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

Rajmund Przybylak,* Andrzej Araźny and Patrycja Ulandowska-Monarcha

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 (Tmax) and minimum (Tmin) 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

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; 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 firm part of the
Werenskiold Glacier (386 m a.s.l.) (Kosiba, 1960). Later, topoclimatic investigations in this region were continued within the so-called ‘Wroclaw expeditions’ between the years 1970 and 1974 (Baranowski and Glowicki, 1974, 1975; Pereyma, 1983) and in more recent times (Brázdil et al., 1988; Pereyma and Piasceki, 1988; Nasiółkowski and Pereyma, 2007; Migala et al., 2008; Arażny 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 Piasceki, 1989; Brázdil et al., 1991; Rachlewicz, 2003; Gluza and Siewek, 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 Forland, 1998; Przybylak and Arażny, 2006; Arażny, 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; Migala et al., 2008; Kejna et al., 2012; Przybylak and Maszewski, 2012; Bednorz et al., 2014; Przybylak et al., 2014; Malecki, 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 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
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 Niedźwieć 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. Niedźwieć (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, Be 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 Niedźwieć’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, Tmax and Tmin) 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.

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

<table>
<thead>
<tr>
<th>No.</th>
<th>Abbreviation</th>
<th>Sites</th>
<th>φ</th>
<th>λ</th>
<th>h (m.a.s.l.)</th>
<th>Distance to the shoreline (m)</th>
<th>Kind of surface (summer)</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KH</td>
<td>Kaffiøyra-Heggodden</td>
<td>78°40′34″N</td>
<td>11°49′38″E</td>
<td>11</td>
<td>160</td>
<td>tundra</td>
<td>MadgeTech/HOBO</td>
</tr>
<tr>
<td>2</td>
<td>SAT</td>
<td>Sarstangen</td>
<td>78°43′38″N</td>
<td>11°28′50″E</td>
<td>2</td>
<td>40</td>
<td>beach</td>
<td>MadgeTech/HOBO</td>
</tr>
<tr>
<td>3</td>
<td>LW1</td>
<td>Waldemar Glacier – front</td>
<td>78°40′31″N</td>
<td>12°00′01″E</td>
<td>130</td>
<td>3800</td>
<td>moraine</td>
<td>MadgeTech/HOBO</td>
</tr>
<tr>
<td>4</td>
<td>LW2</td>
<td>Waldemar Glacier – firm field</td>
<td>78°40′54″N</td>
<td>12°05′16″E</td>
<td>375</td>
<td>5720</td>
<td>glacier</td>
<td>MadgeTech/HOBO</td>
</tr>
<tr>
<td>5</td>
<td>GF</td>
<td>Gråfjellet</td>
<td>78°39′59″N</td>
<td>12°00′33″E</td>
<td>345</td>
<td>3260</td>
<td>mountain peak</td>
<td>MadgeTech/HOBO</td>
</tr>
<tr>
<td>6</td>
<td>PH1</td>
<td>Prins Heinrichfjella – 1</td>
<td>78°40′51″N</td>
<td>11°59′28″E</td>
<td>500</td>
<td>1870</td>
<td>mountain peak</td>
<td>MadgeTech/HOBO</td>
</tr>
</tbody>
</table>
Variability of thermal conditions in the analysed meteorological sites during inflow of air masses within particular circulation type was estimated using standard deviation ($\sigma$).

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 ±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...
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.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
<td>Spring and autumn</td>
<td>Summer</td>
<td>Year</td>
</tr>
<tr>
<td>1</td>
<td>NWa+Na+NEa</td>
<td>39</td>
<td>12.0</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>Ea+SEa</td>
<td>29</td>
<td>9.0</td>
<td>22</td>
</tr>
<tr>
<td>3</td>
<td>Sa+SWa+Wa</td>
<td>12</td>
<td>3.7</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>Ka+Ca</td>
<td>22</td>
<td>6.8</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>ANTICYCLONIC</td>
<td>102</td>
<td>31.5</td>
<td>91</td>
</tr>
<tr>
<td>5</td>
<td>NWc+Nc+NEc</td>
<td>73</td>
<td>22.5</td>
<td>67</td>
</tr>
<tr>
<td>6</td>
<td>Ec+SEC</td>
<td>66</td>
<td>20.4</td>
<td>63</td>
</tr>
<tr>
<td>7</td>
<td>Sc+SWc+Wc</td>
<td>27</td>
<td>8.3</td>
<td>31</td>
</tr>
<tr>
<td>8</td>
<td>Be+Cc</td>
<td>37</td>
<td>11.4</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>CYCLONIC</td>
<td>203</td>
<td>62.7</td>
<td>192</td>
</tr>
<tr>
<td>9</td>
<td>X</td>
<td>19</td>
<td>5.9</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td>324</td>
<td>100</td>
<td>298</td>
<td>100</td>
</tr>
</tbody>
</table>

