BOREAL ENVIRONMENT RESEARCH 23: 283–297 © 2018
ISSN 1797-2469 (online) Helsinki 29 October 2018

Strong anticyclones and deep cyclones over Svalbard in the years 1971–2015

Zuzanna Bielec-Bąkowska* and Artur Widawski

*Department of Climatology, Faculty of Earth Science, University of Silesia, Będzińska 60, PL-41-200 Sosnowiec, Poland (*corresponding author's e-mail: zuzanna.bielec-bakowska@us.edu.pl)*

Received 8 Apr. 2018, final version received 18 Oct. 2018, accepted 18 Oct. 2018

Bielec-Bąkowska Z. & Widawski A. 2018: Strong anticyclones and deep cyclones over Svalbard in the years 1971–2015. *Boreal Env. Res.* 23: 283–297.

This paper presents annual and long-term variability in the occurrence of cyclone and anticyclone centres over Svalbard during the period 1971–2015. The study is based on average daily air pressure values at sea level for 12 grid points and on the typology of synoptic situations. Particular emphasis is placed on the occurrence of deep and very deep cyclones (with a pressure of ≤ 990 hPa and ≤ 970 hPa, respectively) and strong and very strong anticyclones (with a pressure of ≥ 1030 hPa and ≥ 1035 hPa, respectively). On average there were about 17.5 days with a cyclone and 4.9 days with an anticyclone centre over Svalbard annually. The results of the analysis show no clear trend in the number of cyclones moving over the study area, but there was an observable increase in the frequency of anticyclones. There were also no major changes in the annual maximum of occurrence of the pressure systems under study.

Introduction

The warming of the Arctic, which has been growing gradually in recent decades, influences the dynamics and tracks of the pressure systems moving in the region. Studies conducted in recent years have focused primarily on determining how global warming affects cyclone activity in this region (Bengtsson *et al.* 2006, Kim *et al.* 2017, Rinke *et al.* 2017), and on how the trajectories of cyclones change (Yin *et al.* 2005, Catto *et al.* 2011). Most of the research has revealed that there is a positive feedback between Arctic warming and shift of cyclone tracks and a clear shift of the storm tracks towards the north and the north-east (Yin *et al.* 2005, IPCC 2007a, Catto *et al.* 2011, Feser *et al.* 2015). The simulations of the movement of cyclones conducted indicate a slightly different location of the tracks of the pressure systems in question. The differences in these results arising from the scenarios of changes in the amount of CO_2 in the atmosphere of the northern hemisphere and variations in ocean temperatures adopted (Bengtsson *et al.* 2006, Ulbricht *et al*. 2008, Laîné *et al.* 2009, Catto *et al.* 2011).

Other topics frequently addressed by researchers include changes in atmospheric circulation resulting from the impact of global warming and its influence on the dynamics of the development and occurrence of cyclones in the Arctic, which are largely responsible for transporting energy from lower latitudes towards the Arctic regions. This issue is particularly important in the light of the rapid temperature increase in this region (Lambert and Fyfe 2006, Przybylak 2007), which is most clearly seen in autumn

Editor in charge of this article: Antti Arola

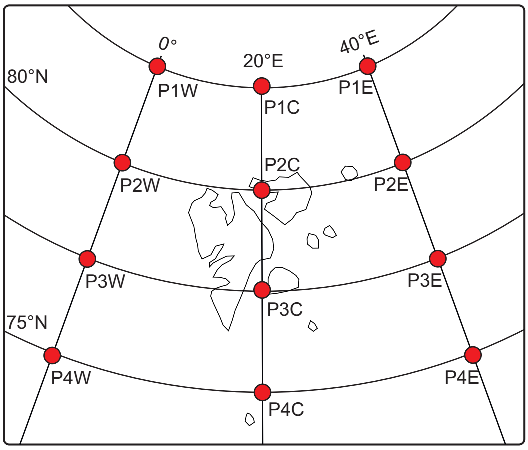

Fig. 1. Grid points used in the study (Bielec-Bąkowska 2016).

and winter (Marsz and Styszyńska 2011, Isaksen *et al.* 2016). According to some researchers (Watterson 2006, Pinto *et al.* 2007, Bengtsson *et al.* 2009, Catto *et al.* 2011), there are no indications of a significant increase in the number and intensity of occurrence of lows on a global scale in the immediate future. Nevertheless, such changes may occur regionally, for example in the area of the Atlantic Ocean to the north of the British Isles, and they are generally strongly dependent on the meridional temperature gradient of the ocean surface. An increase in the frequency of deep cyclones in the Arctic over the period 1979–2015 has been found by, amongst others, Rinke *et al.* (2017), and it can most probably be attributed to a longitudinal influx of heat and humidity from lower latitudes. A particularly strong risk of changes in weather conditions in a given area is posed by the occurrence of cyclones with extremely low pressure values in winter, which are referred to as "weather bombs", and are characterised by a very rapid and intense build-up. They result in distinct pressure drops (up to 12 hPa within six hours), strong gusts of wind, and an increase in temperature, which may cause very active melting of sea ice over vast areas (Boisvert *et al.* 2016, Graham *et al.* 2016, Kim *et al.* 2017).

Much less research has been dedicated to the occurrence and trajectories of high-pressure systems in the Arctic. For the most part, existing studies address the impact of anticyclones on the development of weather over a given area and on the values of selected meteorological components (Degirmendžić 1998, Wu and Wang 2002a, 2002b, Panagiotopoulos *et al.* 2005, Serreze and Barrett 2011). Meanwhile, the few papers concerning the frequency and location of anticyclones at high latitudes of the northern hemisphere point to considerable temporal and regional variations in their number and intensity (Serreze *et al.* 1993, Walsh *et al.* 1996, Cassano *et al.* 2006, Bielec-Bąkowska 2014).

