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## CLOUD COVER OVER SPITSBERGEN AND ITS RELATION TO ATMOSPHERIC CIRCULATION (1983-2015)

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### Abstract

This paper discusses the cloud cover and its relation to atmospheric circulation over Spitsbergen during 1983-2015. It focuses on monthly and seasonal cloud covers and on the frequency of days with specific cloud cover (cloudless, clear, cloudy and completely overcast sky) and their relation to various circulation types. In the research period the cloud cover characteristics were differentiated over the island on both monthly and seasonal scales, and they strongly depended on the direction of air advection. The highest mean daily cloud cover was reported for circulation types with air advection from the south (S+SWc and S+SWa). The greatest variation in the cloud cover distribution was observed during the polar night (at Svalbard Lufthavn and Ny-Ålesund) or in the autumn (Hornsund). The long-term variability in the cloud cover significantly depends on the frequency of N+NEa type (negative correlation) and on S+SWc and W+NWc and Cc+Bc types (positive correlation), particularly in spring.

### Key words

cloud cover • atmospheric circulation • Spitsbergen • the Arctic

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### Introduction

An increase in air temperature, shrinking sea ice extent or a variable pattern of baric field can significantly influence the fraction of the sky obscured by clouds in the Arctic. Unlike majority of climate elements, the cloud cover is measured by visual assessment of the sky fraction covered by clouds. The type and occurrence of cloud cover may indicate a current

state of the atmosphere, or spell its future modification. Clouds may undergo various modifications, thus significantly influencing the radiation balance of the Earth surface and atmosphere and finally impacting air temperature (IPCC 2007; Przybylak 2007; Vavrus et al. 2011; Matuszko & Soroka 2013; Bednorz et al. 2016). Cloud cover modifies the amount of the solar radiation reaching the Earth surface and thus significantly influences human

general sensation (Araźny 2008). Changes and variability in cloud cover are a key factor affecting solar radiation and other climate elements, such as air temperature, precipitation and horizontal visibility (Marsz 2013). Moreover, the knowledge of cloud cover and related precipitation is the basis for understanding the glacier mass-balance (Turner & Gareth 2011). The currently observed shrinking of the sea ice (Meier et al. 2011; Polyakov et al. 2012; Stroeve et al. 2012) is supposed to have a significant influence on the cloud cover over the Arctic (Schweiger & Key 1992; Schweiger 2004; Kay & Gettelman 2009; Eastman & Warren 2010; Palm et al. 2010). Cloud cover is recently pointed to as one of the key indicators of the current climate change (Webber 1994), which creates the need for its research.

This paper aims at assessing the influence of the atmospheric circulation on the amount of the total cloud cover over Spitsbergen, the largest island within the Svalbard Archipelago. The location of the Island in the central part of the Atlantic Sector of the Arctic results in an increased dynamics of weather conditions being shaped by selected circulation types. Heightened cyclonic activity conditioned by the location of the island in the vicinity of the Arctic front is considered to be a characteristic feature of the atmospheric circulation over the Arctic (Niedźwiedź 2006). Apart from the circulation types, the variability in the cloud cover over Spitsbergen is also affected by local conditions, including, among others, the landform and the warm West Spitsbergen Current flowing in the vicinity of the west Spitsbergen coast (Marsz 2013).

The cloud cover in the Arctic has been discussed in several monographs, though admittedly it still remains a little-known climate element. The total cloud cover over the Arctic or its certain regions was researched, among others, by Raatz (1981), Beesley (1999), Przybylak (2003), Marsz and Styszyńska (2013) and Lipiński and Łupikasza (2016). Matuszko and Soroka (2013) performed qualitative and quantitative analysis of the cloud cover over Hornsund and delivered the annual average cloud cover for various circulation types