\*σ-standart deviations calculated for period: 1.01.1951 to 31.12.2009.
表3. 极地气候和空气温度在Forlandsundet (NW Spitsbergen) 地区的差异（℃）

<table>
<thead>
<tr>
<th>站点</th>
<th>冬季</th>
<th>90%</th>
<th>10%</th>
<th>春季和秋季</th>
<th>90%</th>
<th>10%</th>
<th>夏季</th>
<th>90%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAT–KH</td>
<td>-0.9</td>
<td>-1.0</td>
<td>-3.7</td>
<td>1.6</td>
<td>1.9</td>
<td>2.1</td>
<td>-0.9</td>
<td>-1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>LW1–KH</td>
<td>-1.7</td>
<td>-1.6</td>
<td>-2.1</td>
<td>1.0</td>
<td>0.8</td>
<td>2.3</td>
<td>-1.4</td>
<td>-1.5</td>
<td>-2.1</td>
</tr>
<tr>
<td>LW2–KH</td>
<td>-2.8</td>
<td>-3.1</td>
<td>-3.5</td>
<td>0.3</td>
<td>0.3</td>
<td>1.6</td>
<td>-2.8</td>
<td>-3.1</td>
<td>-3.5</td>
</tr>
<tr>
<td>GF–KH</td>
<td>-2.7</td>
<td>-3.0</td>
<td>-3.0</td>
<td>0.7</td>
<td>0.1</td>
<td>2.2</td>
<td>-2.8</td>
<td>-3.1</td>
<td>-3.0</td>
</tr>
<tr>
<td>PH1–KH</td>
<td>-4.4</td>
<td>-4.6</td>
<td>-4.4</td>
<td>-0.2</td>
<td>-0.5</td>
<td>1.4</td>
<td>-4.0</td>
<td>-4.2</td>
<td>-4.2</td>
</tr>
</tbody>
</table>

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


“正如在引言部分所述，大气环流对空气温度的影响在斯匹次卑尔根群岛是显而易见的，但只对狭窄的沿海地区有效，其中所有气象站都位于该地区。结果由Przybyłak (1992a) 和Niedźwiedz (2013) 使用数据从Hornsund (Southern Spitsbergen) 等显示，与某些例外情况相比，那些极端条件时，气旋性涡旋（SWa）和Sa带的暖空气比Ba带的暖空气更明显。在图1中，Tmax在SAT和KH站点之间的差异小于1°C，而Tmin在SAT和KH站点之间的差异小于1°C，这表明在冬季这两个站点之间的差异要小一些。然而，气旋性涡旋大气环流在大多数情况下对温度的影响并不直接导致温度和湿度的多样性。一个例外是Cloudiness（强烈影响大气环流）的区域，这种区域有着显著的山地和冰川化。特别在冬季，当太阳辐射、海平面、局部风等因素（Soda radiation, albedo, local winds, etc.）相互作用时，局部过程（solar radiation, albedo, local winds, etc.）对温度和湿度多样性的影响是间接的。它可能与某些大气环流类型的影响在特定地区更为强烈，甚至在合成尺度大气环流的影响中更为显著。”

表3. 极地气候和空气温度在Forlandsundet (NW Spitsbergen) 地区的差异（℃）

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<td>1.9</td>
<td>2.1</td>
<td>-0.9</td>
<td>-1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>LW1–KH</td>
<td>-1.7</td>
<td>-1.6</td>
<td>-2.1</td>
<td>1.0</td>
<td>0.8</td>
<td>2.3</td>
<td>-1.4</td>
<td>-1.5</td>
<td>-2.1</td>
</tr>
<tr>
<td>LW2–KH</td>
<td>-2.8</td>
<td>-3.1</td>
<td>-3.5</td>
<td>0.3</td>
<td>0.3</td>
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</tr>
<tr>
<td>GF–KH</td>
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<td>0.1</td>
<td>2.2</td>
<td>-2.8</td>
<td>-3.1</td>
<td>-3.0</td>
</tr>
<tr>
<td>PH1–KH</td>
<td>-4.4</td>
<td>-4.6</td>
<td>-4.4</td>
<td>-0.2</td>
<td>-0.5</td>
<td>1.4</td>
<td>-4.0</td>
<td>-4.2</td>
<td>-4.2</td>
</tr>
</tbody>
</table>