Due to the mutual location of the continents and the oceans, the above changes in the atmospheric circulation in the Arctic are most pronounced in the Atlantic part of the northern hemisphere (Polyakov *et al.* 2003). For this reason, this study attempts to determine the seasonal and long-term variability of occurrence of high- and low-pressure systems over Svalbard in 1971–2015. Particular attention is paid to the long-term variability and intra-annual variations in the occurrence of deep lows and strong highs, as well as to the pressure values on days with the baric systems under analysis. Because of the numerous studies that have investigated the changing climatic conditions in Svalbard, the choice of the study area allows to compare the results obtained with the results of the analysis of selected baric systems occurrence. Furthermore, the calendar of atmospheric circulation types developed for Spitsbergen facilitates appropriate determination of pressure systems under study.

Material and methods

This study relies on data concerning average daily sea-level pressure values derived from NCEP/NCAR re-analyses (http://www.cdc.noaa.gov/) and on the typology of synoptic situations presented in the "Calendar of circulation types for Spitsbergen" (http://www.kk.wnoz.us.edu.pl/nauka/kalendarz-typow-cyrkulacji/) spanning the years 1971–2015. The pressure values were determined for 12 grid points ($P1_W$–$P4_E$) with a spatial resolution of 2.5° × 2.5° located over the Svalbard area, within the meridians 0°–40°E and the parallels 75°–82°30′N (Fig. 1). The data selected for analysis is commonly used to study pressure variations and is considered homogeneous (Kalnay *et al.* 1996). It is also ranked among the group of the most reliable grid data — Group A (Kalnay *et al.* 1996). It was decided that average daily pressure values would be used in the present study, rather than specific-hour pressure readings. The decision followed from the assumption that the study would focus on cases in which the pressure systems under consideration were present over a given area for a longer period of the day. Trends were calculated using the Mann-Kendall test (Mann 1945, Kendall 1975). The "Calendar of circulation types for Spitsbergen" was developed on the basis of synoptic maps of Europe. Author identified 21 types of synoptic situations taking into account the direction of air masses advection (N, NE, E, SE, S, SW, W, NW, N) and pressure systems (a = connected with anticyclonic conditions and c = connected with cyclonic conditions). Additionally, four non-advection circulation types (Ca = high centre, Ka = anticyclonic wedge or ridge of high pressure, Cc = centre of low and Bc = trough of low pressure with different directions of air flow and frontal system in the axis of through) and X = unclassified situations or pressure col were distinguished (http://www.kk.wnoz.us.edu.pl/nauka/kalendarz-typow-cyrkulacji/).

In the present study, a day on which, according to "Calendar of circulation types for Spitsbergen", a low-pressure centre (Cc) or a high-pressure centre (Ca) occurred over Svalbard was the main indicator of the presence of the respective pressure system, whereby:

- a deep low-pressure system was assumed to be a cyclone in which the pressure values over the study area were ≤ 990 hPa, while a very deep cyclone was defined as a system with a pressure of ≤ 970 hPa,
- a strong high-pressure system was assumed to be an anticyclone in which the pressure values over the study area were ≥ 1030 hPa, while a very strong anticyclones was one with a pressure of ≥ 1035 hPa.
- it was assumed that the strength of the said systems occurring over the study area would be determined on the basis of the lowest (cyclones) or the highest (anticyclones) pressure value occurring over at least one grid point.

The above threshold values were adopted on the basis of earlier research on the occurrence of high- and low-pressure systems in different regions of the northern hemisphere (Schinke 1993, Kłysik 1995, Kożuchowski 1995, Chen and Zhang 1996, Lambert 1996, Knippertz *et al.* 2000, Leckebusch and Ulbrich 2004, Burt 2007 a, 2007b, Bielec-Bąkowska and Piotrowicz 2011, 2013, Bielec-Bąkowska 2014, 2016), and followed from an analysis of the pressure values recorded over the study area.

Based on pressure data at grid points selected for analysis, it was found that pressure values ranging from 1000 to 1020 hPa were most frequent, representing in total from about 61% ($P4_E$) to about 70% ($P1_W$) of all the values identified (Table 1). Lower pressure were recorded at about 11% ($P1_W$) to 22% ($P4_E$) of all values, while higher pressure values was recorded at about 13% ($P4_W$) to 20% ($P1_E$), with a majority of these values falling within the 990–1000 hPa and 1020–1030 hPa ranges respectively. Exceptionally low (< 950 hPa) or high (≥ 1050 hPa) pressure levels were recorded sporadically, not exceeding three cases in the multi-year period at individual grid points. Taking into account the results obtained and the fact that extreme events are defined as those which "*... is rare at a particular place and time of year ...*" and "*... would normally be as rare as or rarer than the10th or 90th percentile ...*" of all the cases analysed (Beniston *et al.* 2007, IPCC 2007b), it was decided that the 990 hPa and 1030 hPa values respectively would be the most suitable limits for identifying the occurrence of deep cyclones systems and strong anticyclones, while 970 hPa and 1035 hPa would be the most appropriate for identifying very deep cyclones and extremely strong anticyclones, since they represent the 5th or 95th and 1st or 99th percentile of all the pressure values taken into account respectively (Table 2).

Spatial and seasonal variability of the low-pressure systems occurrence

Earlier research on pressure trends over Svalbard indicates that the spatial variability of the annual and long-term pressure changes in the region in 1971–2015 was not very high, which is linked to the small area of Svalbard (Bielec-Bąkowska 2016). The greatest pressure variations were observable between the north-western and south-eastern part of the region. The average annual pressure values decreased between these areas from about 1011 hPa ($P1_W$) to about 1008 hPa ($P4_C$) (Bielec-Bąkowska 2016). During the year, the lowest monthly pressure values were recorded in the winter months (averaging approx. 1001–1009 hPa), while the highest in

Table 1. Frequency of pressure values (%) occurrence over Svalbard in the period 1971–2015; numbers in boldface italics = number of cases, numbers in boldface = the most frequent pressure values.

