INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **38**: 230–251 (2018)
Published online 22 June 2017 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.5172

The influence of atmospheric circulation on the spatial diversity of air temperature in the area of Forlandsundet (NW Spitsbergen) during 2010–2013

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ABSTRACT: The relationship between atmospheric circulation and climate in Svalbard has been described in dozens of studies. However, the data used for that purpose usually came from permanent stations on the coast. The influence of atmospheric circulation on topoclimatic diversity has not been explored so often, and hardly at all for other periods than the Arctic summer. In this article, the relationships between circulation and air temperature are described using daily data sourced from six sites located around Forlandsundet (NW Spitsbergen) during 2010–2013. The analysis was conducted independently for three seasons identified as: winter (Nov–Mar), spring/autumn (Apr–May and Sep–Oct) and summer (Jun–Aug) and also for three air temperature parameters: diurnal mean (Ti), maximum (T_{max}) and minimum (T_{min}) temperature. The atmospheric circulation in the studied area was described using Tadeusz Niedźwiedź's classification of diurnal circulation types for Svalbard. The influence of atmospheric circulation on the spatial pattern of air temperature is not uniform across the Forlandsundet region; in particular, important differences were observed between coastal and inland parts of the study area. Thus, generalization of relationships between air temperature and atmospheric circulation for the entire area of Spitsbergen based on data only from coastal stations is not appropriate. The influence of atmospheric circulation on the spatial pattern of air temperature in the Forlandsundet region also changes through the year. In the cold season (Sep–May) it differs significantly from that observed in summer (Jun–Aug), and this feature is also seen in analyses of the 10% highest (≥ 90th percentile) and lowest (≤ 10th percentile) thermal differences. In summer, the influence of atmospheric circulation on air temperature in the topoclimatic scale is definitely less stable than in the cold season.

KEY WORDS Spitsbergen; Forlandsundet; atmospheric circulation; air temperature; topoclimates

Received 9 September 2016; Revised 17 May 2017; Accepted 18 May 2017

1. Introduction

The rise in the Arctic air temperature in recent decades has exceeded the scale of warming observed in this region in the 1920s and 1930s (Johannessen *et al.*, 2004; Przybylak, 2002, 2007, 2016; Turner *et al.*, 2007; Turner and Marshall, 2011). As a result, large changes in environment (e.g. decline in sea-ice extent and thickness, decreases in glacier surfaces and terminuses, intensification of the hydrological cycle, shrinkage of tundra areas, changes in vegetation and animal species) are more and more clear and dramatic (ACIA, 2005). Monitoring of the Arctic environment, and in particular of the climate (which is a main driver of the observed changes) is important and necessary. The majority of available studies focus, however, on analyses of macroscale climate changes (e.g. Chapman and Walsh, 1993; Kahl *et al.*, 1993a, 1993b; Walsh, 1995; Førland *et al.*, 1997; Przybylak, 2000, 2007; Polyakov *et al.*, 2003; for review see Przybylak, 2016). For such purposes, meteorological data come almost entirely from sites located near the coast in tundra areas. There is a growing need for better climatic information from mountainous and glaciated parts of Arctic islands and continental areas. The change from manual to automatic measurement techniques over recent decades has markedly improved the state of topoclimatic knowledge for some areas of the Arctic. The Svalbard Archipelago, including Spitsbergen (analysed in the present paper), is a good example of our enlargement of this kind of knowledge.

Of all Arctic regions, Svalbard probably has the longest and richest history of topoclimatic observations. The first such measurements were conducted during the Swedish–Russian scientific expedition, which was sent to northern Spitsbergen in 1899 to measure an arc of the Earth's meridian. Two meteorological stations, the main one located by the sea in Treurenberg Bay (21.9 m a.s.l.) and a secondary station situated on Massif Olimp (408 m a.s.l.) worked here from 1st August 1899 to 15th August 1900 (Przybylak and Dzierżawski, 2004). The second oldest topoclimatic investigations were initiated during the Polish Polar Expedition to Spitsbergen organized within the International Geophysical Year 1957–1958 and also continued later in the years 1959–1960. Meteorological measurements were made in Hornsund (11 m a.s.l.) and in the firn part of the

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Werenskiold Glacier (386 m a.s.l.) (Kosiba, 1960). Later, topoclimatic investigations in this region were continued within the so-called 'Wrocław expeditions' between the years 1970 and 1974 (Baranowski and Głowicki, 1974, 1975; Pereyma, 1983) and in more recent times (Brázdil *et al.*, 1988; Pereyma and Piasecki, 1988; Nasiółkowski and Pereyma, 2007; Migała *et al.*, 2008; Araźny *et al.*, 2009, 2010). The second area in Spitsbergen where intensive topoclimatic studies have been conducted since 1975 is the Forlandsundet region (for more details on the history and scope of this activity, see Przybylak *et al.*, 2012a). This type of investigation is also noted in three other regions (Bellsund, Petuniabukta and Kongsfjorden), but on a significantly smaller scale than in the two previously mentioned areas (Gluza and Piasecki, 1989; Brázdil *et al.*, 1991; Rachlewicz, 2003; Gluza and Siwek, 2006, 2007, 2009; Esau and Repina, 2012). It should be added here that the majority of topoclimatic studies is limited to the summer period. Usually, the main aim of topoclimatic studies in Svalbard has been the recognition of the spatio-temporal features of certain meteorological variables (mainly air temperature, humidity and precipitation).

A good knowledge of the influence of atmospheric circulation on the climate in Svalbard is available (see e.g. Przybylak, 1992a, 1992b; Wójcik *et al.*, 1992; Niedźwiedź, 1993, 1997a,1997b, 2001, 2006, 2013; Hanssen-Bauer and Førland, 1998; Przybylak and Araźny, 2006; Araźny, 1998, 2008; Bednorz, 2010; Łupikasza, 2010; Käsmacher and Schneider, 2011; Przybylak *et al.*, 2012b). Climate-circulation relationships, however, were established using meteorological data (mainly air temperature and precipitation) from one coastal station, or more rarely from few such stations. On the other hand, there is a very limited number of works trying to recognize the influence of atmospheric circulation on topoclimate diversity in Svalbard (Wójcik *et al.*, 1993; Migała *et al.*, 2008; Kejna *et al.*, 2012; Przybylak and Maszewski, 2012; Bednorz *et al.*, 2014; Przybylak *et al.*, 2014; Małecki, 2015). Moreover, they are limited mainly to summer time, when campaign measurements were organized in different parts of Spitsbergen.

The main aim of the present paper is to describe for the first time for the Svalbard area the relationships between the spatial distribution of air temperature over all seasons (not only for summer, as has been the case up till now) in the Forlandsundet region (NW Spitsbergen) and atmospheric circulation based on continuous all-year measurements made in the period July 2010 to November 2013. In particular, we want to check which patterns of atmospheric circulation favour the occurrence of extreme values in temperature diversity in the topoclimatic scale. For this purpose, besides mean daily temperature (Ti), daily extreme temperatures (T_{max} and T_{min}) were also used for the first time in this area.

The current potential to identify the causes of the spatial and seasonal differences found is limited to some extent by the fact that Niedźwiedź's classification of circulation types (Niedźwiedź, 1993, 2013) contains no information on the regions from which air masses originate (only type of baric regime and direction of air mass inflow), meaning that an analysis of the regions of origin of – and transformations in – air masses *en route* to Spitsbergen, and thence their impact, is also not possible.

Our scientific hypothesis assumes that atmospheric circulation is an important factor controlling the spatial diversity of air temperature on the topoclimate scale in the study area and that its influence on that diversity changes throughout the year. The existence of a strong influence of atmospheric circulation on the spatial diversity of air temperature may be helpful in reconstruction of the air temperature field in the study area based on Niedźwiedź's classification of circulation types.

2. Area, data and methods

As stated in the Introduction, topoclimatic investigations in the Forlandsundet region were undertaken in 1975 (see also Przybylak *et al.*, 2012a). In the summer of 2010, within the Polish–Norwegian research project *Arctic Climate and Environment of the Nordic Seas and the Svalbard-Greenland Area* (*AWAKE*), as many as 18 measurement sites were established over an area that significantly exceeded the area of observations carried out before. Continuous series of observations with hourly resolution for the period July 2010 to November 2013 were available with only small data gaps (<0.1%), but only for the six sites listed in Table 1 and shown in Figure 1. Fortunately, they were all located near the Nicolaus Copernicus University Polar Station and, very importantly, they represent all main ecotypes and types of surface and relief (beach, tundra, moraine, glacier and mountains) occurring in the study area.

Air temperature measurements with hourly resolution were made at all sites listed in Table 1 using MadgeTech, Temp110 (Jul 2010–Jul 2012) and HOBO U23, Onset (Aug 2012–Nov 2013) sensors. Sensors were placed 2 m above ground in Onset RSI type radiation screens. The accuracy of MadgeTech/HOBO temperature sensors was ±0.5 and ±0.2 °C, respectively. Parallel temperature measurements in the Forlandsundet region carried out in tundra and glacial environments, using both the temperature sensors and mercury thermometers with respective accuracies of 0.2–0.5 and 0.1°C (both thermometers were placed in Stevenson screens) have shown either a lack of – or very small, statistically non-significant – differences between the calculated daily means.

Daily mean temperature (Ti) for each site has been calculated as the simple average of 24-hourly measurements. On the other hand, daily maximum (T_{max}) and minimum (T_{min}) temperatures were determined by choosing the highest and lowest values, respectively, from the daily set of 24-hourly data. The analysis was conducted independently for three seasons identified as: winter (Nov–Mar), spring/autumn (Apr–May and Sep–Oct) and summer (Jun–Aug). This rather non-conventional merging of two seasons was done mainly because the frequency of occurrence of some atmospheric types (see next paragraph) for

Table 1. Measurement sites of air temperature in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013.

No.	Sites		φ	λ	h (m a.s.l.)	Distance to the shoreline (m)	Kind of surface (summer)	Equipment
	Abbreviation	Name						
1	KH	Kaffiøyra-Heggodden	78°40′34″N	11°49′38″E	11	160	tundra	MadgeTech/HOBO
2	SAT	Sarstangen	78°43′38″ N	11°28′50″E	2	40	beach	MadgeTech/HOBO
3	LW1	Waldemar Glacier – front	78°40′31″N	12°00′01″E	130	3800	moraine	MadgeTech/HOBO
4	LW2	Waldemar Glacier – firn field	78°40′54″N	12°05′16″E	375	5720	glacier	MadgeTech/HOBO
5	GF	Gråfjellet	78°39′59″N	12°00′33″E	345	3260	mountain peak	MadgeTech/HOBO
6	PH1	Prins Heinrichfjella – 1	78°40′51″N	11°59′28″E	500	1870	mountain peak	MadgeTech/HOBO

separate seasons (with a duration of only two months) was significantly smaller than that for winter and summer (five and three months, respectively). Both joined transitional seasons have more or less the same values of air temperature, height of sun, and sea ice conditions. In the case of western Spitsbergen (in the Forlandsundet area) sea ice in the months in question, according to maps produced by the Norwegian Meteorological Institute, was not present or was categorized as open waters (concentration 0/0 – 1/10); for details see http://polarview.met.no/.

The description of the atmospheric circulation of the studied area has been provided using the calendar of daily circulation types for Spitsbergen, continuously updated by Tadeusz Niedźwiedź and available at http://klimat.wnoz.us.edu.pl/#!/glowna. The principles of classification of the circulation types are given on the website and are also summarized briefly below. Niedźwiedź (1993, 2013) distinguished 21 circulation types in Spitsbergen (16 types with distinct air advection e.g. from the north (N), north-east (NE), etc.; four non-advectional types: Ka, Ca, Bc and Cc; and one unclassified type X) based on analysis of synoptic maps for the studied years and available from the DWD Archives (http://www.wetter3.de/Archiv/archiv_dwd.html) (for more details see Table S1, Supporting information). The author of the classification used lower-case letters 'a' to describe anticyclonic (high-pressure) systems and 'c' for cyclonic (low-pressure) systems. The rules of Niedźwiedź's classification are similar to the well-known Lamb (1972) classification presented for the British Isles. The period concerned in this paper is, from a synoptic climatology point of view, short (July 2010–November 2013), and therefore the influence of atmospheric circulation on the topoclimates was analysed using the eight combined circulation types for Spitsbergen, as proposed by Przybylak (1992a), and listed in Table 2, so that the statistical samples of the days when an individual synoptic pattern occurred could be increased. Similarities between thermal-humidity conditions occurring during the atmospheric circulation types were taken into account in combining them into greater groups by Przybylak (1992a). As results from Table 2, the number of days of a given circulation type in each season is not lower than 10 (except types Ea+SEa and 'X' in summer; the latter is not taken for analysis, because it represents synoptic situations which cannot be classified).

Seasonal mean anomalies of air temperature differences (Ti, T_{max} and T_{min}) between the SAT, LW1, LW2, GF and PH1 sites on one hand and the KH site on the other have been calculated for each circulation type by subtracting mean differences obtained from days with a given circulation type from the mean difference calculated from all days for which data exist for the given season. Air temperature data from the KH site were used as reference data because the location of KH (close to the coastline) is most similar to the location of the permanent meteorological stations operating in Spitsbergen. The second, and equally important, reason for this decision was the fact that, since 1975, KH has been Nicolaus Copernicus University's main meteorological station in the Kaffiøyra region, and therefore has the longest and most complete series of meteorological observations.