between the 1st July 2009 and 30th June 2012. The modification of solar radiation by clouds was investigated by Vowinckel and Orvig (1962) and Curry et al. (1996), while the relation between cloud cover and sea ice loss was researched by Liu et al. (2007), Kay and Gettelman (2009) and Eastman et al. (2010). Soroka and Matuszko (2013) noted difficulties related to the specificity of the visual cloud cover observations in the Polar Regions. Poor visibility during the polar night, lowered tropopause and limitations in the notation of cloud types in SYNOP messages were specified among the most ultimate ones. Kotarba and Widawski (2008) analysed the cloud cover over Svalbard using satellite images, however the analysis was performed for only one year. Casual relations between the cloud cover and atmospheric circulation were partly recognized by Adamczyk and Ustrnul (2008), who found vast cloud cover variability in five selected grid points in the Arctic. The authors recommended the analysis of cloud cover in smaller spatial scales using station data from direct measurements. The relation between cloud cover and atmospheric circulation in the Polish Polar Station Hornsund was also researched by Niedźwiedź and Ustrnul (1989). On the basis of 9-year chronological series (July 1978–July 1987) they determined the average daily cloud cover and the number of days with characteristic cloud cover for various circulation types. While calculating regression between cloud cover and the annual index of southern oscillation, Marsz et al. (2013) found rapid changes in the cloud cover over Spitsbergen that are in line with the changes in synoptic situations and related changes in the direction of air advection. Marsz (2013) also performed multifaceted discussion on the cloud cover and its relation to the atmospheric circulation indices over Hornsund in comparison with the other stations located on the island (Ny-Ålesund, Svalbard Lufthavn, Björnöya) in the period 1978–2009. While the study by Marsz (2013) aimed at analysing the correlation between the variability in cloudiness and circulation indices, this study focuses on researching the synoptic conditions related to cloud cover and

favouring the occurrence of days with characteristic cloud cover. Moreover, this study covers the latest period, namely beyond 2009. Cloud cover and its relation to atmospheric circulation in the short-term period of 2010-2011 was also discussed over NW Spitsbergen (Kejna 2012). The research on atmospheric conditions during an anomalous cloud cover in winter and summer at Svalbard Lufthavn station indicated its strong dependence on the air pressure pattern at sea level (Bednorz et al. 2016).

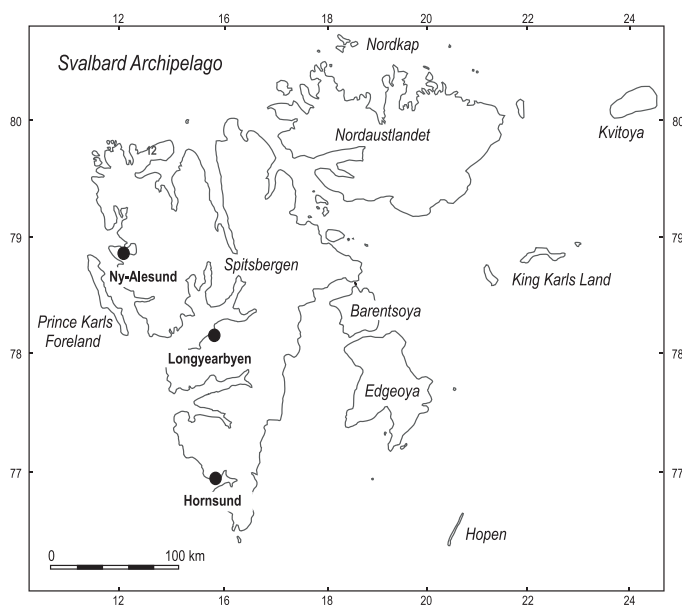
This study discusses the annual course and the seasonal cloud cover over the western part of Svalbard and its relations to atmospheric circulation. The foregoing papers studied the relations using different or single stations. In this paper, in addition to Hornsund, two more stations located to the north of Hornsund were used, namely Svalbard Lufthavn and Ny-Ålesund. Marsz (2013) used these stations only to compare the annual course of cloudiness in Hornsund. Contrary to the above cited papers, in this study the cloud cover is considered during the polar night and the polar day, duration of which is different at the stations. Two much shorter transitional periods are also analysed – spring

(between the polar night and day) and autumn (between the polar day and night). Average cloud cover and the probability of days with a specific cloud cover are considered as well as its relation to circulation types. Clouds play multiple critical roles in the climate system, particularly in the energetic balance of the atmosphere. In particular, they efficiently reflect light into space, and thus contribute to the cooling of the planet (Boucher et al. 2013).