Pressure (hPa)	Frequency (%)											
	$P1_W$	$P1_C$	$P1_E$	$P2_W$	$P2_C$	$P2_E$	$P3_W$	$P3_C$	$P3_E$	$P4_W$	$P4_C$	$P4_E$
< 950	***1***	***0***	***0***	***0***	***0***	***0***	***0***	***1***	***0***	***1***	***1***	***0***
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
⟨950; 960)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0
⟨960; 970)	0.1	0.2	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.5	0.5	0.4
⟨970; 980)	0.4	0.6	0.7	0.6	1.0	0.9	1.1	1.4	1.4	1.8	1.9	1.8
⟨980; 990)	1.7	2.7	3.1	2.7	3.4	3.9	4.1	4.6	4.7	5.3	5.9	5.6
⟨990; 1000)	9.2	10.7	11.3	10.5	11.6	12.6	11.8	12.9	14.0	13.3	14.6	14.6
⟨**1000; 1010**)	**31.1**	**30.8**	**28.9**	**30.8**	**29.3**	**29.0**	**31.0**	**29.5**	**29.3**	**30.5**	**29.4**	**29.2**
⟨**1010; 1020**)	**39.1**	**37.1**	**36.1**	**38.3**	**36.3**	**35.0**	**36.7**	**34.9**	**33.5**	**35.1**	**33.6**	**32.0**
⟨1020; 1030)	15.6	15.3	16.3	14.6	15.8	15.5	13.2	14.3	14.6	12.4	12.6	14.3
⟨1030; 1040)	2.5	2.4	3.1	2.1	2.3	2.8	1.6	2.0	2.2	1.1	1.4	2.0
⟨1040; 1050)	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1
≥ 1050	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	***2***	***2***	***2***	***3***	***1***	***2***	***2***	***1***	***0***	***0***	***0***

Table 2. Pressure values (hPa) over Svalbard in the period 1971–2015.

Value		Pressure values (hPa) at grid points											
		$P1_W$	$P1_C$	$P1_E$	$P2_W$	$P2_C$	$P2_E$	$P3_W$	$P3_C$	$P3_E$	$P4_W$	$P4_C$	$P4_E$
minimum		949.8	953.9	959.7	952.7	953.3	958.3	953.6	948.0	955.0	949.2	945.9	955.9
percentiles	1	984.6	981.5	981.3	981.1	978.9	979.3	976.6	976.4	976.3	973.9	974.0	975.0
	5	994.9	992.4	991.6	992.5	990.6	990.0	989.2	988.1	988.0	986.3	985.6	986.4
	10	999.1	997.2	996.8	997.5	996.0	995.3	995.1	994.0	993.6	992.5	991.6	992.2
	15	1001.7	1000.4	999.8	1000.4	999.3	998.6	998.7	997.7	997.1	996.4	995.4	996.0
	20	1003.7	1002.5	1002.2	1002.6	1001.9	1001.2	1001.1	1000.4	999.8	999.6	998.4	998.9
average		1011.4	1010.6	1010.8	1010.5	1010.3	1010.1	1009.3	1009.2	1009.1	1008.1	1007.8	1008.5
percentiles	80	1019.5	1019.3	1019.9	1019.0	1019.4	1019.4	1018.3	1018.7	1018.8	1017.6	1017.7	1018.7
	85	1021.3	1021.0	1021.8	1020.7	1021.1	1021.3	1020.0	1020.5	1020.7	1019.4	1019.6	1020.6
	90	1023.5	1023.3	1024.2	1022.8	1023.3	1023.5	1022.1	1022.7	1023.1	1021.5	1021.8	1022.9
	95	1027.0	1026.9	1027.9	1026.2	1026.7	1027.1	1025.5	1025.8	1026.4	1024.7	1025.1	1026.4
	99	1034.4	1034.0	1035.0	1033.1	1033.4	1034.1	1031.9	1032.6	1033.1	1030.5	1031.4	1033.0
maximum		1057.1	1055.7	1058.7	1054.2	1055.3	1056.7	1054.2	1053.9	1051.5	1048.5	1049.4	1046.0

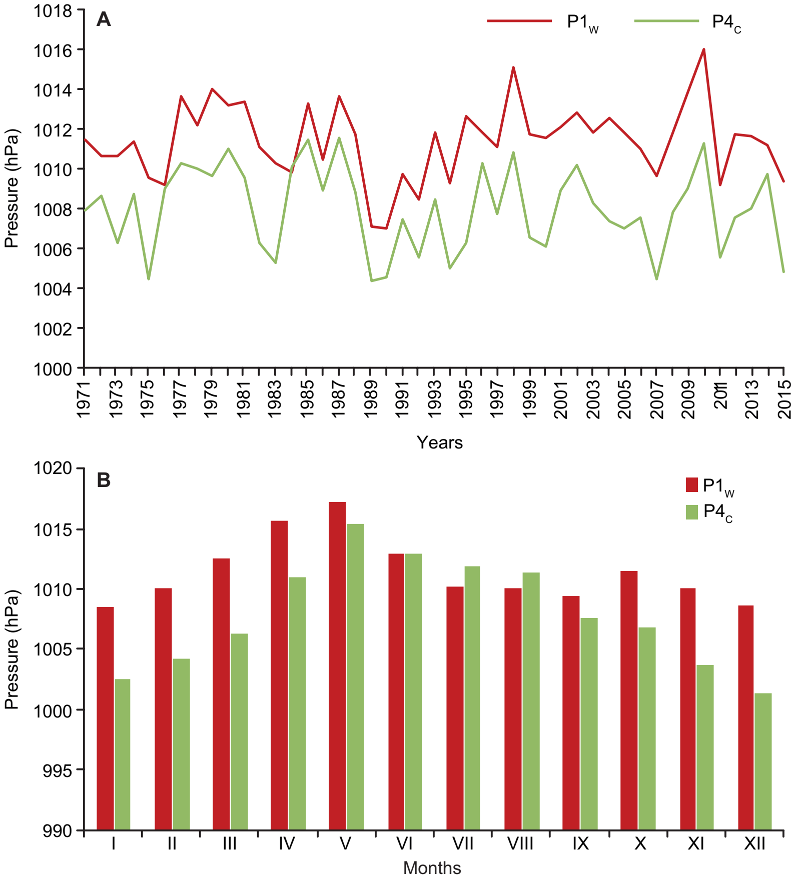

Fig. 2. (**A**) Annual and (**B**) average monthly pressure values (hPa) at P1$_W$ and P4$_C$ grid points in the period 1971–2015 (Bielec-Bąkowska 2016).

