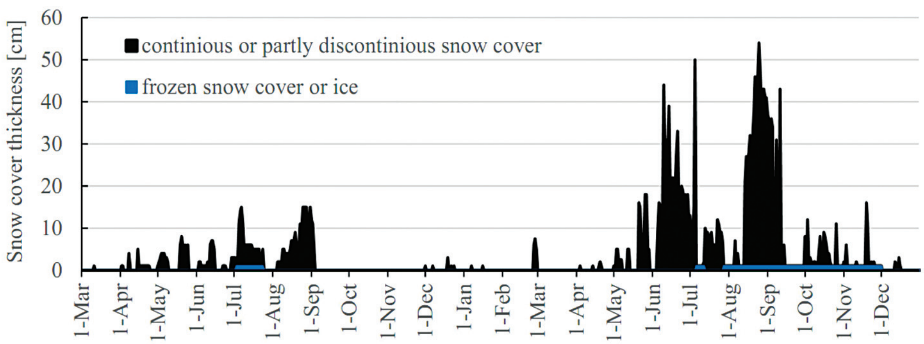

Fig. 15. Snow cover thickness at Arctowski Station from March 2016 to December 2017.

Table 12

Number of days with snow cover (N) and maximum thickness of snow cover (D max; in cm) at Arctowski Station from March 2016 to December 2017.

	2016		2017	
	N	D max	N	D max
Jan	–	–	2	1
Feb	–	–	3	7.5
Mar	1	0.5	0	0
Apr	13	5	5	2
May	16	8	17	18
Jun	18	7	26	44
Jul	24	14	31	50
Aug	27	15	31	53
Sep	3	12	30	42
Oct	0	0	31	11
Nov	0	0.5	30	10
Dec	5	3	4	3
Year	107	15	210	53

Concluding remarks

After a relatively long period, a summarise of meteorological measurements at Arctowski Station is published. These measurements have been collected during a period of great interest in the cooling effects, and intense data analysis has been conducted from various meteorological stations located on the Antarctic Peninsula. In general, at Arctowski Station, there are only minor differences between meteorological conditions during 1977–1998 and 2013–2017. Nevertheless data collected at Arctowski Station during 2013–2017 confirm the decrease in air temperature in the summer months compared to the previous years, particularly the years during the 1980s and 1990s. Differences in climatic conditions between Arctowski Station and other stations located in the Maxwell bay may be related to the topography of the island – Arctowski station is in the lee of the 400–600 m high central ridge of King George Island, while the other stations are directly exposed to the prevailing south-westerly winds.

Installation of the AWS at Arctowski Station, was the first step to a deeper analysis and a larger project, with the aim to understand the climate conditions of the King George Island. In 2017, another station was installed in the region of

Puchalski Grave, and the next station will be launched in the nearest season in the King George Bay area with the purpose of supplementing the data collected for environmental monitoring carried out at western shore of King George Bay (Fig. 1). Two additional AWSs are planned to be launched in 2020 in the Demay Point area and near Penguin Island. We hope that the recent measurements presented in this work near Arctowski Station will also allow for a more detailed analysis of oceanographic, hydrological or biological processes, and our next plans will fit into the directions of research being conducted in the Antarctic Peninsula.

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