## Data and Methods

Chronological series of the average daily total cloud cover over the period of 33 years between 1983 and 2015 for three synoptic stations located on Svalbard were used (Fig. 1, Tab. 1). The northernmost station is Ny-Ålesund. The Svalbard Lufthavn is located several kilometres to the northwest of Longyearbyen, while Hornsund – Polish Polar Station of the Institute of Geophysics, Polish Academy of Sciences – is placed in the southern part of the island.

The data for Ny-Ålesund and Svalbard Lufthavn stations come from the Norwegian Meteorological Institute database 'e-klima' (<http://eklima.met.no/>). The data



**Figure 1.** Location of meteorological stations on Spitsbergen

**Table 1.** Characteristics of meteorological stations and periods conditioned by seasonal variation in solar radiation

Index	Ny-Ålesund	Svalbard Lufthavn	Hornsund
ø	78°55'N	78°15'N	77°00'N
λ	11°56'E	15°28'E	15°33'E
H	8 m a.s.l	27 m a.s.l	10 m a.s.l
Polar Day*	18.04-24.08	21.04 - 21.08	24.04 do 18.08
Days	129	123	117
Autumn	25.08-24.10	22.08-27.10	19.08-30.10
Days	61	67	73
Polar Night*	25.10-17.02	28.10 - 14.02	31.10 do 11.02
Days	116	110	104
Spring	18.02-17.04	15.02 - 20.04	12.02-23.04
Days	59	65	71

ø - latitude, λ - longitude, h - altitude in m a.s.l., \* durations of polar day and night after <http://hornsund.igf.edu.pl/hornsund.old/swiatlo.html>

for Hornsund (for the period 1982/1983-1999/2000) were taken from Meteorological Yearbooks 'Hornsund' published by Maritime Branch of the IMGW in Gdynia under the guidance of M. Miętus (IMGW 2000-2001). The further yearbooks, for the periods 2000/2001 and 2001/2002 were published by the Institute of Geophysics, Polish Academy of Sciences under the guidance of Kwaczyński and Nowosielski (Institute of Geophysics 2001, 2003). The latest data for the Hornsund station (for 2003-2013) come from the database of the Institute of Geophysics, Polish Academy of Sciences. Moreover, the shortened version of the synoptic types catalogue by Niedźwiedź (2015) was used to analyse the relations between atmospheric circulation and cloud cover (Niedźwiedź 2013a). The calendar consists of 11 synoptic types including 5 anticyclonic types (Ca+Ka, N+NEa, E+SEa, S+SWa, W+NWa), 5 cyclonic types (Cc+Bc, N+NEc, E+SEc, S+SWc, W+NWc) and one unidentified type „x” attributed to days with the col or fuzzy atmospheric pressure field.

The main body of the paper consists of two parts divided into further two subchapters. The first part discusses the climatology of cloud cover (first subchapter) and days with a characteristic cloud cover (second subchapter). This