May (approx. 1015–1017 hPa on average), when the region is often under the influence of strong Greenland anticyclones (Niedźwiedź 2001). It can also be noted that pressure values in the north-western part of the study area were usually much higher than in the south-east, with the exception of the summer period (June–August), when the opposite was the case (Fig. 2). Over the multiannual period, changes in the annual pressure values were very similar throughout the area and there were no clear tendency in the average annual pressure values. At the turn of the 1980s and 1990s, a distinct decrease in pressure value was observable, with the greatest regional variations in annual pressure values seen in the years preceding and following the decrease. In the northern and western parts of the study area, after 1995, pressure values tended to be higher than at the beginning of the multiannual period, while in the southeastern regions, markedly higher pressure levels were recorded in the 1970s and 1980s (Bielec-Bąkowska 2016).

The Svalbard area is dominated by cyclonic activity (the centre of the cyclone is not necessarily over Svalbard), which tends to determine the weather of the study area for around 56.5% of the days of the year, while anticyclonic situations account for about 40.6% of all synoptic situations (Niedźwiedź 2013). Over the multi-year period, there were 789 days in Svalbard when the area was influenced by a cyclone centre (Cc). This means that on average 17.5 days with such a synoptic situation were recorded annually, which represented 4.8% of all days of the year. The average monthly number of such days varied slightly (ranging from an average of 1.8 days in May and July to 2.6 days in December; Fig. 3A). However, in individual years a cyclone centre occurred over the study area from 1 to as many as 7 days per month (February 1993

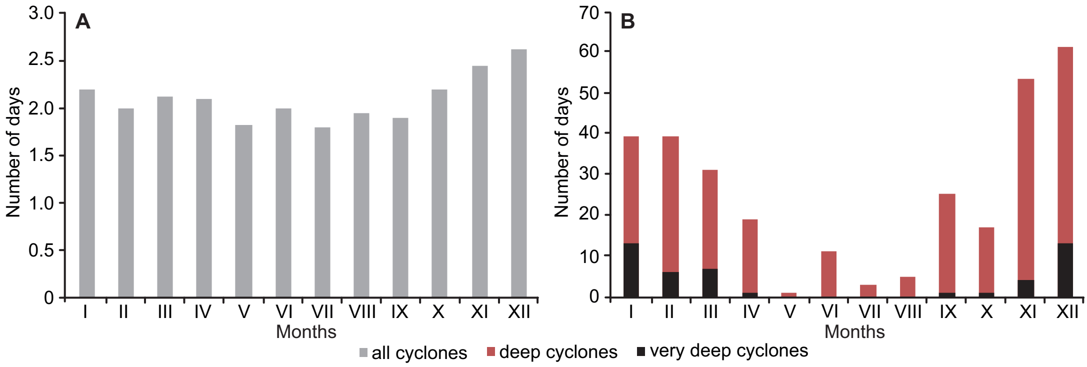

Fig. 3. (**A**) Average monthly number of days with cyclones and (**B**) number of days with deep (pressure ≤ 990 hPa) and very deep (pressure ≤ 970 hPa) cyclones over Svalbard in the period 1971–2015.

and November 1996; Fig. 4). It must also be emphasised that in around 30% of all the months analysed, no cyclone centre moved directly over Svalbard. And even though the predominance of such systems in winter (December–February) has been growing ever more pronounced in recent decades (Fig. 4), the annual maximum of the number of days with a cyclone centre has not always been recorded in winter. This is exemplified by the years 1972, 1976, 1981 and 1999, when the maximum was observed in the period from April to August, with as many as six days with a cyclone centre in a month in each case.

The variations of baric systems analysed are more pronounced for the occurrence of deep cyclones (with pressure values in the centre of the system lower than or equal to 990 hPa) and very deep cyclones (with pressure values in the centre of the system lower than or equal to 970 hPa). In the multiannual period, Svalbard saw an average of 6.8 days a year with deep low-pressure systems (overall 304 days during the period 1971–2015) and only approximately 1 day (46 days in total) with pressure lower than or equal to 970 hPa. During the year, the systems in question predominate in winter (Fig. 3B). Even though the annual maxima of occurrence of deep cyclones were recorded in February, April, or even in June (Fig. 5), the highest numbers of such systems were noticed in December (61 days in total) and in November (53 days), while the lowest numbers were recorded in summer (1 day in May and 3 days in July). The annual maximum number of days with very deep cyclones occurred in December and January (13 days in each of these months during the multi-year period), while from May to August, there were no such systems over the study area at all (Fig. 5).

There were also no major changes in the long-term variability of the occurrence of the low-pressure systems (Fig. 6). Such days occurred least frequently in 1998 and 2008 — only nine times, and most frequently in 1976 — in a string of 27 days. From year to year, the number of such days tended to fluctuate by 1–5 days, even though the greatest variation (from 1976 to 1977) amounted to as many as 17 days. The most characteristic feature of the long-term trend of occurrence of cyclone centres over Svalbard is their low frequency in 1977–1985 (around 12.9 days on average, with 17.5 days in the period 1971–2015), as well as an increased number of cyclones in the mid-1970s and towards the end of the second and third decades of the study period. The number of deep cyclones moving over the study area during the long-term period displays a similar trend as a number of all cyclones (correlation coefficient of 0.7; Fig. 6). Their annual number varied from 1 day in 1980 and 1985 to 12 days in 1976 and 1992 (with a long-term average of 6.8 days). At the same time, there was a more pronounced decline in the frequency of the systems in question from the end of the 1970s to the late 1980s, as well as at the turn of the 21st century. This is confirmed by changes in the share of the number of days with deep cyclones in the overall number of systems analysed. With the long-term average of around 38% of all cyclones, in the