On the other hand, to delimit lowest and highest seasonal temperature differences between the KH site and other meteorological sites, values of 10th and 90th percentiles, respectively, determined from all days, have been used as thresholds (see Table 3). These threshold values allowed days which fulfil the required criteria to be chosen and for them to be attributed to circulation types. In the next step, the frequency of circulation types and mean values of extreme temperature differences have been calculated separately for each season and also for each type of circulation (Table 4, Table S2a, b). Days with the largest negative/positive anomalies of average air temperature differences between KH and other study sites were analysed. The largest negative anomalies encompass days with greater than normal near-surface lapse rates of air temperature in the study area (i.e. the decrease of values of air temperature parameters is significantly greater than average with rise of altitude). In turn, the largest positive anomalies describe days with smaller than normal near-surface lapse rates of air temperature, including inversion changes.

In addition, frequencies of air temperature differences close to 0 (−0.5–+0.5 °C) stratified into circulation types were also calculated.

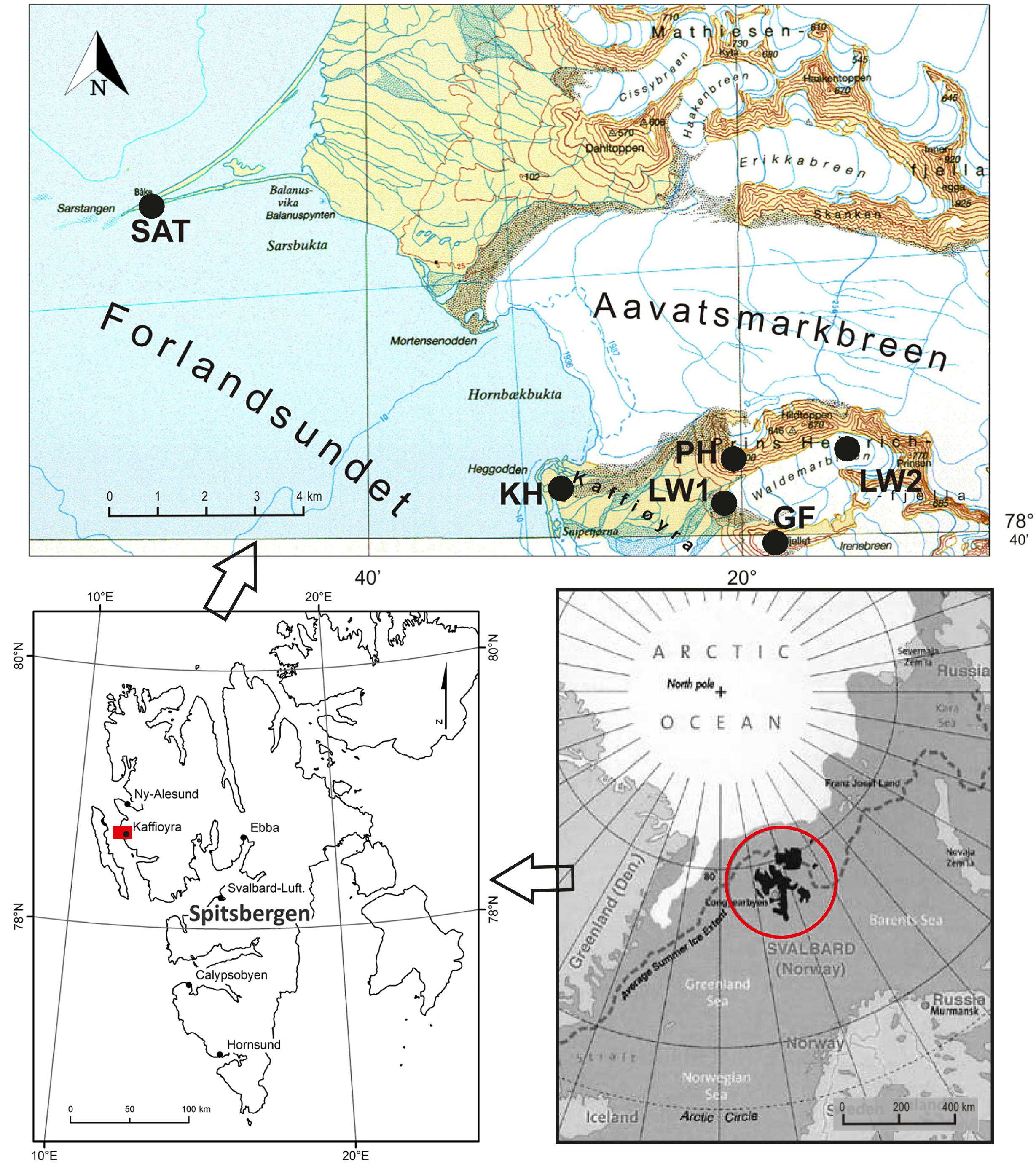

Figure 1. Location of the study region and measurement sites. [Colour figure can be viewed at wileyonlinelibrary.com].

Variability of thermal conditions in the analysed meteorological sites during inflow of air masses within particular circulation type was estimated using standard deviation (σ).

3. Results

3.1. Mean spatial thermal diversity and atmospheric circulation

The frequencies of circulation types which occurred in the study period (Jul 2010–Nov 2013) and the long-term reference period January 1951 to July 2010 are shown in Table 2. As results from the table, frequency differences between types were not large, and rarely exceeded $\pm 5\%$. Particularly small differences between the two analysed periods were observed in winter. The highest frequency difference (11%) was noted in summer for type NWa+Na+NEa. On the other hand, the occurrence of other anticyclonic types in this season was lower than normal, and the total frequency of all of them was therefore only slightly smaller (-2.7%) than in the reference period (Table 2). The frequency of all anticyclonic types in spring and autumn was much lower (by 13.6%) in the

Table 2. Absolute (n) and relative (%) frequencies of occurrence of circulation types and their variability (σ) in winter (Nov–Mar), summer (Jun–Aug), spring (Apr–May) and autumn (Sep–Oct) in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013.

No.	Type of circulation	2010–2013[a]								1951–2010[b]												Differences (2010–2013)–(1951–2010)			
		Winter		Spring and autumn		Summer		Year		Winter			Spring and autumn			Summer			Year			Winter (%)	Spring and autumn (%)	Summer (%)	Year (%)
		n	%	n	%	n	%	n	%	n	%	σ (%)	n	%	σ (%)	n	%	σ (%)	n	%	σ (%)				
1	NWa+Na+NEa	39	12.0	33	11.1	38	20.5	110	13.6	1058	11.7	6.8	1067	14.7	5.2	525	9.6	5.7	2650	12.2	4.3	0.3	−3.6	11.0	2.5
2	Ea+SEa	29	9.0	22	7.4	8	4.3	59	7.3	935	10.4	5.3	811	11.2	4.7	564	10.3	6.9	2310	10.6	3.9	−1.4	−3.8	−6.0	−3.7
3	Sa+SWa+Wa	12	3.7	15	5.0	14	7.6	41	5.1	320	3.6	2.8	389	5.4	3.3	541	9.9	5.4	1250	5.7	2.5	0.2	−0.3	−2.3	−0.8
4	Ka+Ca	22	6.8	21	7.0	23	12.4	66	8.2	633	7.0	3.0	939	12.9	3.7	974	17.8	7.4	2546	11.7	2.8	−0.2	−5.9	−5.3	−3.8
ANTICYCLONIC		102	31.5	91	30.5	83	44.9	276	34.2	2946	32.7	10.5	3206	44.2	8.6	2604	47.5	13.6	8756	40.3	7.6	−1.2	−13.6	−2.7	−5.8
5	NWc+Nc+NEc	73	22.5	67	22.5	37	20.0	177	21.9	1725	19.1	6.6	1189	16.4	5.6	747	13.6	6.8	3661	16.8	4.3	3.4	6.1	6.4	5.3
6	Ec+SEc	66	20.4	63	21.1	11	5.9	140	17.3	1950	21.6	7.1	1093	15.1	5.5	530	9.7	4.4	3573	16.4	4.2	−1.3	6.1	−3.7	0.4
7	Sc+SWc+Wc	27	8.3	31	10.4	26	14.1	84	10.4	984	10.9	4.8	700	9.6	3.8	735	13.4	8.0	2419	11.1	3.4	−2.6	0.8	0.6	−0.4
8	Bc+Cc	37	11.4	31	10.4	19	10.3	87	10.8	1173	13.0	4.1	853	11.8	3.4	678	12.4	5.4	2704	12.4	2.8	−1.6	−1.3	−2.1	−1.7
CYCLONIC		203	62.7	192	64.4	93	50.3	488	60.5	5832	64.7	10.2	3835	52.8	8.1	2690	49.1	13.2	12357	56.8	7.4	−2.0	11.6	1.2	3.6
9	X	19	5.9	15	5.0	9	4.9	43	5.3	236	2.6	1.5	218	3.0	1.7	184	3.4	2.5	638	2.9	1.2	3.2	2.0	1.5	2.3
Total		324	100	298	100	185	100	807	100	9014	100	–	7259	100	–	5478	100	–	21751	100	–	–	–	–	–

[a]2010–2013 – period from 21.07.2010 to 22.11.2013.
[b]1951–2010 – period from 1.01.1951 to 20.07.2010.
σ-standard deviations calculated for period: 1.01.1951 to 31.12.2009.

Table 3. Threshold values of air temperature (Ti, T_{max} and T_{min}) differences (°C) used to delimit extreme situations in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013.

Sites	Winter						Spring and autumn						Summer					
	10%			90%			10%			90%			10%			90%		
	Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}
SAT–KH	−0.9	−1.0	−3.7	1.6	1.9	2.1	−0.4	−0.9	−1.0	1.3	1.2	1.8	−0.9	−1.7	−0.6	0.6	0.8	1.1
LW1–KH	−1.7	−1.6	−2.1	1.0	0.8	2.3	−1.4	−1.5	−2.1	0.6	2.2	0.3	−1.2	−1.2	−1.6	0.7	1.4	0.0
LW2–KH	−2.8	−3.1	−3.5	0.3	0.3	1.6	−2.8	−3.1	−3.5	−0.1	1.5	−0.4	−3.1	−3.2	−3.5	0.3	1.5	−0.2
GF–KH	−2.7	−3.0	−3.0	0.7	0.1	2.2	−2.8	−3.1	−3.0	−0.4	0.0	0.1	−2.9	−3.0	−3.1	0.8	1.3	0.4
PH1–KH	−4.4	−4.6	−4.4	−0.2	−0.5	1.4	−4.0	−4.2	−4.2	−0.4	0.9	−1.0	−3.4	−3.4	−3.7	1.6	2.8	1.1

For full names of sites (KH, SAT, etc.) see Table 1.

study period than in the period 1951–2010, while the frequency of cyclonic types was greater by 11.6%. However, the frequency differences in each analysed circulation type between the periods 2010–2013 and 1951–2010 are lower than 1–2 σ (calculated using data from 1951–2010) in transitional seasons and below 1σ in winter and in summer (except type NWa+Na+NEa, which is about 2 σ) (see Table 2).

As was underlined in the Introduction section, the influence of atmospheric circulation on air temperature in Spitsbergen is well-known but only for the narrow coastal areas, where all working meteorological stations are located. Results presented by Przybylak (1992a) and Niedźwiedź (2013) using data from Hornsund (southern Spitsbergen) showed that, with some exceptions, during the entire year the coolest types of circulation are NWa+Na+NEa and NWc+Nc+NEc, and the warmest are Sa+SWa+Wa and Sc+SWc+Wc. In particular, warm air masses come from southern and south-western sectors, while cold air masses come from the opposite directions. Both eastern types (Ea+SEa and Ec+SEc) as well as non-advectional type Ka+Ca bring colder-than-average air masses in the cold-half year and warmer-than-average masses in the warm-half year. On the other hand, air masses within the type Bc+Cc are usually warmer than average in all seasons except summer (Przybylak 1992a).

Average air temperature (Ti, T_{max} and T_{min}) differences between the KH site, which is always used as the reference station, and other sites are shown as a function of circulation types for all analysed seasons in Figures 2a–c, while mean values of Ti, T_{max} and T_{min} differences calculated from data for all days in a given season (i.e. for all circulation types) are presented in Table 5 (see the rows entitled 'Mean differences'). In that table, anomalies of Ti, T_{max} and T_{min} for each circulation type in reference to mean differences calculated from all days (a state of differences between sites which we refer to in this work as 'normal' or 'normal conditions/spatial pattern') are also shown. This permits the easy distinction of circulation types which favour the occurrence of warmer (positive anomalies) or colder (negative anomalies) temperatures in the study area in relation to thermal conditions at the KH site. For clarity, we must add here that physical conditions of air masses coming to the study area from different directions and within different baric systems (described here using circulation types) are usually unable, when air masses move very fast, to directly cause temperature and humidity diversity in the topoclimatic scale. One exception here is cloudiness (strongly dependent on atmospheric circulation) which has such an ability in mountainous and glaciated areas in particular. On the other hand, atmospheric circulation most often influences diversity indirectly by strengthening/weakening the influence of local processes (solar radiation, albedo, local winds, etc.). It is possible that during some circulation types, the impact of local factors on topoclimatic conditions is even stronger than the impact of synoptic scale atmospheric circulation.