chapter includes the average, maximum and minimum monthly, seasonal and annual cloud cover as well as the probability of days with characteristic cloud cover. Days with characteristic cloud cover were defined according to the meteorological glossary by IMGW (Polish Institute of Meteorology and Water Management, Niedźwiedź 2003). Accordingly, clear days were defined as days with daily average cloud cover lower than 20% ( $N < 20\%$ ), cloudy days are those with average daily cloud cover higher than 80% ( $N > 80\%$ ). Moreover, completely overcast days ( $N = 100\%$ ) and cloudless days ( $N = 0\%$ ) were also included into the analysis due to the relevance for bioclimatology. The second part of the paper concerns relations between the cloud cover characteristics and atmospheric circulation. Average cloud cover and conditional probability of the days with a characteristic cloud cover were calculated for every circulation type. Conditional probability is a method used to assess relationships between variables while taking into account the frequency of these variables. The statistics provide information about the degree to which each of the considered circulation types favours the occurrence of days with a characteristic cloud cover, and thus has a prognostic value. The probability of the

occurrence of Event  $E_1$  (a day with a specific cloud cover) on condition of the occurrence of Event  $E_2$  (a specific type of synoptic situation) is expressed as (Wilks 2006):

$$\Pr \left\{ \frac{E_1}{E_2} \right\} = \frac{\Pr \{E_1 \cap E_2\}}{\Pr \{E_2\}}$$

Spearman correlation coefficients were also calculated between seasonal cloud cover characteristics and the number of days with particular circulation types to assess the impact of atmospheric circulation on the long-term variability in cloud cover indices. The correlation coefficients were not calculated for W+NWa type for the polar night and spring due to a very rare occurrence of the type in these seasons.

### Cloud cover

The Norwegian Arctic is counted as one of the most clouded areas in the world (Przybylak 2003). The highest annual cloud cover was found in Hornsund (72.7%), while at the other

two stations it reached ca. 67%. This difference results from the various impact of warm West Spitsbergen Current on the cloud cover conditioned by the distance between the station and the current. Similarities were found in the seasonal variation in the cloud cover at the analysed stations (Tab. 2). At each station, the highest cloud cover was found during the polar day and in the autumn transitional period. In these seasons glaciers ablation takes place – usually between June and September (Kryza et al. 2011). Moreover, there is an increased flow of maritime air masses from the south-western direction over Spitsbergen during that time. These air masses bring heat and moisture over the land cooled at that time of the year (Arażny 2003; Niedźwiedź 2006).

What distinguishes Hornsund from the other stations is a distinctly higher cloud cover throughout the whole year. This is due to its southernmost location, which exposes the station to the frequent influences of low pressure systems with their centres passing south to the island (Marsz et al. 2013). Moreover, orography and the distance between the

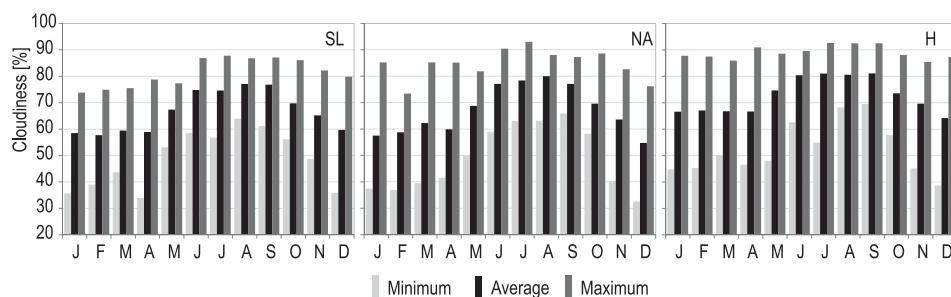
**Table 2.** Mean monthly, seasonal and annual cloudiness [%] in Spitsbergen (1983-2015) and the variability ranges