Year	Number of cyclones													Number of anticyclones												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Sum	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Sum
1971			3	1	2		2		2	2		3	15													0
1972	2	4	2		1		2	6	2	1		2	22													0
1973		1	2	2		1		1	1	2			10													0
1974	1	3	1	2				1	3		4	4	19							1						1
1975	1	2	4	3	2	1	1	1	4	1	3	1	24										1			1
1976		2		6	2	1	3	5	3	1	4		27										3			3
1977	1	1			3	1					1	3	10													0
1978				1		1		1	1	3	2	1	10			1	1		1	3	1					7
1979		2			3	1					3	2	11													0
1980		1		4	3	2		2	2	1	1		16			1										1
1981		2	1	1	1	6		1			2		14									1				1
1982		1		1	1	2	2		2	2	2	1	14		1											1
1983		5	1		2			1	2		1		12					2				1				3
1984	1	2		1	4	2			1			3	14			1					1	1	1		1	5
1985	1	4	2	1	1		1	2		1	2		15	1				2								3
1986		1	4	1	1	2		4	1	5	1		20		1				1						1	3
1987	1	1	1	3	2		3	1	2	2	4	2	22						2		1	1	1			5
1988	1		3	3	1	2	1		1	1	1	1	15		2	2					1					5
1989	3	1	4	5	3		1	1	1	2	1		22			1					1					2
1990		1		3	3			1	1	3	3	3	18						2	4	5					11
1991	5	1		2				2	1	6		4	21						5	5						10
1992	3	1	3		3	3		1	1		2	3	20													0
1993	3	7	2	3	1					1			17			1	4	1	1		1	2				10
1994			2	3		4	3		3	2	2	2	21	1				2	1			2	1			7
1995	2		2	2		1	2	1	4	1	3	4	22									1				1
1996	2		4	4		1		2	2		7	3	25	1	3		3	3	2		2		1			15
1997	5	1	1	1	1	1	1	1				4	16			2			7	1				1	1	12
1998	1		2	1	1						2	2	9		2	1	5	1	4	1	2	2		1		19
1999	2	1		2	1	6	1	3	2	2	4		24					5			2					7
2000	3		3		4			1	1	1	1		14				1									1
2001	6		2	1	1		1		3	1	2	2	19				1	2		1						4
2002	4		1	1		1	1		1		2	3	14					6	1					1		8
2003	2	2	5	1	1		2		3		1	2	19	1					1				1			3
2004	1	1	1	3	1		2	1	1	2	2	4	19	1			2		1			1	1			6
2005	2	1	1	2	2		1	2	3	5	3		22				1		3						4	8
2006	4	1	1			3	2	2	2	2	2	4	23							2			1			3
2007	1	4		2		1	1		3	4	3	2	21					2		3						5
2008	1	1		2				2			1	2	9	1				1	1		3					6
2009	2	2		2		3			1	4		2	16			1					2					3
2010	3		1	1	1			1	2	2	2	1	14					1	1		1			2		5
2011	2	1	2	2	1	2	3	3		2	4	4	26		1			2			3			1		7
2012	1	5	1		1	1	3	1	1	1	1		16									2	2	2	1	7
2013	1	1		1	2		3	5			4		17			1		1	1			5				8
2014			1	2	2	1	2		1		5	5	19	1			1	5		3	2		2			14
2015		2	3	1			1		2	3	2	2	16								1					1
Sum	68	66	66	77	58	50	45	56	66	66	90	81	789	7	10	12	19	36	35	24	29	19	15	8	8	222
Average	2.2	2.0	2.1	2.1	1.8	2.0	1.8	1.9	1.9	2.2	2.4	2.6	17.5	0.2	0.2	0.3	0.4	0.8	0.8	0.5	0.6	0.4	0.3	0.2	0.2	4.9

Fig. 4. Number of cyclones and anticyclones over Svalbard in the period 1971–2015.

Year	Number of cyclones with pressure ≤ 990 hPa													Number of cyclones with pressure ≤ 970 hPa												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Sum	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Sum
1971				1					2			3	6													0
1972		4	1						1	1		2	9		1	1									1	3
1973		1	2					1		1			5													0
1974	1	3									1	4	9													0
1975	1	2	2						3		2	1	11	1											1	2
1976		2		5				2			3		12		1											1
1977											1	3	4													0
1978										1	2		3											2		2
1979											2	1	3													0
1980				1									1													0
1981				1							2		3													0
1982		1							2		2	1	6													0
1983		3	1								1		5													0
1984	1	1		1					1			2	6	1												1
1985		1											1													0
1986			2							4	1		7										1			1
1987	1			1							2	2	6	1												1
1988			1			1				1	1	1	5												1	1
1989	3	1	3						1				8			1										1
1990		1		3								3	7		1		1									2
1991	3			1					1	1		4	10	1											1	2
1992	3	1	3			1					2	2	12	1												1
1993	3	6	1	1									11	2	2											4
1994			1			4				1	2	2	10												1	1
1995	2		2				2		2		1	2	11	1		2										3
1996											5		5											1		1
1997	4		1	1				1				3	10	2		1										3
1998			1									1	2													0
1999		1				3			2		3		9		1							1				2
2000	2		1		1				1				5													0
2001	2								1		2	1	6													0
2002	4					1							5	2												2
2003			3						1			2	6													0
2004	1								1		1	3	6												1	1
2005	2	1					1		3	2	2		11													0
2006	3	1				1					2	4	11	1											2	3
2007	1	1								2	3	2	9											1	1	2
2008	1	1									1	1	4													0
2009		1							1			1	3													0
2010			1							1		1	3													0
2011			2	2						1	2	3	10												3	3
2012	1	4							1				6													0
2013								1			4		5													0
2014				1							1	4	6													0
2015		2	3						1	1	2	2	11			2									1	3
Sum	39	39	31	19	1	11	3	5	25	17	53	61	304	13	6	7	1	0	0	0	0	1	1	4	13	46

Fig. 5. Number of deep (≤ 990 hPa) and very deep (≤ 970 hPa) cyclones over Svalbard in the period 1971–2015.