In winter (Table 5, Figure 2(a)), all sites were on average colder than KH, except SAT, which is located on a narrow peninsula surrounded by water from almost all directions (see Figure 1). Tmin at SAT had a lower value (by 0.5 °C) than at KH, while T_{max} and Ti were warmer by about 0.5 °C. Smaller differences of T_{min} than for the other two thermal parameters are seen in the rest of the studied pairs of data series, but they are particularly great between PH1 and KH, and between GF and KH (Table 5). Topographic conditions (at sites located on the ridge of the Prins Heinrichfjella and the summit of the Grafjellet mountain, respectively) and the occurrence of stronger winds here than in the Tundra area prevent cold air from being kept in both areas. As a result, the decrease in T_{min} with altitude was smaller than the decrease in T_{max}.

Greater Ti differences (usually by about 0.5 °C) than average ones noted in winter between the Waldemar Glacier and its surrounding mountains on one side and the KH site on the other occurred mainly during advection of air masses from the northern sector (types NWc+Nc+NEc, NWa+Na+NEa) and during the occurrence of circulation type Bc+Cc (Table 5, Figure 2(a)). On the other hand, the opposite pattern (i.e. smaller differences than average) were noted when air masses came from the southern and eastern sectors, in particular during anticyclonic types (anomalies often exceed 1 °C, see Table 5). In the case of air advection from the eastern sector, smaller than average differences were probably connected with the occurrence of foehn winds, which has warm mountainous and glaciated areas more than Tundra areas (Wójcik *et al.* 1998). It should also be noted here that temperature conditions over the Greenland Sea (Forlandsundet) represented by SAT reveal generally

Table 4. Absolute (n) and relative (%) frequencies of occurrence of days with largest (≥90%) and smallest (≤10%) anomalies of Ti differences and their mean values for given type of circulation in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013.

Type of circulation	SAT−KH						LW1−KH					
	Frequency				Mean differences (°C)		Frequency				Mean differences (°C)	
	n		%				n		%			
	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%
Winter												
NWa+Na+NEa	2	5	6.7	16.1	−2.0	1.9	5	1	16.1	3.2	−1.8	2.4
Ea+SEa	4	3	13.3	9.7	−2.7	1.9	1	6	3.2	19.4	−1.7	3.1
Sa+SWa+Wa	3	2	10.0	6.5	−1.2	1.9	0	3	·	9.7	·	2.9
Ka+Ca	1	4	3.3	12.9	−1.8	2.0	4	2	12.9	6.5	−1.8	3.7
NWc+Nc+NEc	4	8	13.3	25.8	−1.3	2.0	15	4	48.4	12.9	−2.0	1.7
Ec+SEc	11	6	36.7	19.4	−2.0	2.2	4	12	12.9	38.7	−2.0	2.3
Sc+SWc+Wc	2	0	6.7	·	−1.8	·	1	2	3.2	6.5	−2.1	1.4
Bc+Cc	3	3	10.0	9.7	−1.2	2.4	1	1	3.2	3.2	−1.8	1.8
Spring and autumn												
NWa+Na+NEa	2	4	6.7	14.3	−0.9	1.6	3	2	10.0	6.7	−1.7	0.7
Ea+SEa	1	3	3.3	10.7	−0.6	1.7	0	5	·	16.7	·	1.1
Sa+SWa+Wa	2	0	6.7	·	−0.5	·	0	1	·	3.3	·	0.7
Ka+Ca	0	1	·	3.6	·	1.7	1	2	3.3	6.7	−1.7	1.0
NWc+Nc+NEc	4	12	13.3	42.9	−0.6	1.7	17	1	56.7	3.3	−1.8	0.7
Ec+SEc	8	7	26.7	25.0	−0.7	1.8	6	8	20.0	26.7	−1.8	0.8
Sc+SWc+Wc	9	0	30.0	·	−0.8	·	0	4	·	13.3	·	0.7
Bc+Cc	4	1	13.3	3.6	−0.8	1.3	3	7	10.0	23.3	−2.1	1.0
Summer												
NWa+Na+NEa	2	2	10.5	10.5	−1.0	1.2	2	8	12.5	42.1	−2.1	1.1
Ea+SEa	3	1	15.8	5.3	−2.9	0.6	1	2	6.3	10.5	−1.6	1.5
Sa+SWa+Wa	4	2	21.1	10.5	−1.6	1.2	0	1	·	5.3	·	1.0
Ka+Ca	1	0	5.3	·	−1.2	·	5	0	31.3	·	−1.3	·
NWc+Nc+NEc	5	4	26.3	21.1	−1.7	0.8	1	3	6.3	15.8	−1.3	1.4
Ec+SEc	1	1	5.3	5.3	−0.9	0.7	2	2	12.5	10.5	−1.3	0.8
Sc+SWc+Wc	3	5	15.8	26.3	−1.0	1.2	1	0	6.3	·	−1.3	·
Bc+Cc	0	4	·	21.1	·	0.8	4	3	25.0	15.8	−1.5	0.8

Table 4. Continued.

Type of circulation	LW2–KH						GF–KH						PH1–KH					
	Frequency				Mean differences (°C)		Frequency				Mean differences (°C)		Frequency				Mean differences (°C)	
	n		%				n		%				n		%			
	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%	≤10%	≥90%
Winter																		
NWa+Na+NEa	4	1	14.3	3.2	−3.2	1.9	4	2	13.8	6.3	−3.0	2.0	3	2	10.0	6.3	−5.0	1.5
Ea+SEa	0	6	·	19.4	·	2.9	0	7	·	21.9	·	3.3	0	7	·	21.9	·	2.1
Sa+SWa+Wa	0	3	·	9.7	·	1.6	0	3	·	9.4	·	1.6	0	1	·	3.1	·	1.0
Ka+Ca	1	2	3.6	6.5	−2.8	2.3	2	1	6.9	3.1	−2.9	4.3	1	3	3.3	9.4	−4.4	1.2
NWc+Nc+NEc	15	3	53.6	9.7	−3.4	1.3	14	4	48.3	12.5	−3.3	1.9	20	2	66.7	6.3	−4.9	0.7
Ec+SEc	1	12	3.6	38.7	−3.1	2.4	1	12	3.4	37.5	−2.8	2.4	2	13	6.7	40.6	−4.5	1.4
Sc+SWc+Wc	2	3	7.1	9.7	−3.5	1.5	2	2	6.9	6.3	−3.5	1.3	1	2	3.3	6.3	−5.1	0.6
Bc+Cc	5	1	17.9	3.2	−3.2	0.4	6	1	20.7	3.1	−3.0	1.1	3	2	10.0	6.3	−4.6	0.1
Spring and autumn																		
NWa+Na+NEa	4	0	13.3	0.0	−3.2	·	3	2	10.7	6.7	−3.2	0.2	2	3	6.9	10.3	−4.3	0.0
Ea+SEa	1	5	3.3	17.2	−3.1	1.6	1	6	3.6	20.0	−2.8	1.9	1	6	3.4	20.7	−4.7	1.6
Sa+SWa+Wa	0	0	·	·	·	·	0	0	·	·	·	·	0	0	·	·	·	·
Ka+Ca	1	0	3.3	·	−2.8	·	3	0	10.7	·	−3.1	·	0	2	·	6.9	·	0.4
NWc+Nc+NEc	13	3	43.3	10.3	−3.2	0.3	11	4	39.3	13.3	−3.1	0.2	18	2	62.1	6.9	−4.7	−0.1
Ec+SEc	2	15	6.7	51.7	−2.9	0.8	2	14	7.1	46.7	−3.0	0.8	1	11	3.4	37.9	−4.5	0.8
Sc+SWc+Wc	7	1	23.3	3.4	−3.1	0.4	5	1	17.9	3.3	−2.9	−0.1	4	1	13.8	3.4	−4.3	−0.4
Bc+Cc	2	5	6.7	17.2	−3.1	0.7	3	3	10.7	10.0	−3.0	0.2	3	4	10.3	13.8	−4.3	0.1
Summer																		
NWa+Na+NEa	2	5	11.8	26.3	−3.3	0.7	6	6	33.3	33.3	−3.0	1.3	0	10	·	55.6	·	2.5
Ea+SEa	0	4	·	21.1	·	1.2	0	4	·	22.2	·	2.1	0	1	·	5.6	·	3.6
Sa+SWa+Wa	1	1	5.9	5.3	−3.3	1.1	0	1	·	5.6	·	1.7	3	0	17.6	·	−3.7	·
Ka+Ca	4	1	23.5	5.3	−3.3	0.5	2	2	11.1	11.1	−3.1	1.3	0	2	·	11.1	·	2.4
NWc+Nc+NEc	3	2	17.6	10.5	−3.4	1.6	9	1	50.0	5.6	−3.2	1.2	5	2	29.4	11.1	−3.7	2.1
Ec+SEc	0	6	·	31.6	·	0.9	0	4	·	22.2	·	1.5	0	3	·	16.7	·	3.1
Sc+SWc+Wc	6	0	35.3	·	−3.3	·	1	0	5.6	·	−2.9	·	8	0	47.1	·	−3.5	·
Bc+Cc	1	0	5.9	·	−3.2	·	0	0	·	·	·	·	1	0	5.9	·	−3.5	·

For full names of sites (KH, SAT, etc.) see Table 1.

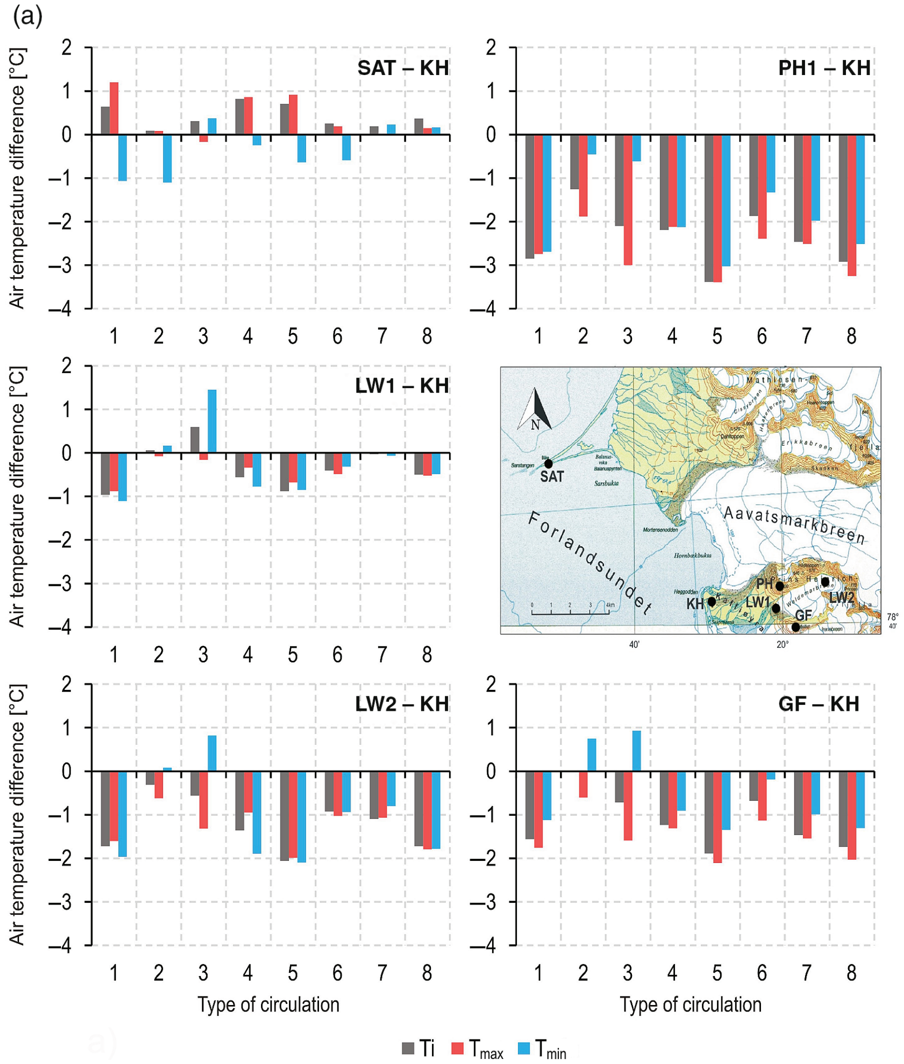

Figure 2. Seasonal (a – winter; b – spring and autumn, and c – summer) mean differences of air temperature parameters (Ti, T_{max} and T_{min}) between pairs of sites (KH as reference site) in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013 observed during individual circulation types. Key: for full names of sites see Table 1; circulation types: 1 – NWa+Na+NEa, 2 – Ea+SEa, 3 – Sa+SWa+Wa, 4 – Ka+Ca, 5 – NWc+Nc+NEc, 6 – Ec+SEc, 7 – Sc+SWc+Wc, 8 – Bc+Cc; bars from left to right show results for Ti, T_{max} and T_{min}, respectively. [Colour figure can be viewed at wileyonlinelibrary.com].

opposite relationships with atmospheric circulation than those described earlier for glacier and mountainous areas. Northern circulation types, as well as Ka+Ca type, favour the occurrence of greater Ti differences between SAT and KH than usual (see Table 5, Figure 2(a)). Inspection of Table 5 and Figure 2(a) clearly shows that Ti and T_{max} are more similarly dependent on atmospheric circulation, while T_{min} differs from them significantly in the case of some circulation types. For example, for types Sa+SWa+Wa and Ea+SEa temperature differences GF–KH and LW2–KH for T_{min} are positive, while for T_{max} and Ti they are negative. From Figure 3, showing frequency of occurrence of days with small Ti differences (−0.5–+0.5 °C) between study sites, it is evident that such situations are clearly more frequent (15–40%) during cyclonic types Ec+SEc and NWc+Nc+NEc, except for the LW1–KH area where the greatest share (20–25%) belongs to types Sc+SWc+Wc and Bc+Cc. The smallest air temperature differentiation during anticyclonic types is noted for type Ea+SEa (upper glaciated and mountainous areas) and type NWa+Na+NEa (for sites located below 200 m a.s.l.). Small Ti differences occur most rarely during type Sa+SWa+Wa (Figure 3). Roughly similar relationships to those described for Ti between circulation types favouring/not favouring the occurrence of small differences is also seen for T_{max} and T_{min} (see Figures S1(a) and S1(b), respectively).