Statistic	Year	Polar Night	Spring	Polar Day	Autumn
Ny-Ålesund					
N	67.2 (±0.7)	58.4 (±1.5)	61.2 (±1.4)	74.6 (±0.7)	75.0 (±0.9)
δ n	3.8	7.7	7.8	3.9	4.8
N max	74.7	73.1	78.7	80.9	82.0
N min	58.1	43.7	47.3	65.5	64.3
Svalbard Lufthavn					
N	66.7 (±0.5)	60.4 (±1.3)	58.9 (±1.0)	72.1 (±0.6)	74.1 (±0.8)
δ n	2.9	7.1	5.9	3.5	4.3
N max	74.2	75.8	70.0	78.5	82.6
N min	61.4	43.4	43.0	64.0	61.7
Hornsund					
N	72.7 (±0.6)	66.6 (±1.3)	66.8 (±1.1)	78.6 (±0.6)	77.7 (±0.7)
δ n	3.3	7.2	6.4	3.7	4.1
N max	79.3	82.2	80.9	84.9	84.8
N min	64.5	48.9	52.5	67.4	68.2

Explanations: N – mean cloudiness (±standard error), δ n – standard deviation, N max and N min – average maximum and minimum of cloudiness

station and the open waters of the Greenland Sea are other important factors. Low-level clouds appearing over the Greenland Sea are 'pushed' into the fiords of the Western Spitsbergen, however they do not frequently reach the Svalbard Lufthavn station, which is distant from the fjord entrance (Marsz 2013). Generally, the highest cloud cover within a year was found in July, August or September (Hornsund 81.2%; Svalbard Lufthavn 77.1%; Ny-Ålesund 80.0%, Fig. 2). Except for the station located further to the land, the maximum monthly cloud cover crossed the threshold of 90% (Fig. 2). At each station the variability in the cloud cover was vividly higher in December

and April than in the other months, which was indicated by high standard deviations. Considering seasonal values, the highest cloud cover was noticed during the polar day and the autumn transitional season, when it varied from 72.1% at Svalbard Lufthavn to 78.6% at Hornsund station. A high cloud cover in that part of the year is due to an intense cyclogenesis and low pressure systems more frequent in autumn then in winter (Brümmer et al. 2000). Clear weather occurred most often between December and April. During the polar night, when radiation is negligible, atmospheric circulation is the most important factor impacting upon weather conditions.



**Figure 2.** Annual course of average, maximum and minimum total cloudiness in Svalbard Lufthavn (SL), Ny-Ålesund (NA) and Hornsund (H) in the period 1983-2015

## Days with characteristic cloud cover

The probability of days with a characteristic cloud cover is a very important climate index of bioclimatological and environmental importance. The fraction of the sky obscured by clouds determines the dynamics of many processes taking part in the environment including human general sensation. Despite relatively short distances between the considered stations, the number of characteristic days varied noticeably depending on location.

The probability of cloudless days ( $N=0\%$ ) on Spitsbergen is very low (Tab. 3). At Hornsund and Svalbard Lufthavn stations it is lower than 1%. The days occur more frequently at Ny-Ålesund station, with the maximum during the polar night when the probability