根据Przybyłak (1992a) 以及Niedźwiedz (2013) 使用的数据，我们可以在Hornsund (Southern Spitsbergen) 地区看到一些例外情况。其中，当特定条件时，气旋性涡旋（SWa）和Sa带的暖空气比Ba带的暖空气更明显。在图1中，Tmax在SAT和KH站点之间的差异小于1°C，而Tmin在SAT和KH站点之间的差异小于1°C，这表明在冬季这两个站点之间的差异要小一些。然而，气旋性涡旋大气环流在大多数情况下对温度的影响并不直接导致温度和湿度的多样性。一个例外是Cloudiness（强烈影响大气环流）的区域，这种区域有着显著的山地和冰川化。特别在冬季，当太阳辐射、海平面、局部风等因素（Soda radiation, albedo, local winds, etc.）相互作用时，局部过程（solar radiation, albedo, local winds, etc.）对温度和湿度多样性的影响是间接的。它可能与某些大气环流类型的影响在特定地区更为强烈，甚至在合成尺度大气环流的影响中更为显著。”

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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.

<table>
<thead>
<tr>
<th>Type of circulation</th>
<th>SAT–KH</th>
<th></th>
<th></th>
<th>LW1–KH</th>
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<th></th>
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<tbody>
<tr>
<td></td>
<td>Frequency</td>
<td>Mean differences (°C)</td>
<td>Frequency</td>
<td>Mean differences (°C)</td>
<td>Frequency</td>
<td>Mean differences (°C)</td>
</tr>
<tr>
<td></td>
<td>n &lt;10%</td>
<td>≥90%</td>
<td>≤10%</td>
<td>≥90%</td>
<td>≤10%</td>
<td>≥90%</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>NWa+Na+NEa</td>
<td>2</td>
<td>5</td>
<td>6.7</td>
<td>16.1</td>
<td>−2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>Ea+SEa</td>
<td>4</td>
<td>3</td>
<td>13.3</td>
<td>9.7</td>
<td>−2.7</td>
<td>1.9</td>
</tr>
<tr>
<td>Sa+SWa+Wa</td>
<td>3</td>
<td>2</td>
<td>10.0</td>
<td>6.5</td>
<td>−1.2</td>
<td>1.9</td>
</tr>
<tr>
<td>Ka+Ca</td>
<td>1</td>
<td>4</td>
<td>3.3</td>
<td>12.9</td>
<td>−1.8</td>
<td>2.0</td>
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<td>NWCc+Nc+NEc</td>
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<td>13.3</td>
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<tr>
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<td>6.7</td>
<td>9.7</td>
<td>−1.2</td>
<td>2.4</td>
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<tr>
<td>Bc+Cc</td>
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<td>3</td>
<td>10.0</td>
<td>9.7</td>
<td>−1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Spring and autumn</td>
<td></td>
<td></td>
<td></td>
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<td>3.6</td>
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<tr>
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<td>6.7</td>
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<td>1.3</td>
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<td>Summer</td>
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<td>21.1</td>
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<td>1.0</td>
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<td>9.7</td>
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## Table 4. Continued.

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<th>PH1–KH</th>
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<td>Frequency</td>
<td>Mean differences (°C)</td>
<td>Frequency</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>%</td>
<td>≤10%</td>
</tr>
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<td></td>
<td></td>
</tr>
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<td>7.1</td>
</tr>
<tr>
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<td>1</td>
<td>17.9</td>
</tr>
<tr>
<td>Spring and autumn</td>
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<td></td>
<td></td>
</tr>
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<td>13.3</td>
</tr>
<tr>
<td>Ea+SSEa</td>
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<tr>
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<td>6.7</td>
</tr>
<tr>
<td>Summer</td>
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<td></td>
<td></td>
</tr>
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</tr>
<tr>
<td>Ea+SSEa</td>
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<td>.</td>
</tr>
<tr>
<td>Sa+SWa+Wa</td>
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<td>1</td>
<td>5.9</td>
</tr>
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<td>6</td>
<td>.</td>
</tr>
<tr>
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<td>35.3</td>
</tr>
<tr>
<td>Be+Cc</td>
<td>1</td>
<td>0</td>
<td>5.9</td>
</tr>
</tbody>
</table>