In spring and autumn, similarly to winter, all sites were on average colder than KH, except SAT and LW1 for T_{max} (Table 5, Figure 2(b)). On the other hand, conversely to winter, reactions of Ti and T_{min} to advection of air masses during particular circulation types reveal greater similarity than Ti and T_{max}. This is very well seen in particular across the Waldemar Glacier area (see LW1–KH and LW2–KH graphs in Figure 2(b)). Similarly as in winter, the greater than average temperature differences (in terms of Ti and T_{min}) noted between mountainous and glaciated parts of the study area on one side and the KH

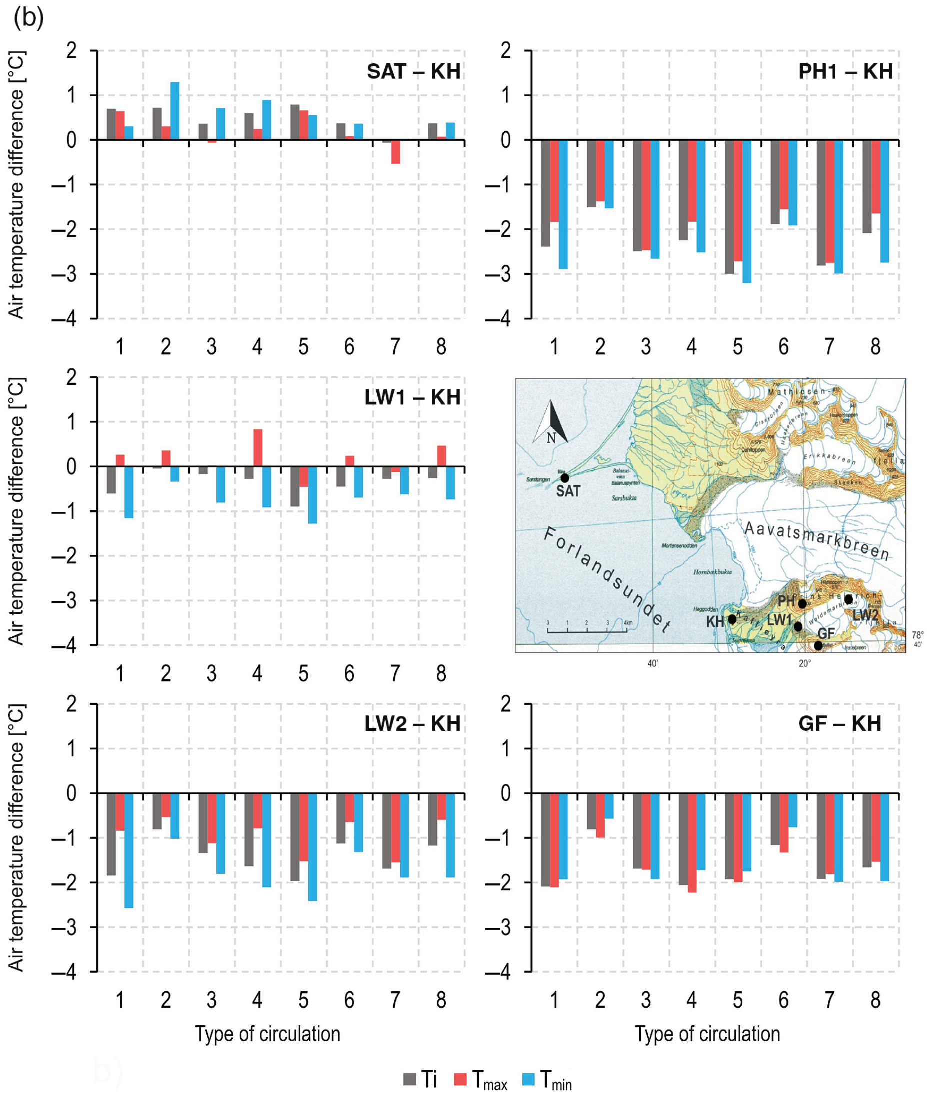

Figure 2. Continued. [Colour figure can be viewed at wileyonlinelibrary.com].

site on the other occurred mainly during advection from the northern sector, particularly strongly expressed (but only for Ti) within cyclonic situations NWc+Nc+NEc (Table 5, Figure 2(b)). Similar thermal differentiation (i.e. negative anomalies, although usually smaller) is seen for type Sc+SWc+Wc but – unlike for winter – not for type Bc+Cc. The Sc+SWc+Wc type also favours the occurrence of that kind of temperature difference anomaly (for all thermal parameters) between SAT and KH (Table 5, Figure 2(b)). With regards to T_{max}, mountainous and glaciated parts are colder than coastal parts during advection from both northern and southern sectors, but only within cyclonic types. Greater heating of the mountainous and glaciated areas (in terms of all thermal parameters) in comparison to coastal ones is noted mainly during advection from the eastern sector (types Ea+SEa and Ec+SEc) and, in the case of T_{max}, also during Bc+Cc type. Anomalies of Ti and T_{max} between SAT and KH sites are greatest for both northern types while, in the case of T_{min}, for Ea+SEa and Ka+Ca types (Table 5, Figure 2(b)).

Zero or little change in Ti with altitude was markedly more often noted in the study area during cyclonic types of atmospheric circulation than anticyclonic, similarly as was observed in winter (see Table 5 and Figure 3). In the entire area in the spring and autumn seasons, the greatest frequency of occurrence of small differences was observed during Ec+SEc type. The second circulation type which favoured the occurrence of such thermal situations was most often the NWc+Nc+NEc type. In the case of anticyclonic situations, type-to-type changes of frequency are not high, except Prins Heinrichfjella mountain, where very small differences were noted quite often (24%) during NWa+Na+NEa type, while for type Sa+SWa+Wa such cases did not occur. T_{max} and T_{min} in the study season generally show similar dependencies on types of atmospheric circulation as Ti, although some differences – sometimes significant – are also noted (compare Figure 3 with Figures S1(a) and S1(b), e.g. for mountainous areas). A greater diversity of type frequencies favouring the occurrence of small differences in T_{max} and T_{min} in the study area was noted in the spring/autumn season than

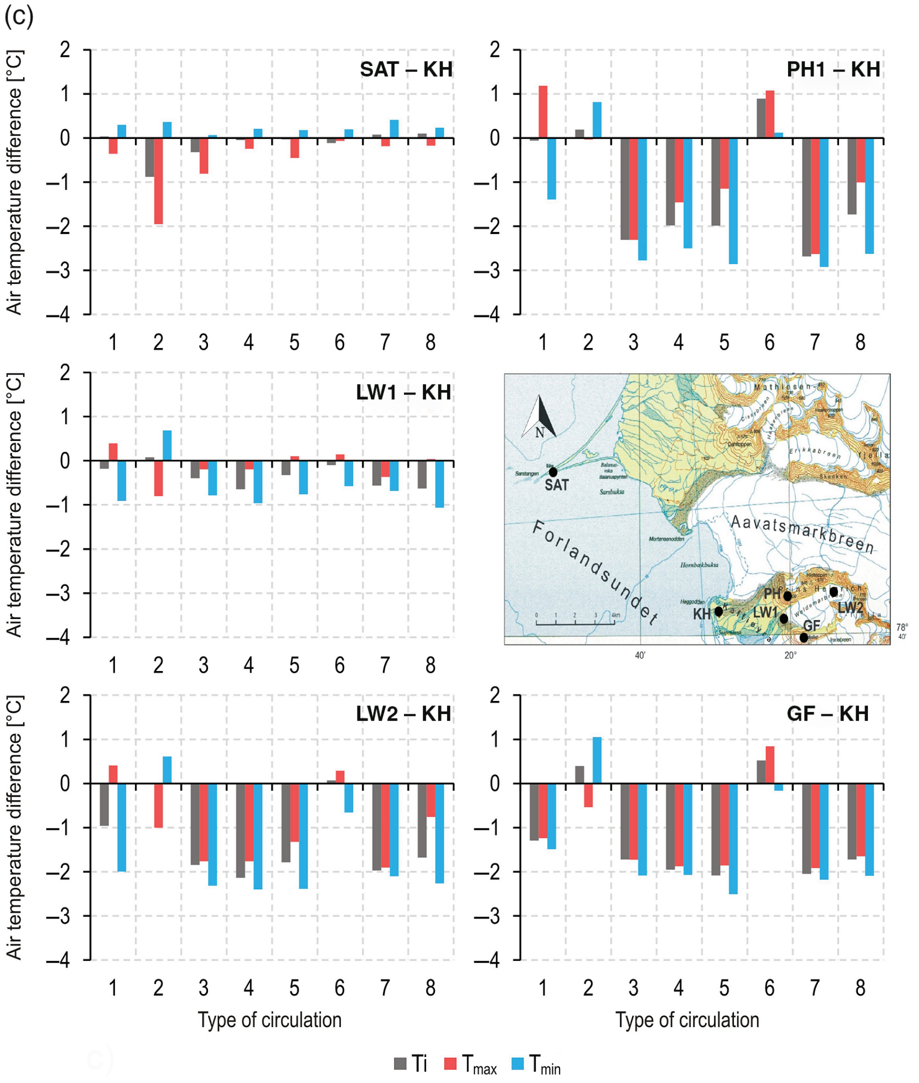

Figure 2. Continued. [Colour figure can be viewed at wileyonlinelibrary.com].

in winter (Figures S1(a) and S1(b)). As a result, in the former season, a majority of days (> 40% for T_{min} and > 20% for T_{max} in the upper part of the study area) with very similar thermal conditions were noted during circulation type Ec+SEc, while during type Sa+SWa+Sa such situations very often did not occur, in the case of T_{min} in particular.

On average, all non-coastal sites are colder in summer than the KH site. Ti at the SAT and KH sites was the same, while T_{max} was colder (by 0.4 °C) and T_{min} warmer (by 0.2 °C). This spatial pattern is in line with expectations because the first site is located 2 m a.s.l. near the end of the narrow Sarstangen Peninsula, and is surrounded by water from almost all directions, while the KH site is located 11 m a.s.l. on a flat surface of lateral-side moraine of the Aavatsmark Glacier, 200 m from the shoreline (see Figure 1).

In summer, the influence of atmospheric circulation on the spatial distribution of air temperature is markedly different than in the two seasons described earlier (see Table 5 and Figures 2(a)–(c)), if negative anomalies of air temperature differences are analysed. For example, the frequency of negative anomalies of Ti differences was greater by 38% than in the two other studied periods. This kind of anomalies (meaning the occurrence of greater than normal values of lapse rates in the region) for Ti and T_{max} was noted at all sites (except SAT) during advection from the south-western sector (types Sa+SWa+Wa and Sc+SWc+Wc) and also during Ka+Ca type. On the other hand, atmospheric circulation's influence on T_{min} was similar as in winter, except for type NWa+Na+NEa, which in summer (conversely to winter) usually causes positive anomalies in differences, in particular in mountainous areas (Table 5, Figure 2(c)). Air over the Greenland Sea (SAT site) was colder than usual in comparison to the KH site (except for T_{min}) clearly during two anticyclonic types Ea+SEa and Sa+SWa+Wa (respectively by 0.9/0.3 °C for Ti and 1.6/0.4 °C for T_{max}). Positive anomalies of air temperature differences (weakening of normal lapse rates including inversion situations) are most common in terms of Ti and T_{min} mainly during air advection from the eastern sector (types Ea+SEa and Ec+SEc), as was also stated for two other seasons. T_{max} also has large positive

Table 5. Anomalies of air temperature (Ti, T_{max} and T_{min}) differences (°C) between KH and other sites in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013.