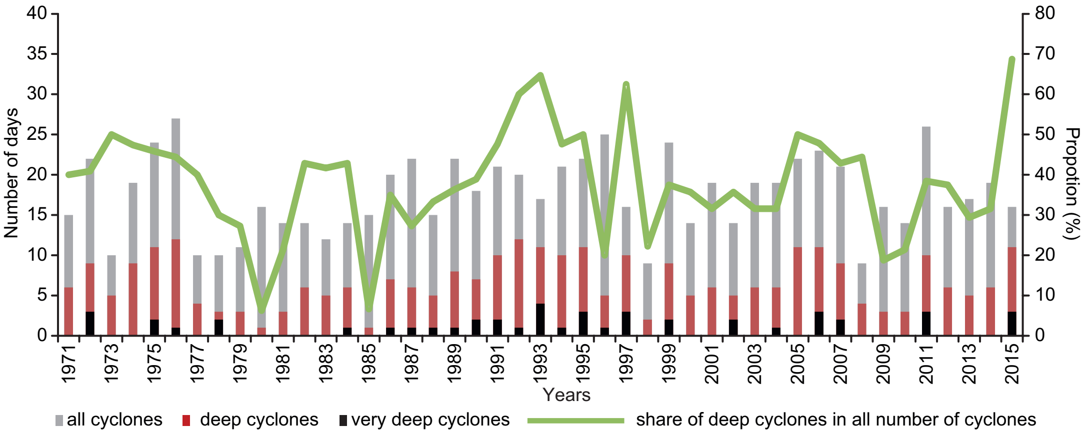

Fig. 6. Annual number of days with cyclones, deep (pressure ≤ 990 hPa) and very deep (p ≤ 970 hPa) cyclones over Svalbard in the period 1971–2015.

above periods the share would often drop to around 22%–33%, and in 1980 and 1985, even to 6.3% and 6.7% respectively. In the years when an increase of the number of cyclones moving over Svalbard was recorded, this rate tended to exceed 40%, reaching almost 69% in 2015. Very deep cyclones were recorded sporadically and never more often than on four days during the year. In 21 of the years such systems did not occur at all. Their greatest frequency was seen in 1986–1999, when a total of 23 out of 46 of them were recorded, and they occurred in each year of the period.

On days when deep cyclones moved over the region, pressure values lower than or equal to 990 hPa were most frequently recorded over only some of the study area. However, it is worth noting that on over 33 days (about 11% of all cases) such a low pressure occurred at all grid points (Fig. 7) and only 6 of those days pre-dated 1988. During the passage of such intense pressure systems, the average daily pressure values would drop as low as 949.8 hPa (8 January 2002). On days with deep cyclones, pressure values lower than or equal to 990 hPa tended to continue for not more than one day. There were only 30 cases when such a low pressure spanned two days and four cases in which it lasted for three days (in March 1989, February 1993 and 2012, and June 1999). The year 1993 was characteristic too, recording as many as 11 days with deep cyclones, including four days (at the turn of January and February) during which the average daily pressure fell below 970 hPa in the study area (at 8–11 grid points during one day).

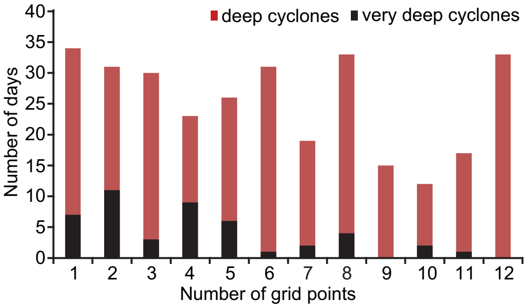

Fig. 7. Number of days with pressure ≤ 990 hPa or ≤ 970 hPa registered at particular number of grid points over Svalbard in the period 1971–2015.

Spatial and seasonal variability of the high-pressure systems occurrence

As has been mentioned above, on average anticyclone systems (the centre of the baric system is not necessarily over Svalbard) represent 40.6% of all synoptic situations occurring over the Svalbard area (Niedźwiedź 2013). By contrast, an anticyclone centre occurs much less frequently, and in the years 1971–2015, it accounted for a mere 1.4% of all cases. This means that on average there were around 4.9 such days during

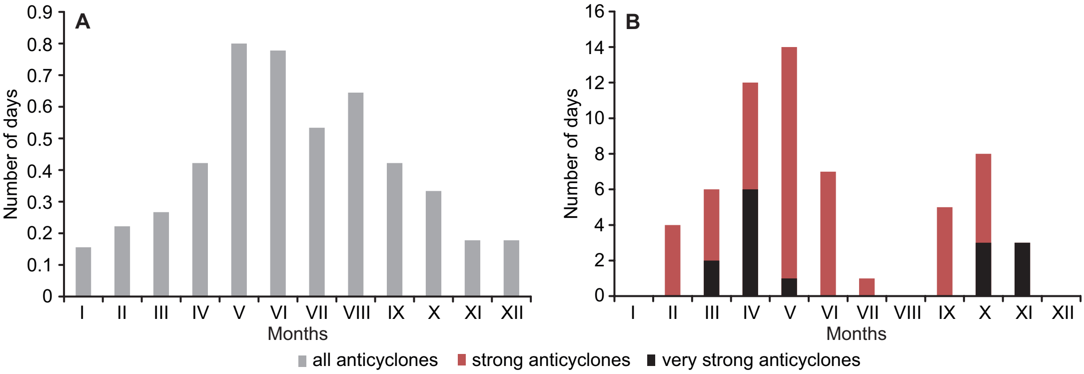

Fig. 8. (**A**) Average monthly number of days with anticyclones and (**B**) number of days with strong (pressure ≥ 1030 hPa) and very strong (pressure ≥ 1035 hPa) cyclones over Svalbard in the period 1971–2015.

the year, with the largest number of days with an anticyclone centre over the study area (19 days) recorded in 1998. High-pressure systems are least frequent in the cold period and most common in spring, which is characteristic of the region. The annual maximum of their frequency is usually seen from May to August (Fig. 4). On average, the months observe from 0.5 to 0.8 days with an anticyclone centre, even though the highest number of such days over the entire multiannual period was recorded in May (36 days), followed by June—only one fewer day (Fig. 8A). Strong and very strong anticyclones mainly occurred in spring and autumn, accounting — in the months of their greatest frequency — for 39%–63% (pressure ≥ 1030 hPa) and 17%–32% (pressure ≥ 1035 hPa) of all cases in spring, and for 26%–53% and 17%–38% in autumn, respectively (Figs. 8B and 9).