For full names of sites (KH, SAT, etc.) see Table 1.
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 $T_{\text{max}}$ are more similarly dependent on atmospheric circulation, while $T_{\text{min}}$ 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 $T_{\text{min}}$ are positive, while for Ti and $T_{\text{max}}$ 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+NEc+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 $T_{\text{max}}$ and $T_{\text{min}}$ (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 $T_{\text{max}}$ (Table 5, Figure 2(b)). On the other hand, conversely to winter, reactions of Ti and $T_{\text{min}}$ to advection of air masses during particular circulation types reveal greater similarity than Ti and $T_{\text{max}}$. 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 $T_{\text{min}}$) noted between mountainous and glaciated parts of the study area on one side and the KH...
A 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 \( T_{\text{max}} \), 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 \( T_{\text{max}} \), also during Bc+Cc type. Anomalies of Ti and \( T_{\text{max}} \) between SAT and KH sites are greatest for both northern types while, in the case of \( T_{\text{min}} \), 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. \( T_{\text{max}} \) and \( T_{\text{min}} \) 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 \( T_{\text{max}} \) and \( T_{\text{min}} \) in the study area was noted in the spring/autumn season than...
in winter (Figures S1(a) and S1(b)). As a result, in the former season, a majority of days (> 40% for $T_{\text{min}}$ and > 20% for $T_{\text{max}}$ 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 $T_{\text{min}}$ in particular.

On average, all non-coastal sites are colder in summer than the KH site. $T_i$ at the SAT and KH sites was the same, while $T_{\text{max}}$ was colder (by 0.4 °C) and $T_{\text{min}}$ 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 $T_i$ 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 $T_i$ and $T_{\text{max}}$ 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 $T_{\text{min}}$ 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 $T_{\text{min}}$) clearly during two anticyclonic types Ea+SEa and Sa+SWa+Wa (respectively by 0.9/0.3 °C for $T_i$ and 1.6/0.4 °C for $T_{\text{max}}$). Positive anomalies of air temperature differences (weakening of normal lapse rates including inversion situations) are most common in terms of $T_i$ and $T_{\text{min}}$, mainly during air advection from the eastern sector (types Ea+SEa and Ec+SEc), as was also stated for two other seasons. $T_{\text{max}}$ also has large positive
Table 5. Anomalies of air temperature (Ti, $T_{\text{max}}$ and $T_{\text{min}}$) differences (°C) between KH and other sites in the Forlandsundet region in the period from 21 July 2010 to 22 November 2013.

<table>
<thead>
<tr>
<th>Type of circulation</th>
<th>Winter</th>
<th>Spring and autumn</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
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<td>Ti</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWa+Na+NEa</td>
<td>0.2</td>
<td>-0.5</td>
<td>-0.3</td>
</tr>
<tr>
<td>Ea+SEa</td>
<td>-0.3</td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Sa+SWa+Wa</td>
<td>-0.1</td>
<td>1.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Ka+Ca</td>
<td>0.4</td>
<td>-0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>NWc+Nc+NEc</td>
<td>0.3</td>
<td>-0.4</td>
<td>-0.7</td>
</tr>
<tr>
<td>Ec+SEc</td>
<td>-0.1</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Sc+SWc+We</td>
<td>-0.2</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Bc+Cc</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.3</td>
</tr>
<tr>
<td>Mean differences</td>
<td>0.4</td>
<td>-0.5</td>
<td>-1.4</td>
</tr>
</tbody>
</table>

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.
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; Migala 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 $T_{\text{max}}$ than Ti and $T_{\text{min}}$ 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 $T_{\text{max}}$, this kind of differences between KH and other studied sites occurs with a frequency of 20–40%. For $T_{\text{min}}$, 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