Type of circulation	Winter					Spring and autumn					Summer				
	SAT−KH	LW1−KH	LW2−KH	GF−KH	PH1−KH	SAT−KH	LW1−KH	LW2−KH	GF−KH	PH1−KH	SAT−KH	LW1−KH	LW2−KH	GF−KH	PH1−KH
Ti															
NWa+Na+NEa	0.2	−0.5	−0.3	−0.3	−0.3	0.2	−0.1	−0.3	−0.4	0.0	0.0	0.2	0.5	0.3	1.3
Ea+SEa	−0.3	0.6	1.1	1.3	1.2	0.2	0.5	0.7	0.9	0.9	−0.9	0.5	1.5	2.0	1.6
Sa+SWa+Wa	−0.1	1.1	0.8	0.6	0.4	−0.1	0.3	0.2	0.0	−0.1	−0.3	0.0	−0.3	−0.1	−0.9
Ka+Ca	0.4	−0.1	0.0	0.1	0.3	0.1	0.2	−0.1	−0.4	0.2	−0.1	−0.2	−0.6	−0.4	−0.6
NWc+Nc+NEc	0.3	−0.4	−0.7	−0.6	−0.9	0.3	−0.4	−0.5	−0.2	−0.6	0.0	0.1	−0.3	−0.5	−0.6
Ec+SEc	−0.1	0.1	0.5	0.6	0.6	−0.1	0.1	0.4	0.5	0.5	−0.1	0.3	1.6	2.1	2.3
Sc+SWc+Wc	−0.2	0.5	0.3	−0.2	0.0	−0.6	0.2	−0.2	−0.2	−0.4	0.1	−0.2	−0.5	−0.4	−1.3
Bc+Cc	0.0	0.0	−0.3	−0.4	−0.4	−0.1	0.2	0.3	0.0	0.3	0.1	−0.2	−0.2	−0.1	−0.3
Mean differences	0.4	−0.5	−1.4	−1.3	−2.5	0.5	−0.5	−1.5	−1.7	−2.4	0.0	−0.4	−1.5	−1.6	−1.4
T_{max}															
NWa+Na+NEa	0.7	−0.4	−0.2	−0.3	0.0	0.4	0.2	0.2	−0.4	0.3	0.0	0.4	1.4	0.3	2.0
Ea+SEa	−0.4	0.4	0.8	0.9	0.8	0.1	0.3	0.5	0.7	0.7	−1.6	−0.8	0.0	1.0	0.8
Sa+SWa+Wa	−0.7	0.3	0.1	−0.1	−0.3	−0.3	−0.1	−0.1	0.0	−0.4	−0.4	−0.2	−0.8	−0.2	−1.5
Ka+Ca	0.4	0.2	0.5	0.2	0.6	0.0	0.7	0.2	−0.5	0.3	0.2	−0.2	−0.8	−0.4	−0.7
NWc+Nc+NEc	0.4	−0.2	−0.6	−0.6	−0.7	0.5	−0.6	−0.5	−0.3	−0.6	−0.1	0.1	−0.3	−0.4	−0.4
Ec+SEc	−0.3	0.0	0.4	0.4	0.3	−0.1	0.1	0.4	0.4	0.5	0.3	0.1	1.3	2.3	1.9
Sc+SWc+Wc	−0.5	0.5	0.3	0.0	0.2	−0.7	−0.2	−0.5	−0.1	−0.7	0.2	−0.4	−0.9	−0.4	−1.8
Bc+Cc	−0.4	0.0	−0.4	−0.5	−0.5	−0.1	0.4	0.4	0.2	0.5	0.2	0.0	0.2	−0.1	−0.2
Mean differences	0.5	−0.5	−1.4	−1.5	−2.7	0.2	0.1	−1.0	−1.7	−2.1	−0.4	0.0	−1.0	−1.5	−0.8
T_{min}															
NWa+Na+NEa	−0.6	−0.7	−0.7	−0.4	−0.6	−0.2	−0.3	−0.7	−0.4	−0.3	0.1	−0.1	0.0	0.3	0.7
Ea+SEa	−0.6	0.6	1.4	1.4	1.6	0.8	0.6	0.9	0.9	1.1	0.2	1.5	2.6	2.9	2.9
Sa+SWa+Wa	0.9	1.9	2.1	1.6	1.5	0.2	0.1	0.1	−0.4	−0.1	−0.1	0.0	−0.3	−0.3	−0.7
Ka+Ca	0.3	−0.4	−0.6	−0.2	0.0	0.4	0.0	−0.2	−0.2	0.1	0.0	−0.2	−0.4	−0.3	−0.4
NWc+Nc+NEc	−0.1	−0.4	−0.8	−0.6	−0.9	0.1	−0.4	−0.5	−0.2	−0.6	0.0	0.0	−0.4	−0.7	−0.8
Ec+SEc	−0.1	0.1	0.4	0.5	0.8	−0.1	0.2	0.6	0.7	0.7	0.0	0.2	1.3	1.6	2.2
Sc+SWc+Wc	0.7	0.3	0.5	−0.3	0.1	−0.5	0.3	0.0	−0.5	−0.4	0.2	0.1	−0.1	−0.4	−0.8
Bc+Cc	0.7	−0.1	−0.5	−0.6	−0.4	−0.1	0.2	0.0	−0.5	−0.1	0.0	−0.3	−0.3	−0.3	−0.5
Mean differences	−0.5	−0.4	−1.3	−0.7	−2.1	0.5	−0.9	−1.9	−1.5	−2.6	0.2	−0.8	−2.0	−1.8	−2.1

For full names of sites (KH, SAT, etc.) see Table 1. As references values temperature differences calculated from all days in a season have been used.

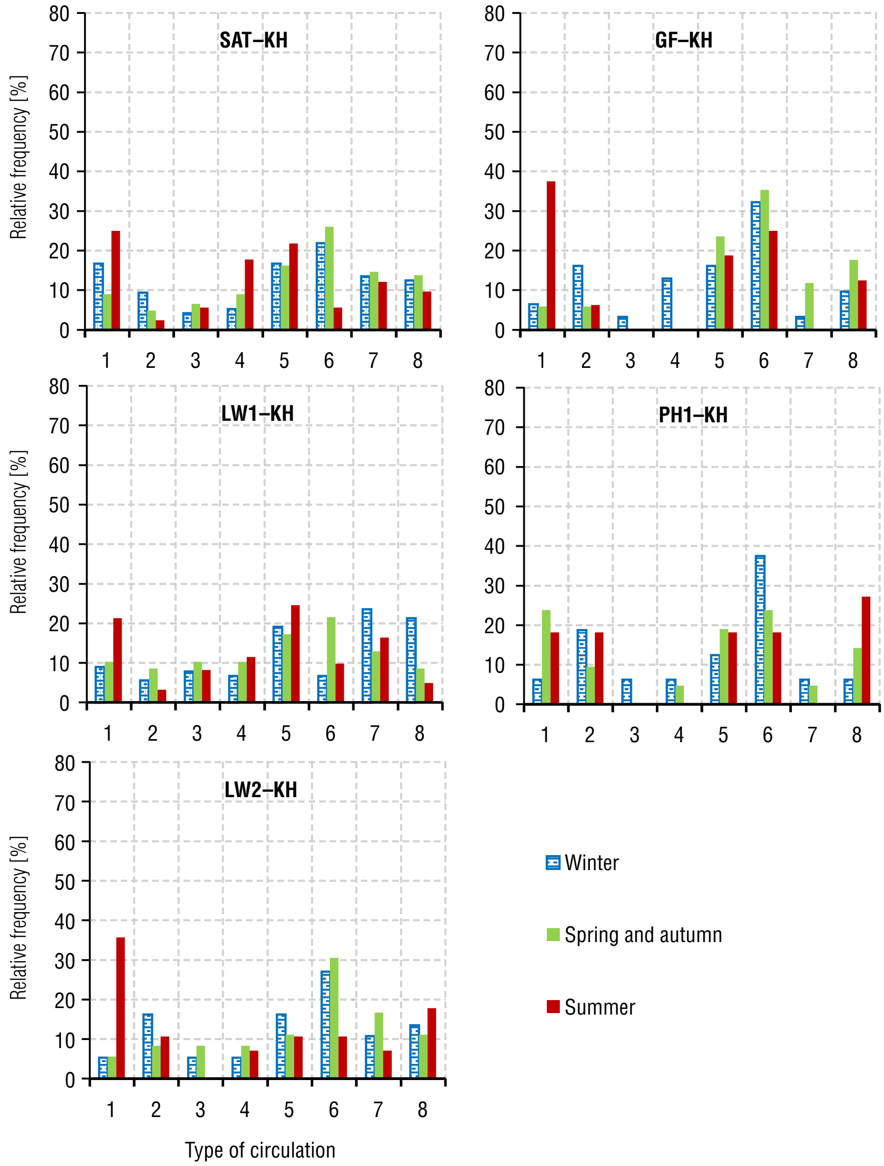

Figure 3. Seasonal relative frequencies of occurrence of small Ti differences (−0.5–+0.5 °C) between pairs of sites (KH as reference site) in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013 observed during individual circulation types. Key: for full names of sites see Table 1; circulation types: 1 – NWa+Na+NEa, 2 – Ea+SEa, 3 – Sa+SWa+Wa, 4 – Ka+Ca, 5 – NWc+Nc+NEc, 6 – Ec+SEc, 7 – Sc+SWc+Wc, 8 – Bc+Cc; bars from left to right show results for winter, spring and autumn and summer, respectively. [Colour figure can be viewed at wileyonlinelibrary.com].

anomalies during the occurrence of these types, particularly in the upper part of the study area, (Table 5, Figure 2(c)). In addition, such changes were also noted during the NWa+Na+NEa type. Thus, throughout the entire year greater warming of the mountainous and glaciated parts of the study area, in comparison to coastal areas, was observed during air advection from the eastern sector. The physical mechanisms connected with the occurrence of foehn winds are responsible for this specific spatial differentiation of air temperature. Such a pattern of temperature distribution is also very well-known for other locations on the western part of Spitsbergen (e.g. Pereyma, 1983; Maciejowski and Michniewski, 2007; Migała *et al.*, 2008; Bednorz and Kolendowicz, 2010; Gluza and Siwek, 2012). In summer, similarly as in winter, there is a clearly more similar reaction of Ti and T_{max} than Ti and T_{min} to atmospheric circulation, evident in high located sites LW2, GF and PH1 in particular (see Table 5 and Figures 2(a)–(c)).

In summer, near-zero temperature differences between KH and other studied sites show a definitely different dependence on atmospheric circulation than in the two other described seasons (see Figure 3 and Figures S1(a) and S1(b)). The leading role of cyclonic situations, evidently observed in winter as well as in spring/autumn, is now not so clear. Moreover, NWa+Na+NEa type most often favours the occurrence of near-zero temperature differences. In the case of Ti and T_{max}, this kind of differences between KH and other studied sites occurs with a frequency of 20–40%. For T_{min}, almost identical values at the PH1 and KH sites were only noted during the two types NWa+Na+NEa and Ea+SEa with a frequency of 75% and

25%, respectively (Figure S1(b)). The greatest chance of occurrence of small temperature differences between KH and other sites is possible for Ti during NWc+Nc+NEc, Ec+SEc and Bc+Cc (seen in the upper part of the study area in particular), for T_{max} during NWc+Nc+NEc, and for T_{min} during Ec+SEc, but only in LW2 and GF sites (Figure 3 and Figures S1(a) and S1(b)).

Variability of daily air temperature (Ti, T_{max} and T_{min}) within the analysed seasons during the occurrence of the same circulation type was estimated using standard deviation (σ) (Table 6). In winter and spring and autumn (hereinafter referred to as 'the cold period') the greatest variability (for all analysed thermal parameters) was observed during air advection from the eastern sector, both in anticyclonic and cyclonic types, ranging most often from 5 to 6 °C. On the other hand, the smallest variability ($\sigma = 2–3$ °C and $\sigma = 3$ °C) in these seasons was mainly observed within air advection from the southern sector (Sa+SWa+Wa and Sc+SWc+Wc types, respectively). In summer, air temperature variability was significantly smaller than in the cold period, exceptionally exceeding 4 °C, while the lowest values fall near 1 °C. The highest variability, ranging from 2 to 4 °C, was mainly noted during Ea+SEa and NWc+Nc+NEc types (see Table 6). The most stable thermal conditions in summer are brought by Ka+Ca type ($\sigma = 1–2$ °C).

3.2. Extremes of spatial thermal diversity and atmospheric circulation

Besides a recognition of the influence of atmospheric circulation on average spatial diversity of air temperature parameters (Ti, T_{max} and T_{min}) in the study region, it is also very important to determine the circulation types which most often caused the occurrence of extremes in that diversity. We investigated days with the largest negative/positive anomalies in average air temperature differences between KH and other study sites (see Section 2 for details of method used to determine these days).

Absolute (n) and relative (%) frequencies of occurrence of days with the largest positive (≥90%) and largest negative (≤10%) anomalies of Ti differences between KH and other studied sites and their mean values for a given type of circulation in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013 are shown in Table 4. As in the case of average Ti differences, the influence of atmospheric circulation on extreme differences is seen to be different between coastal (SAT and KH sites) and mountainous and glaciated parts (all other sites) of the study region. In winter, over the Greenland Sea type Ec+SEc was most often (about 37%) responsible for the greatest negative anomalies of Ti differences in comparison with KH, while inland for this type the greatest frequency (about 40%) of large positive anomalies of differences (up to almost 2 °C) was observed (Table 4). The foehn winds which are relatively frequent when air masses cross over Spitsbergen from east to west were one of the processes responsible for this spatial distribution of air temperature in the study region. It has been stated (Przybylak 1980) that during the occurrence of a foehn (in particular in the phase of its development) the greatest warming was noted in the upper part of the Waldemar Glacier, which systematically fell down the glacier and further towards the coast of the Greenland Sea. A similar mechanism for the Werenskiold Glacier region (southern Spitsbergen) was described by Pereyma (1983) and recently also by Migała *et al.* (2008). Extreme positive anomalies of SAT−KH Ti differences (about 2 °C) were noted with greatest frequency during advection from the northern sector (slightly > 40%), in particular within cyclonic circulation (25.8%). The opposite relationship (i.e. greatest negative anomalies of differences reaching on average −2 °C for LW1 and −4.9 °C for PH1) has been observed for sites located in the mountainous and glaciated part of the study area (Table 4).