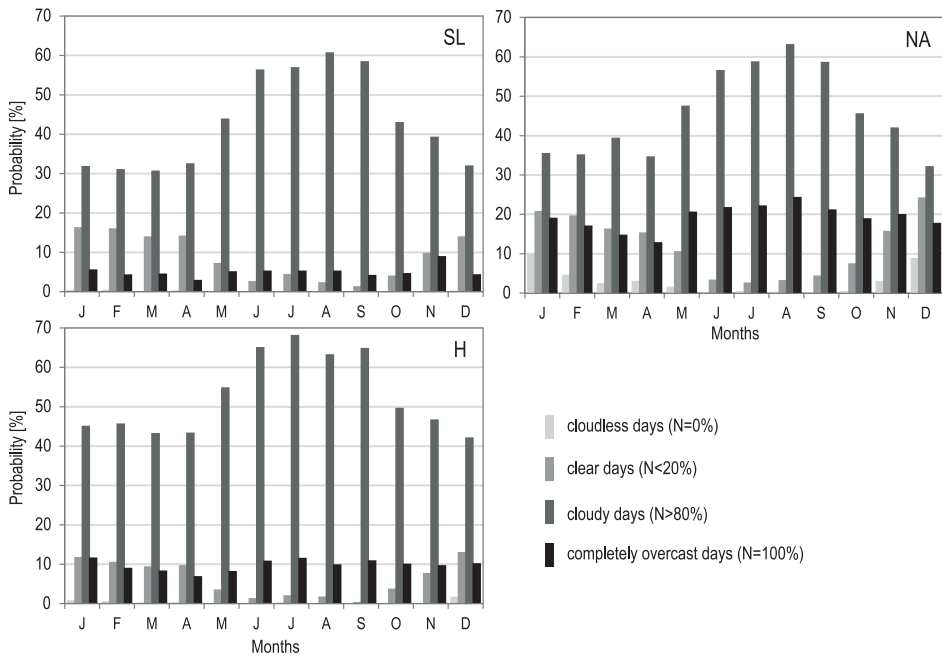
of their occurrence reached 7.1%. Cloudless days did not appear in autumn, particularly in Hornsund and Svalbard Lufthavn. At every station cloudless days were the most probable in winter months, from December to February – from 0.3% in Svalbard Lufthavn in December to 10.0% in Ny-Ålesund in January (Fig. 3). According to Marsz (2013) and Marsz et al. (2013), the low number of cloudless days in Hornsund is due to the frequent and rapid development of orographic clouds in the visual field of an observer and their rapid transformation.

The highest probability of clear days ( $N < 20\%$ ) on both annual and seasonal scales was found in Ny-Ålesund (Tab. 3). At every station the probability reached its maximum during the polar night (from 11.3% in Hornsund to 20.4% in Ny-Ålesund) and was quite high

**Table 3.** Probability of days [%] with characteristic cloudiness: cloudless days (N = 0%), clear days (N<20%), cloudy (N>80%) and the completely overcast (N = 100%) [%] in Spitsbergen (1983-2015)

Station	Days with characteristic cloudiness	Year	Polar Night	Spring	Polar Day	Autumn
NA	N = 0%	3.2	7.1	3.0	0.9	0.3
	N < 20%	24.3	20.4	17.1	6.1	5.3
	N > 80%	46.0	36.2	37.1	54.5	53.5
	N = 100%	19.6	18.9	14.9	22.0	19.3
SL	N = 0%	0.2	0.4	0.2	0.1	-
	N < 20%	9.0	14.0	14.2	5.2	2.4
	N > 80%	43.2	34.0	31.4	52.2	52.9
	N = 100%	3.4	4.1	2.6	3.7	3.1
H	N = 0%	0.4	0.9	0.3	0.1	-
	N < 20%	6.3	11.3	9.5	2.6	2.0
	N > 80%	52.8	44.4	43.3	62.1	59.5
	N = 100%	9.9	10.3	8.1	10.2	10.5

“-“ no characteristic days occurred in the research period



**Figure 3.** Probability of days with characteristic cloudiness (N) at Svalbard Lufthavn (SL), Ny-Ålesund (NA) and Hornsund (H) stations in the period 1983-2015

in spring (from 9.5% in Hornsund to 17.1% in Ny-Ålesund). Spatial differentiation in the probability of clear days was smaller than in the case of the other days with the characteristic cloud cover, particularly between June and September. In the other months the chance of clear days occurrence increases to the north.

At every station cloudy days ( $N > 80\%$ ) dominated throughout the year. The probability of cloudy days at Hornsund station was clearly higher than at the other ones. During the majority of the months, except for July and September, the lowest probability was found at Svalbard Lufthavn station located deep into the fjord (Fig. 3). In Hornsund cloudy conditions are likely to occur for about a half-year (52.8%), whereas in Ny-Ålesund and Svalbard Lufthavn the annual probability of their occurrence was admittedly the highest, although lower than 50% (Tab. 2). The extreme probability of cloudy days fell on the polar day (maximum) and spring or the Polar Night (minimum). The monthly probability of cloudy days occurrence varies from 42.2% (December) to 68.2% (July) at Hornsund station, from 30.8% (March) to 60.8% (August) in Svalbard Lufthavn and from 32.3% (December) to 63.3% (August) in Ny-Ålesund.