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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+5Ec and Be+Cc (seen in the upper part of the study area in particular), for T\text{max} during NWc+Nc+NEc, and for T\text{min} during Ec+5Ec, but only in LW2 and GF sites (Figure 3 and Figures S1(a) and S1(b)). Variability of daily air temperature (Ti, T\text{max} and T\text{min}) within the analysed seasons during the occurrence of the same circulation type was estimated using standard deviation (\(\sigma\)) (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 \(^\circ\)C. On the other hand, the smallest variability (\(\sigma = 2–3 \, ^{\circ}\)C and \(\sigma = 3 \, ^{\circ}\)C) in these seasons was mainly observed within air advection from the southern sector (Sa+SWa+W and Sc+SWi+Wc+WC types, respectively). In summer, air temperature variability was significantly smaller than in the cold period, exceptionally exceeding 4 \(^\circ\)C, while the lowest values fall near 1 \(^\circ\)C. The highest variability, ranging from 2 to 4 \(^\circ\)C, was mainly noted during Ea+Sæa and NWc+Nc+NEc types (see Table 6). The most stable thermal conditions in summer are brought by Ka+Ca type (\(\sigma = 1–2 \, ^{\circ}\)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\text{max} and T\text{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 (\(\geq 90\%\)) and largest negative (\(\leq 10\%\)) 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 \(^\circ\)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 Waldermar 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 Migala et al. (2008). Extreme positive anomalies of SAT–KH Ti differences (about 2 \(^\circ\)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 \(- 2 \, ^{\circ}\)C for LW1 and \(- 4.9 \, ^{\circ}\)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+SWi+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 \(^\circ\)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 Heinrich fjella ridge. Secondly, cloudiness during this advection is small, favouring the greater heating of air in the upper part of the Waldermar Glacier valley than in the Tundra area (Kaffiøya Plain) due to strong winds occurring in the latter area and its proximity to cold (4–5 \(^\circ\)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\text{max} differences in the study
The largest positive anomalies of T\textsubscript{min} differences, with average values ranging between about 0.5 and 2.0 \(^\circ\)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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{min} patterns in the study region. This hypothesis was confirmed by the fact that the largest negative anomalies of T\textsubscript{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 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\textsubscript{max} differences are most often noted during the Ka+Ca type.

Some interesting features confirming the individual character of behaviour of extreme T\textsubscript{max} 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\textsubscript{max} were responsible for the occurrence of the largest negative (NWc+NC+NEc) and largest positive (Ec+SEc) anomalies of T\textsubscript{min} differences (compare Table S2(b) with Tables 4 and S2(a)). In the case of T\textsubscript{min}, however, both mentioned types had the same influence in the entire area of the study, while in the case of Ti and T\textsubscript{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\textsubscript{min} – conversely to Ti and T\textsubscript{max} – showed such a pattern across the entire area. For example, in the case of T\textsubscript{max} and T\textsubscript{min} the two most frequent types favouring the occurrence of that kind of anomaly were 90% the same (see Tables S2(a) and (b)).
cannot be estimated. Another type which in some sites (mainly SAT, GF and PH) more frequently ‘produces’ the largest negative anomalies of $T_{\text{min}}$ 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 $T_{\text{min}}$ 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 ($\geq 90\%$) and smallest ($\leq 10\%$) anomalies of $T_i$ 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 $T_{\text{min}}$ are less stable at all sites. On the other hand, in spring and autumn $T_{\text{max}}$ is most unstable, i.e. usually has the largest distances between values of $T_i$ differences representing the 90th and 10th percentile thresholds. In summer, $T_i$ is most stable in this respect, except for the PH1 site, where this parameter is most unstable, and SAT, where $T_{\text{min}}$ is most stable by a slight margin (see Figure 4).
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 Kafföya 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; Migala 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
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, Tmax and Tmin) 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 Tmax than Ti and Tmin 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 Tmin. 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 Tmax and Tmin.
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+NEnA 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 (σ = 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 (σ = 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.

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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+NwEA, 2 – Ea+SWEa, 3 – Sa+SWa+Wa, 4 – Ka+Ca, 5 – NWC+Nc+NwEc, 6 – Ec+SWEc, 7 – Sc+SWE+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+NwEA, 2 – Ea+SWEa, 3 – Sa+SWa+Wa, 4 – Ka+Ca, 5 – NWC+Nc+NwEc, 6 – Ec+SWEc, 7 – Sc+SWE+WC, 8 – Bc+Cc.

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