In the spring and autumn seasons, the influence of atmospheric circulation on extreme anomalies of Ti differences in the study region was very similar to winter (see Table 4). On the other hand, in summer, in comparison to both the abovementioned seasons, important changes in patterns of circulation−Ti relations were noted. Firstly, other types than in the two previous seasons were responsible for the largest negative/positive anomalies of Ti differences and, secondly, their spatial diversity was markedly less stable. For example, in the coastal area the largest negative/positive anomalies most often occurred (26.3%) during types NWc+Nc+NEc/Sc+SWc+Wc, respectively. In the mountainous and glaciated part of the study area, the largest negative anomalies of Ti differences were noted with greatest frequency in as many as three types (Ka+Ca for LW1−KH; NWc+Nc+NEc for GF−KH and Sc+SWc+Wc for LW2−KH and PH1−KH). More stable spatial relationships have been observed between the occurrence of circulation types and largest positive anomalies of Ti differences in the study region (see Table 4). They occurred with a frequency of about 30−60% during NWa+Na+NEa type, except at the LW2 site, where the frequency was also quite high (26.3%) in this type, although slightly smaller than for the Ec+SEc type (31.6%). The mentioned large positive anomalies of Ti differences in the study region occurring during NWa+Na+NEa type are the effect of two mechanisms. Firstly, winds coming from the northern sector (most frequent in summer from all sectors, see Przybylak *et al.*, 2016) which bring 2−3 °C colder air masses (Wójcik *et al.*, 1998) than wind from the southern sector (the second most frequent wind direction) cause greater cooling of the SAT and KH sites (open areas) than other sites protected from the north by the Prins Heinrichfjella ridge. Secondly, cloudiness during this advection is small, favouring the greater heating of air in the upper part of the Waldemar Glacier valley than in the Tundra area (Kaffiøyra Plain) due to strong winds occurring in the latter area and its proximity to cold (4−5 °C) sea water. In addition, katabatic winds carrying cold air masses from the glacier to its forefield, as well as shallow fogs, could also play an important role in this temperature pattern.

The influence of atmospheric circulation on the occurrence of extreme values of T_{max} differences in the study

Table 6. Seasonal values of air temperature (°C, Ti, T_{max} and T_{min}) standard deviations stratified into types of circulation in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013.

Type of circulation	Season	KH			SAT			LW1			LW2			GF			PH1		
		Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}	Ti	T_{max}	T_{min}
NWa+Na+NEa	Wi	4.4	4.4	4.6	4.8	4.3	5.8	4.4	4.4	4.6	4.3	4.1	4.6	4.2	4.1	4.4	4.4	4.1	4.8
	Sp+Au	4.2	4.2	4.7	4.1	3.9	5.4	4.3	4.4	4.7	4.2	4.8	4.5	4.3	4.5	4.5	4.2	4.2	4.6
	Su	2.1	2.4	2.0	1.9	2.1	1.8	2.2	2.5	2.1	2.4	3.2	2.5	3.1	3.4	2.9	3.2	3.5	3.0
Ea+SEa	Wi	5.8	5.6	6.2	6.7	6.0	7.3	5.2	5.1	5.3	5.0	4.7	5.2	4.8	4.6	5.0	4.7	4.5	4.9
	Sp+Au	2.9	3.3	2.9	2.9	3.2	2.8	3.4	3.6	3.9	4.2	4.5	4.1	4.6	4.8	4.4	4.8	5.0	4.7
	Su	2.4	3.7	1.9	1.9	1.9	1.5	3.2	3.3	3.3	3.5	2.8	4.2	4.1	3.8	4.5	3.6	3.5	4.5
Sa+SWa+Wa	Wi	3.1	2.0	4.2	3.0	2.0	4.8	2.7	1.6	3.9	2.4	1.5	3.2	2.4	1.5	3.2	2.4	1.4	3.5
	Sp+Au	2.4	2.1	2.7	2.3	2.4	2.5	2.4	2.1	3.1	2.3	1.8	3.1	2.5	2.3	2.8	2.2	2.0	2.6
	Su	1.7	2.2	1.6	1.3	1.2	1.5	2.0	2.3	2.3	2.4	2.7	2.3	2.6	2.9	2.2	2.7	2.8	2.4
Ka+Ca	Wi	3.6	3.8	3.7	3.7	3.7	4.5	3.8	3.8	3.7	3.5	3.7	3.8	3.7	3.9	3.6	3.3	3.3	3.5
	Sp+Au	3.6	3.3	4.0	3.7	3.4	5.0	3.9	3.9	4.7	3.7	4.1	4.1	3.7	3.7	3.8	3.5	3.7	3.8
	Su	1.2	1.2	1.4	1.1	1.1	1.3	1.3	2.0	1.1	1.7	2.0	1.6	1.9	2.5	1.7	2.2	2.9	1.9
NWc+Nc+NEc	Wi	4.0	4.2	4.1	4.1	4.2	4.7	3.7	4.1	3.6	3.7	4.1	3.6	3.8	4.2	3.8	3.8	4.2	3.8
	Sp+Au	3.9	3.5	4.3	3.9	3.4	4.8	4.2	4.0	4.6	4.4	4.5	4.7	4.0	3.9	4.2	4.4	4.4	4.5
	Su	2.4	3.1	2.2	2.1	2.4	2.0	2.7	3.2	2.4	3.1	4.1	2.6	3.3	3.9	2.9	3.6	4.3	3.1
Ec+SEc	Wi	5.9	5.6	6.6	6.4	5.8	7.5	5.2	5.3	5.4	5.2	5.1	5.5	5.1	5.1	5.4	4.9	4.8	5.2
	Sp+Au	5.1	4.9	5.7	4.8	4.3	5.8	5.3	5.0	5.8	5.5	5.2	5.9	5.4	5.4	5.5	5.4	5.4	5.5
	Su	1.7	2.5	1.5	1.5	1.8	1.3	1.7	2.6	1.3	2.1	3.0	1.9	2.4	2.9	2.3	2.9	3.4	2.8
Sc+SWc+Wc	Wi	3.0	2.5	4.4	2.8	2.2	3.9	2.9	2.6	4.1	3.0	2.5	3.6	2.9	2.4	3.4	2.9	2.5	3.3
	Sp+Au	3.1	3.0	3.2	3.0	2.6	3.8	2.8	2.5	3.1	2.9	2.7	3.2	3.2	2.9	3.3	2.9	2.8	3.3
	Su	1.9	2.3	1.9	1.6	1.7	1.6	1.9	2.3	1.8	2.3	2.6	2.1	2.3	2.8	2.1	2.4	2.8	2.2
Bc+Cc	Wi	4.1	3.9	5.1	4.2	3.6	6.0	4.1	4.1	4.6	4.3	4.1	5.0	4.2	4.1	4.7	4.2	4.1	4.8
	Sp+Au	3.7	3.5	4.1	3.7	3.5	4.7	4.2	4.1	4.5	4.1	4.3	4.4	4.0	3.9	4.2	3.9	3.7	4.4
	Su	2.3	2.5	2.4	2.0	2.2	2.2	2.0	2.3	2.1	2.3	2.9	2.7	3.0	3.4	2.9	3.0	3.5	2.8
All	Wi	5.3	5.3	5.6	5.5	5.1	6.5	5.2	5.3	5.3	5.2	5.1	5.3	5.1	5.1	5.1	5.1	5.0	5.2
	Sp+Au	4.4	4.3	4.8	4.2	3.9	5.1	4.7	4.5	5.1	4.8	4.8	5.1	4.8	4.7	4.8	4.8	4.8	5.0
	Su	2.2	2.7	2.0	1.9	2.1	1.8	2.3	2.7	2.2	2.8	3.5	2.7	3.2	3.6	3.0	3.5	4.0	3.2

Wi – winter, Sp – spring, Au – autumn, Su – summer, for full names of sites (KH, SAT, etc.) see Table 1.

area is very similar to that described for Ti (compare Table S2(a) with Table 4). Generally, only one significant difference should be mentioned, namely that in summer in the mountainous and glaciated part of the area in question (except PH1 site), the largest negative anomalies of T_{max} differences are most often noted during the Ka+Ca type.

Some interesting features confirming the individual character of behaviour of extreme T_{min} differences in the study area in relation to atmospheric circulation can be found. Roughly speaking, in the winter and spring and autumn seasons the same types as for Ti and T_{max} were responsible for the occurrence of the largest negative (NWc+Nc+NEc) and largest positive (Ec+SEc) anomalies of T_{min} differences (compare Table S2(b) with Tables 4 and S2(a)). In the case of Tmin, however, both mentioned types had the same influence in the entire area of the study, while in the case of Ti and T_{max}, this was not the case for coastal areas. In summer, there was again a very good correspondence between all analysed thermal parameters as regards circulation types most frequently causing the largest positive anomalies of temperature differences between pairs of sites but, again, T_{min} – conversely to Ti and T_{max} – showed such a pattern across the entire area. For example, in the case of T_{max} and T_{min} the two most frequent types favouring the occurrence of that kind of anomaly were 90% the same (see Tables S2(a) and (b)). The largest positive anomalies of T_{min} differences, with average values ranging between about 0.5 and 2.0 °C, with the greatest frequencies (25–50%) occurred during NWa+Na+NEa type. The most unexpected result of the investigated circulation relationships – the largest negative anomalies of T_{min} differences – is the fact that the type most frequently favouring the occurrence of that kind of differences (NWa+Na+NEa) in a large part of the study area was also most often responsible for the largest positive anomalies of T_{min} differences (Table S2(b)). To explain this interesting phenomenon type NWa+Na+NEa was stratified into three independent subtypes: NWa, Na and NEa. For each of them average anomalies of T_{min} differences were calculated, which showed insignificant changes between them. Thus, local conditions (in particular cloudiness and wind speed) were probably the main factors responsible for such big differences in spatial T_{min} patterns in the study region. This hypothesis was confirmed by the fact that the largest negative anomalies of T_{min} differences were observed during days with great cloudiness (on average between 5 of 10 and 7 of 10), while the largest positive anomalies were observed during days with little cloudiness (on average between 4 of 10 and 5 of 10). Wind data as well as other kinds of data (e.g. heat balance and its components) are not available for the study area, and therefore their role in this process

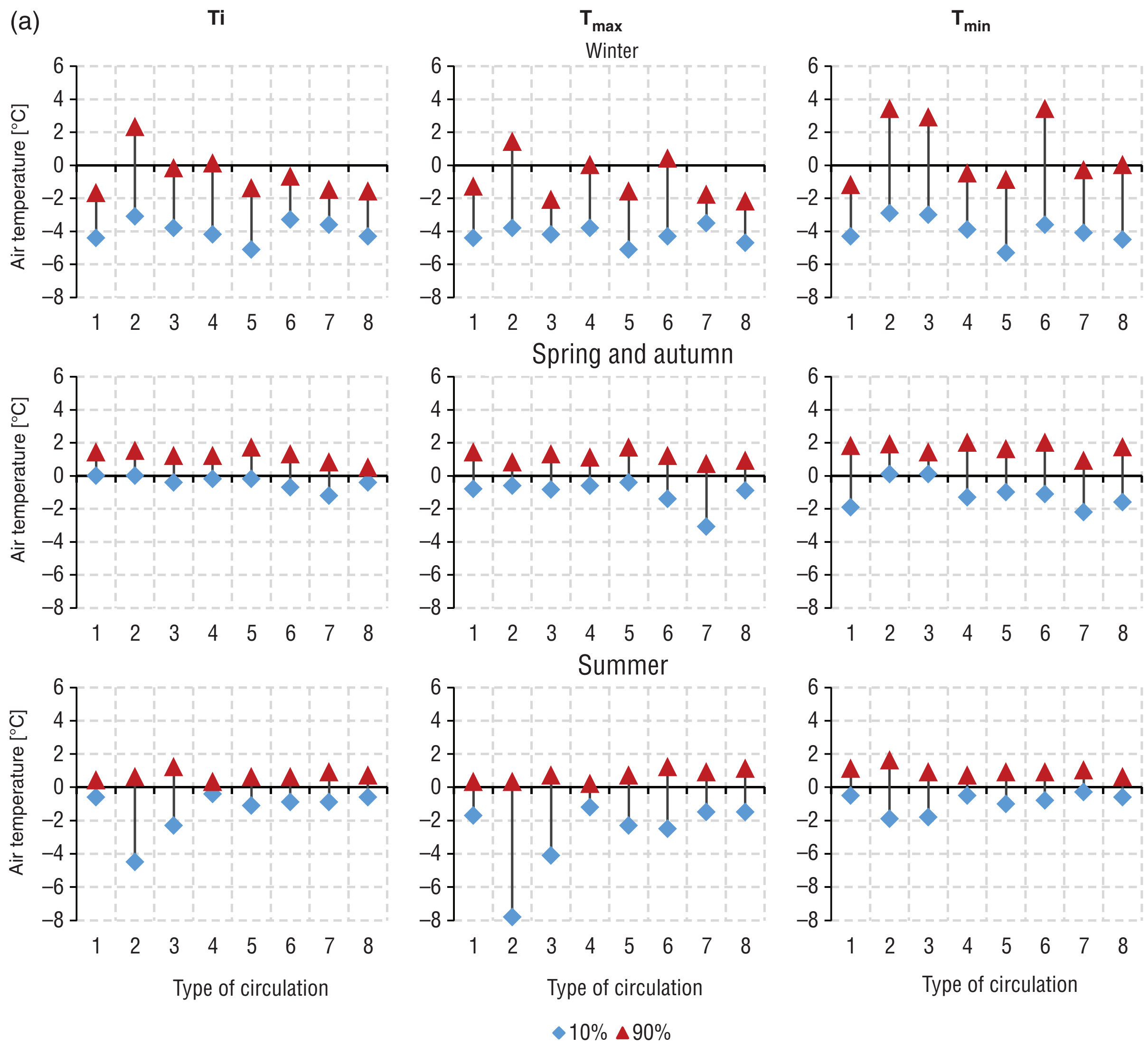

Figure 4. Distribution of threshold values (10th and 90th percentile) of Ti, T_{max} and T_{min} differences between KH and other measurement sites (SAT–KH, LW1–KH, etc.) calculated for each season and type of circulation in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013, and ranges between them. Key: (a) SAT–KH, (b) LW1–KH, (c) LW2–KH, (d) GF–KH and (e) PH1–KH for full names of sites see Table 1; circulation types: 1 – NWa+Na+NEa, 2 – Ea+SEa, 3 – Sa+SWa+Wa, 4 – Ka+Ca, 5 – NWc+Nc+NEc, 6 – Ec+SEc, 7 – Sc+SWc+Wc, 8 – Bc+Cc. [Colour figure can be viewed at wileyonlinelibrary.com].

cannot be estimated. Another type which in some sites (mainly SAT, GF and PH) more frequently 'produces' the largest negative anomalies of T_{min} differences is NWc+Nc+NEc.