Unlike the long-term variability in the number of days with a cyclone centre, the number of days with an anticyclone centre over the area investigated saw a large growth from the beginning of the period (an increase of 1.5/10 years, statistically significant at 0.01; Fig. 10). The above increase is mainly attributable to the very small number of systems in the first decade of the multiannual period (with 13 of the 222 days in question), which also observed an increased frequency of cyclone centres. This means that, in the years 1971–1980, the annual average number of days with an anticyclone centre was only 1.3, while in the remaining period — around 6.0, with a multiannual average of 4.9 days. Anticyclone centres moved over Svalbard most frequently in the 1990s, which saw an average of more than eight such days during the year. The trend in the annual number of days with an anticyclone centre over the study area described may result from the distinct decrease in their frequency in the years 1971–1980. If the number of anticyclones had been considered from 1950, the increase would be much less noticeable (0.9/10 years), which is due to the number of anticyclones occurred in 1951–1970 (average 5.2 days during the year). Strong (pressure ≥ 1030 hPa) and very strong (pressure ≥ 1035 hPa) anticyclones were much less frequent, occurring on 60 and 15 days in the multi-year study period respectively (averaging approx. 1.3 and 0.3 days/year). In many of the years, they were not recorded at all, and they were slightly more frequent from the 1990s (Fig. 10).

On days when an anticyclone centre appeared over Svalbard, pressure values at individual grid points most frequently ranged between 1020 and 1030 hPa (38.0% at $P1_W$, 55.7% at $P4_C$). High pressure values were recorded over only a part of the study area relatively frequently, which is confirmed by the share of values from the 1010–1020 hPa range which reached from 22.6% ($P3_C$) to 48.0% ($P3_W$) at individual points, with values of 1030 hPa and more recorded at only 6.3% ($P1_W$) to 22.2% ($P3_C$). The highest pressure on days with an anticyclone centre over Svalbard was 1051.0 hPa which occurred on 21 March 2013.

Although, as a rule, anticyclones are horizontally extensive systems, very high pres-

Year	Number of anticyclones with pressure ≥ 1030 hPa													Number of anticyclones with pressure ≥ 1035 hPa												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Sum	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Sum
1971													0													0
1972													0													0
1973													0													0
1974													0													0
1975													0													0
1976										3			3													3
1977													0													0
1978				1									1				1									1
1979													0													0
1980			1										1													1
1981													0													0
1982		1											1													1
1983					1								1													1
1984													0													0
1985					2								2													2
1986													0													0
1987										1			1										1			1
1988		2	1										3													3
1989													0													0
1990							1						1													1
1991													0													0
1992													0													0
1993			1	3	1								5				2	1								5
1994					1								1													1
1995													0													0
1996				2									2				2									2
1997			1			2							3													3
1998			1	2		4			2		1		10			1								1		10
1999					2								2													2
2000				1									1													1
2001													0													0
2002					3								3													3
2003										1			1										1			1
2004				2									2													2
2005				1		1							2				1									2
2006										1			1													1
2007													0													0
2008					1								1													1
2009													0													0
2010					1						2		3											2		3
2011		1			2								3													3
2012										1			1													1
2013			1						3				4			1										4
2014										1			1										1			1
2015													0													0
Sum	0	4	6	12	14	7	1	0	5	8	3	0	60	0	4	6	12	14	7	1	0	5	8	3	0	60

Fig. 9. Number of strong (≥ 1030 hPa) and very strong (≥ 1035 hPa) anticyclones over Svalbard in the period 1971–2015.

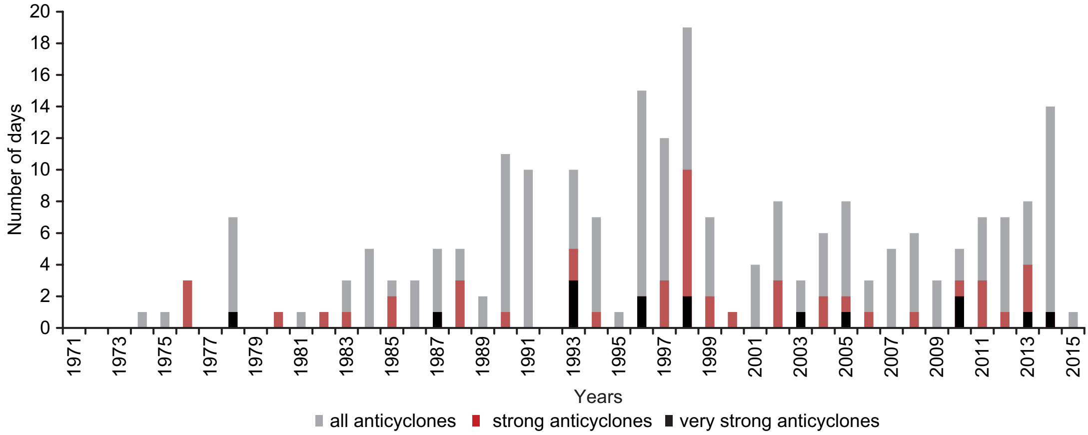

Fig. 10. Annual number of days with anticyclones, strong (pressure ≥ 1030 hPa) and very strong (pressure ≥ 1035 hPa) anticyclones over Svalbard in the period 1971–2015.