In summary then, it should be noted that air advection from the northern sector most definitely favours the occurrence of extremely large negative anomalies of T_{min} differences in the entire area. It is worth adding here that in the case of the smallest air temperature differences, the influence of atmospheric circulation on them is significantly different for each analysed air temperature parameter. Thus, generalization of the results studying the relationships between atmospheric circulation and air temperature should not be made based on only one parameter. Similarly, results from investigations of relationships between atmospheric circulation and air temperature using data only from summer (the most commonly investigated period of the year) should rather not be used as the basis for generalization to other seasons. More topoclimatic investigations into the winter half of the year are urgently needed to solve this problem.

The two aforementioned general conclusions are also confirmed by analysis of frequencies of occurrence of the days with the largest (≥90%) and smallest (≤10%) anomalies of Ti differences and their mean values for a given type of circulation in the Forlandsundet region (Figure 4). As results from the figure they differ significantly depending on the season and thermal parameter. For example, in winter it is very well seen that values of T_{min} are less stable at all sites. On the other hand, in spring and autumn T_{max} is most unstable, i.e. usually has the largest distances between values of Ti differences representing the 90th and 10th percentile thresholds. In summer, Ti is most stable in this respect, except for the PH1 site, where this parameter is most unstable, and SAT, where T_{min} is most stable by a slight margin (see Figure 4).

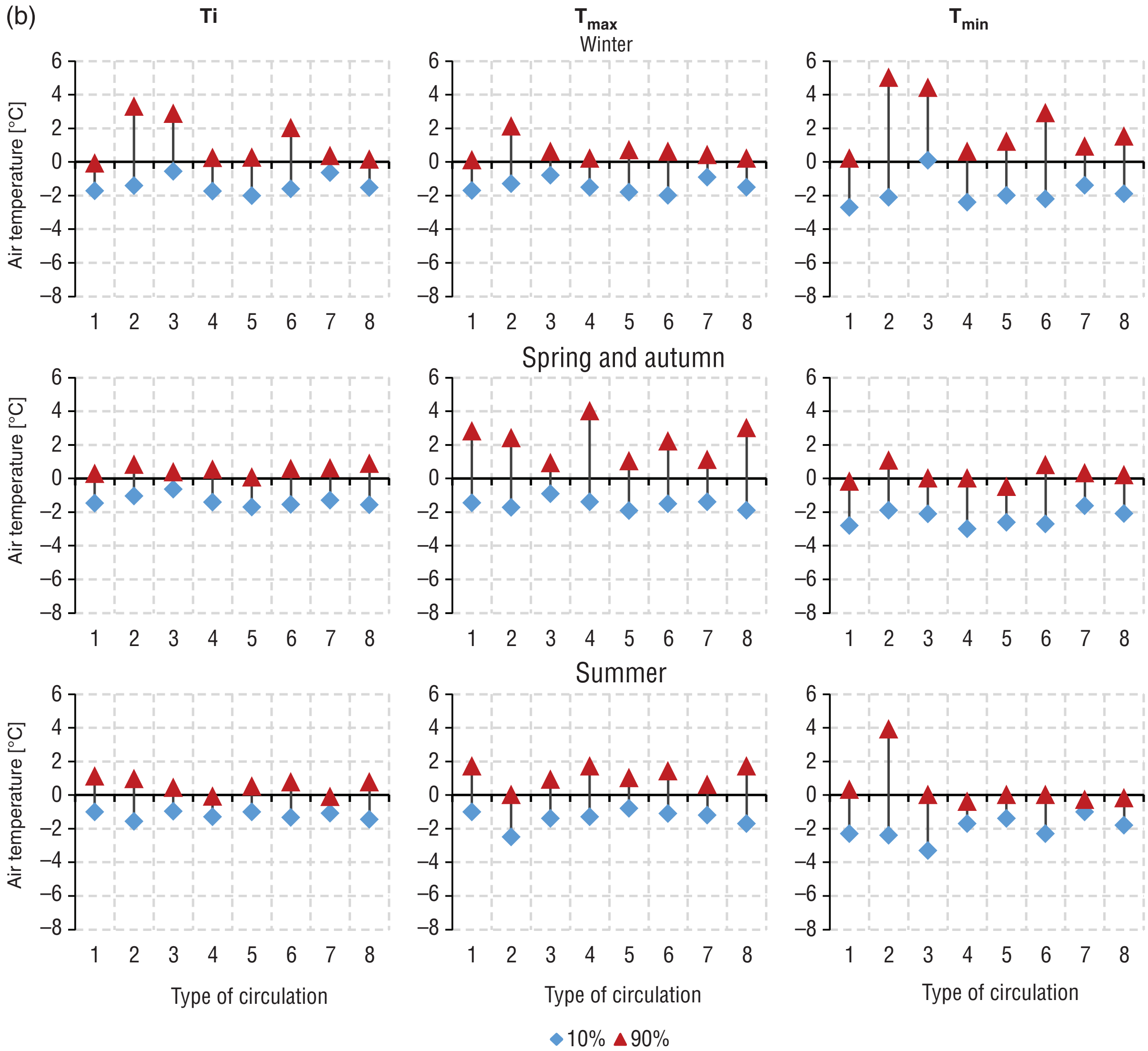

Figure 4. Continued. [Colour figure can be viewed at wileyonlinelibrary.com].

4. Discussion and conclusions

As was stated in the Introduction, nobody has previously published a similar work for Svalbard (Spitsbergen) presenting relationships between air temperature and atmospheric circulation in the topoclimatic scale based on data for the entire year and for three thermal parameters. For this reason, the discussion of our results must be limited to summer season and to average temperatures. Wójcik *et al.* (1998), based on data from four summer seasons (1979, 1980, 1982 and 1989) and three sites (KH, LW1 and LW2), stated that southern/northern atmospheric circulation strengthen/weaken the near surface lapse rate of air temperature in the hypsometric profile in the Kaffiøyra region, frequently leading in the latter case to the occurrence of temperature inversions. Our results, also including additional measurements from mountainous parts of the study area, fully confirm these statements (see Table 4). It is very important to carry out a separate analysis of the influence of atmospheric circulation on occurrence of thermal extremes in order to obtain more reliable results of real relationships. For example, investigation of circulation types favouring the occurrence of inversions may be misleading based on anomalies of mean Ti differences calculated for each circulation type. From analysis of the results in Table 5, mean anomalies are significantly higher during air advection from the eastern sector (types Ea+SEa and Ec+SEc) than from the northern sector (NWa+Na+NEa and NWc+Nc+NEc). Based only on these results one might wrongly conclude that the strongest temperature inversions should also be observed mainly within the former types. Such a conclusion could easily be drawn because it is very well-known that air advection from the eastern sector favours the occurrence of foehns, during which the greatest maxima of air temperature are usually noted on the western coast of Spitsbergen (Marciniak and Przybylak, 1983; Pereyma, 1983; Migała *et al.*, 2008). It is also possible that absolute values of Ti differences both in our study region and in other areas of western Spitsbergen are connected with this phenomenon, but because foehns are not frequent in summer (usually

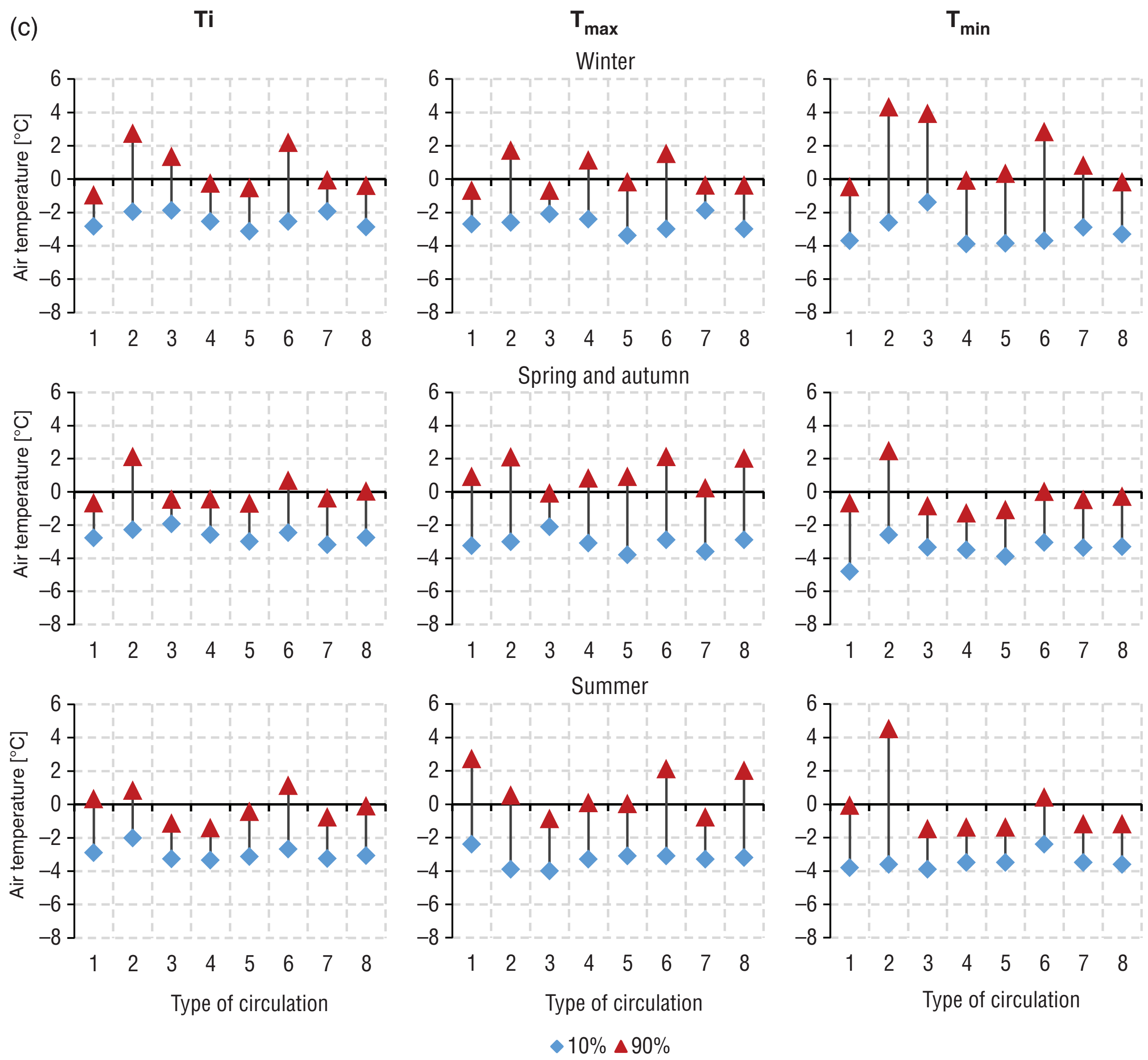

Figure 4. Continued. [Colour figure can be viewed at wileyonlinelibrary.com].

1–3 cases), they (and equally the eastern circulation types favouring them) are not the main reason for the occurrence of the 10% largest Ti differences.

Based on a limited number of data taken from August 1979 Pereyma (1983) tried to describe the influence of atmospheric circulation on spatial temperature diversity in the Werenskiold Glacier region (topoclimatic measurement sites located similarly as in our case). For northern and southern circulations he found that temperature distribution was 'basically a reflection of hypsometry', i.e. normal near-surface lapse rates occurred. This finding is different from what we found for the Forlandsundet region, but because in both cases his analyses were based only on data from one day, the presenting results should rather be treated as a case study. On the other hand, for eastern circulation, which is actually very characteristic for Spitsbergen, a good correspondence was found, i.e. weakening of normal distribution and also the occurrence of temperature inversions. Pereyma (1983) was aware of the fact that some of his results might not be correct and therefore on page 73 wrote the following conclusion: 'A number of days with a definite circulation is essential in the image of air thermal conditions, in the glacier's area'. After so many years since his publication, we have carried out this suggestion in the present paper. The discussion presented above reveals that comparison of our and other authors' results from studying atmospheric circulation–air temperature relationships in the topoclimatic scale in Spitsbergen cannot be done reliably even for summer (for which some publications exist) due to the decidedly too-large discrepancies in methodology and number of data used in our work and in other authors' works.

The main results of the present work can be summarized as follows.

1. The influence of atmospheric circulation on the spatial pattern of air temperature in the Forlandsundet region is not homogeneous. Different reactions on circulation were noted for coastal (SAT and KH sites) and mountainous and glaciated (other sites) parts of

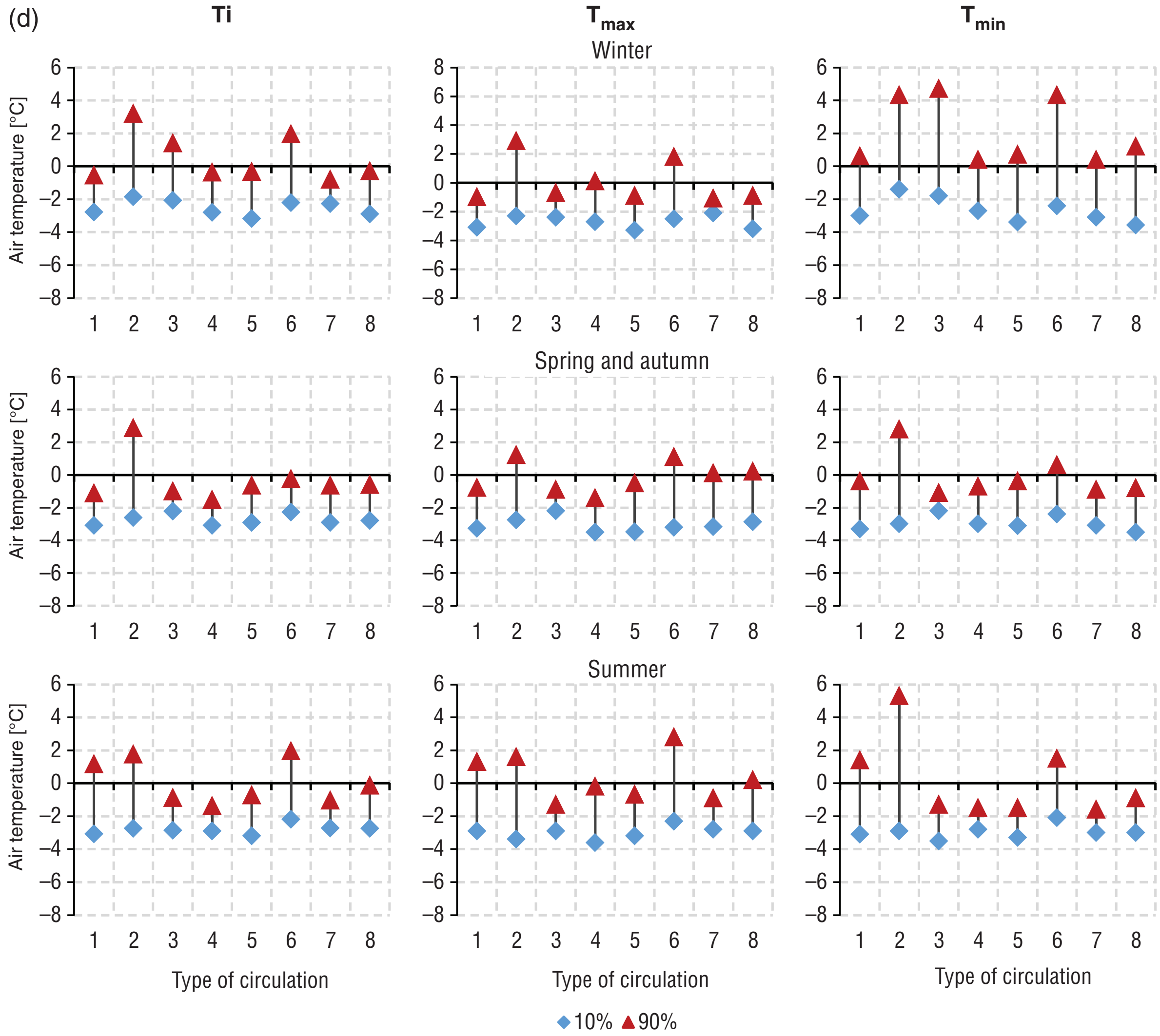

Figure 4. Continued. [Colour figure can be viewed at wileyonlinelibrary.com].

the study area. This means that generalization of air temperature–atmospheric circulation relationships on topoclimatic scales for the entire area of Spitsbergen based only on data from coastal stations is not appropriate, even for areas lying not so far from the coast, as was the case in our study, i.e. only 3–6 km. More topoclimatic investigations into mountainous and glaciated areas, in particular for the winter half of the year are urgently needed to solve this problem.

2. The influence of atmospheric circulation on the spatial pattern of air temperature in the Forlandsundet region is also not homogeneous throughout the year. In the cold season (Sep–May) relationships differ significantly from those noted in summer (Jun–Aug). In summer, relationships of atmospheric circulation to air temperature in the topoclimatic scale are definitely less stable than in the cold seasons, and different types also favour the occurrence of negative/positive anomalies of air temperature differences between the KH site and other sites. The main reasons for this are changing insolation in the annual cycle (no solar radiation during the polar night) and the different kinds of surface occurring in summer (snow, ice, tundra, rocks, etc.) in comparison to wintertime (domination of snow).
3. The reaction of the three analysed thermal parameters (Ti, T_{max} and T_{min}) to atmospheric circulation is also different, which is easily seen in Figures 2(a)–(c). Differences are observed not only in the magnitude of either positive or negative values of air temperature differences, but also sometimes in the direction of temperature change, i.e. one parameter has a positive difference while another has a negative difference. In winter and summer a more similar reaction of Ti and T_{max} than Ti and T_{min} on atmospheric circulation was observed, which was particularly evident in the high-located sites LW2, GF and PH1 (see Table 5 and Figures 2(a)–(c)). On the other hand, in spring and autumn, Ti shows better correlation with T_{min}. Such knowledge can be important if studies include different processes which depend more on day or night temperatures than on average daily temperature. Again, simple generalization of the results based on Ti cannot be made for T_{max} and T_{min}.

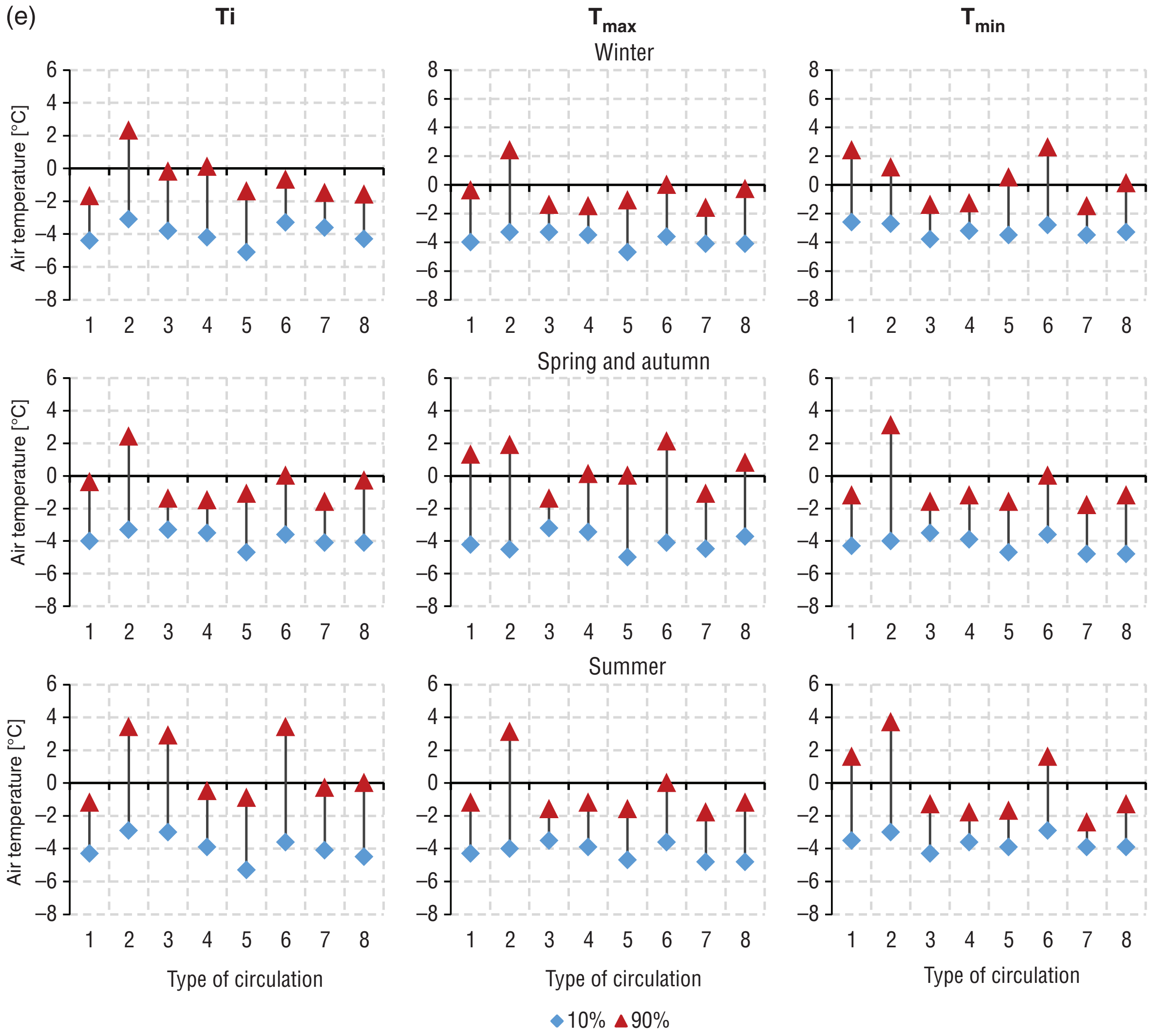

Figure 4. Continued. [Colour figure can be viewed at wileyonlinelibrary.com].

4. Zero or little change in Ti with altitude was noted markedly more often during cyclonic types of atmospheric circulation than anticyclonic in the cold season in the study area. In summer this relationship was not so clear, mainly due to the frequent occurrence of such thermal situations within NWa+Na+NEa type (see Table 5 and Figure 3). Also, in the case of this characteristic there exist differences, sometimes large, between the three studied thermal parameters.
5. In the cold season, the greatest variability (for all analysed thermal parameters) was observed during air advection from the eastern sector, ranging most often from 5 to 6 °C. On the other hand, the smallest variability in these seasons was connected mainly with Sa+SWa+Wa type ($\sigma = 2-3$ °C). In summer, air temperature variability was significantly smaller than in the cold period, exceptionally exceeding 4 °C, while the lowest values fall near 1 °C. The highest variability, ranging from 2 °C to 4 °C, was mainly noted during Ea+SEa and NWc+Nc+NEc types (see Table 6). The most stable thermal conditions in summer are brought by Ka+Ca type ($\sigma = 1-2$ °C).
6. In spring and autumn, the influence of atmospheric circulation on extreme Ti differences in the study region was very similar to winter (see Table 4). On the other hand, in summer, significant differences were noted. Firstly, other types than in the two previous seasons were responsible for the occurrence of the smallest and largest Ti differences and, secondly, their spatial diversity was markedly less stable. It was also shown that the circulation types which on average cause the greatest anomalies of thermal differences in the study region are not necessarily also those types most frequently responsible for the occurrence of the 10% largest or smallest thermal differences observed between the KH site and other measurement sites.
7. Threshold values of Ti, T_{max} and T_{min} differences between the KH site and other sites calculated for the 10th and 90th percentiles for each season and type of circulation differ significantly depending on season and thermal parameter (Figures 4(a)–(e)).
8. Our analysis shows that local conditions, and not only atmospheric circulation, are of great importance for spatial diversity of air temperature.

9. Similar analyses for other parts of Spitsbergen are needed to check if the relationships described here between air temperature parameters and atmospheric circulation in the topoclimatic scale have a more general character.

Acknowledgements

The research work was supported by the grant entitled ‘Contemporary and Historical Changes in the Svalbard Climate and Topoclimates’, funded by the National Science Centre with decision No. DEC 2011/03/B/ST10/05007. We thank three anonymous reviewers for their constructive comments which allowed for substantial improvements to our paper. The authors wish to express their heartfelt thanks to the participants in the Toruń Polar Expeditions who conducted meteorological measurements and observations in the years 2010–2013.

Supporting information

The following supporting information is available as part of the online article:

Table S1. Synoptic situations (types) used in the study (after Niedźwiedź, 1981).

Table S2. (a) Absolute (*n*) and relative (%) frequencies of occurrence of days with largest (≥90%) and smallest (≤10%) anomalies of T_{max} differences and their mean values for given type of circulation in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013. Key: for full names of sites (KH, SAT, etc.) see Table 1. (b) Absolute (*n*) and relative (%) frequencies of occurrence of days with largest (≥90%) and smallest (≤10%) anomalies of T_{min} differences and their mean values for given type of circulation in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013. Key: for full names of sites (KH, SAT, etc.) see Table 1.

Figure S1. (a) Seasonal relative frequencies of occurrence of small T_{max} differences (−0.5–+0.5 °C) between pairs of sites (KH as reference site) in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013 observed during individual circulation types. Key: for full names of sites see Table 1; circulation types: 1 – NWa+Na+NEa, 2 – Ea+SEa, 3 – Sa+SWa+Wa, 4 – Ka+Ca, 5 – NWc+Nc+NEc, 6 – Ec+SEc, 7 – Sc+SWc+Wc, 8 – Bc+Cc. (b) Seasonal relative frequencies of occurrence of small T_{min} differences (−0.5–+0.5°C) between pairs of sites (KH as reference site) in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013 observed during individual circulation types. Key: for full names of sites see Table 1; circulation types: 1 – NWa+Na+NEa, 2 – Ea+SEa, 3 – Sa+SWa+Wa, 4 – Ka+Ca, 5 – NWc+Nc+NEc, 6 – Ec+SEc, 7 – Sc+SWc+Wc, 8 – Bc+Cc.

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