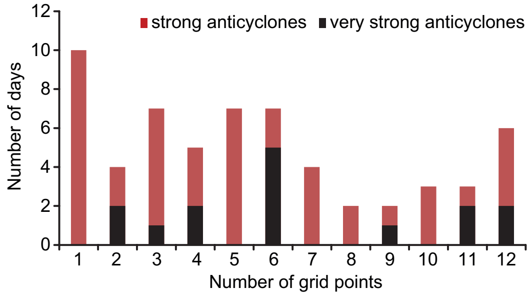

Fig. 11. Number of days with pressure ≥ 1030 hPa or ≥ 1035 hPa registered at particular number of grid points over Svalbard in the period 1971–2015.

sure values (not lower than 1030 hPa) were most often recorded at 1–6 grid points on the same day (Fig. 11). Pressure of ≥ 1030 hPa was recorded at 12 points merely six times. The pressure values fluctuated over the study area on the days in question: 1021.4–1051.0 hPa, when pressure ≥ 1030 hPa was recorded at 10–12 grid points; and 1030.9–1051.0 hPa, when pressure ≥ 1030 hPa was recorded at 12 grid points. Cases in which a pressure of ≥ 1030 hPa covered the entire or almost the entire area mainly occurred from the 1990s (Table 3).

Discussion and conclusions

The Arctic is one of those areas which are very sensitive to climate change, in particular to changes in atmospheric circulation, which accounts for the greater part of the energy that flows into the area. A unique role in this process is played by dynamic low-pressure systems moving from the Atlantic towards the polar regions. However, the presence of high-pressure systems is equally important. On the one hand, such systems favour cloudless weather and strong long-wave radiation into the atmosphere, and on the other, they often become blocking systems, which modify cyclone trajectories. Deep low-pressure systems and strong high-

Table 3. Days with pressure ≥ 1030 hPa noted in at least 10 grid points over Svalbard in the period 1971–2015.

Year	Month	Day	Number of grid points with pressure	
			≥ 1030 hPa	≥ 1035 hPa
1978	IV	23	11	2
1987	X	22	12	4
1993	IV	1	11	6
1993	V	20	12	6
1996	IV	9	10	9
1998	XI	12	11	6
2005	IV	29	12	12
2010	V	15	10	0
2010	XI	26	12	11
2010	XI	27	12	11
2013	III	21	12	12
2014	X	8	10	4

pressure systems, which have an exceptionally important influence on weather, are particularly important. Therefore, learning about changes in the frequency of occurrence of low- and high-pressure systems may provide better insight into the climate change which takes place over the study area.

The study presented in this paper focuses on the occurrence of low- and high-pressure systems over Svalbard, an area which is under a strong influence of the atmospheric circulation from the Atlantic and the thermal effect of the ocean. The results obtained indicate that, despite the observable and forecasted shift of cyclone tracks towards Polar Regions (Leckebusch and Ulbrich 2004, Zhang *et al.* 2004, Yin *et al.* 2005, Catto *et al.* 2011), there are no pronounced changes in the number of cyclones occurring over the study area in the period 1971–2015. This concerns both all cyclones and deep and very deep cyclones, thus confirming the results of research by other authors, who point to an absence of changes or even a decrease in the number of cyclones in these regions (Watterson 2006, Pinto *et al.* 2007, Bengtsson *et al.* 2009, Catto *et al.* 2011). A characteristic feature of the long-term trend of low-pressure systems is a clear decrease in their frequency in 1977–1985, and an increase in the 1990s. It is worth noting that, in the years which stand out, a high number of days with a cyclone centre over Svalbard was usually associated with a high frequency of deep lows. In those years, their share in the total number of low-pressure systems exceeded 40%, reaching even 69% in 2015. As regards the annual maximum of the occurrence of the systems analysed, there is a slight predominance of cyclones occurring in November and December, especially towards the end of the multiannual period under study. This predominance is more pronounced in the case of deep and very deep cyclones, which usually demonstrate the highest annual values in December and November and December and January respectively. On account of the small area covered by cyclonic systems and the dynamics with which they move, cyclone centres with pressure $\leq$ 990 hPa spanned more than half of the study area in only 42% of the cases, with deep cyclones (pressure $\leq$ 970 hPa) continuing for as many as 3 days only 4 times.

Anticlones are much less frequent over Svabard (Niedźwiedź 2013), and an anticyclone centre extended over the area on merely 1.4% of all days in the multi-year study period. However, compared to cyclonic systems, the increase in the number of the anticyclones in question was evident. It seems that this mainly resulted from the very small number of anticyclones occurring at the beginning of the period analysed, which was dominated by an increased number of cyclones. However, similar relationships are not noticeable during the rest of the multi-year period, since an increased number of anticyclones in the 1990s is accompanied by a large number of cyclones moving over Svalbard. Perhaps this can be explained by other changes in circulation over the study area, including the pressure value changes (Bielec-Bąkowska 2016), increased westerly flow and strong cyclonic circulation (Walsh *et al.* 1996, Polyakov *et al.* 2003, Niedźwiedź 2004, Zhang *et al.* 2004), and the north-westward movement of the Siberian High, as a result of which it can influence the weather within the study area to a greater extent (Zhang *et al.* 2012). Although the increase was not statistically significant for strong and very strong anticyclones, certain signs of an increase in their frequency can be observed from the beginning of the 1990s. The changes described were not accompanied by a variation in the annual course of occurrence of high-pressure systems. Such systems were most frequent in the warm half of the year, with the annual maxima falling in May, although these anticyclones should be treated as weak pressure systems. Meanwhile, strong and very strong highs occurred chiefly in spring and autumn, when they usually took the form of vast pressure systems covering a large part of the region, with pressure reaching 1050 hPa.

Acknowledgements: The publication has been partially financed from the funds of the Leading National Research Centre (KNOW) received by the Centre for Polar Studies of the University of Silesia, Poland.

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