The completely overcast day probability at Svalbard Lufthavn station was calculated on the basis of the data covering the period 1983-2003. It was noticed that after 2003 the number of days with  $N = 100\%$  was enormously lower than in the previous years. It probably results from some non-meteorological reasons that were not possible to identify at that moment. Such differences were not found in the case of the other characteristics of cloud cover. The annual probability of completely overcast days varied over Spitsbergen from 3.4% (Svalbard Lufthavn) to 19.6% (Ny-Ålesund). The probability did not change considerably throughout the year, however its spatial differentiation was noticeable with Ny-Ålesund being characterised by the greatest likelihood of the overcast days occurrence. At Hornsund and Ny-Ålesund stations, completely overcast days were the most likely to occur during the

polar day (10.2% and 22.0% respectively) and in autumn (10.5% and 19.3% respectively). In contrast, at Svalbard Lufthavn station the days were the most probable during the polar night (4.1%). The lowest probability of completely overcast days was found in spring (Hornsund: 8.1% and Ny-Ålesund: 14.9%, Svalbard Lufthavn: 2.6%).

## Relations between cloud cover and atmospheric circulation

Atmospheric circulation and solar radiation are crucial factors determining climate and weather conditions. The air pressure field is very variable throughout the year over Svalbard (Niedźwiedź 2013b) and is affected by the seas surrounding the archipelago. They are a source of heat, which in future may be released with an increased intensity due to the loss of sea ice extend in the Arctic (Schweiger 2004; Kay & Gettelman 2009; Eastman & Warren 2010; Palm et al. 2010).

The location of Spitsbergen in high latitudes determines the westerly direction of dominant winds. In the researched period, Spitsbergen was mostly affected by cyclonic situations that occurred during 60.0% of the days compared to 36.5% of days with anticyclonic situations. The frequency of cyclonic situations in the period 1983-2015 was higher than in 1951-2006 (c.a. 56% after Niedźwiedź 2013b), which indicates an increase in the cyclonic activity over Svalbard (Niedźwiedź and Łupikasza 2015). In the research period, air masses flowed over Spitsbergen mostly from the south-eastern (E+SEc, 17.6%) and north-eastern (N+NEc, 15.0%) sectors. The anticyclonic situation W+NWa (2.9%) was the rarest in the research period. Non-advective types Cc+Bc and Ca+Ka were also relatively frequent, constituting one quarter of all the circulation types.

The highest annual cloud cover over Spitsbergen is related to the air advection from the southern sector, regardless of the type of pressure system (S+SWa and S+SWc) (e.g. Niedźwiedź & Ustrnul 1989; Przybylak et al. 2012; Marsz 2013; Soroka & Matuszko 2013). High cloud cover is favoured by the low



pressure system developing between Greenland and Spitsbergen, which triggers an inflow of warm and moist maritime air masses (Soroka & Matuszko 2013). High cloud cover amount over Spitsbergen also occurs in Cc+Bc and W+NwC circulation types. In contrary, the sky is the clearest in N+NEa circulation type. The cloud cover in anticyclonic situations is noticeably lower than in cyclonic ones, except for S+Swa type.

The relations between the cloud cover and atmospheric circulation changed throughout the year (Fig. 4), however the main pattern – the highest cloud cover in S+Swa and S+Swa and the lowest one in N+NEa and N+NEc – did not change during the year. In type S+Swa the cloud cover varied between 81.3% during the polar night in Svalbard Lufthavn to 94.7% during the polar day in Hornsund, while in type N+NEa the cloud cover reached form 30.5% in Ny-Ålesund (polar night) to 65.2% in Hornsund (polar day). The relations between the cloud cover and atmospheric circulation

during the polar night and in spring were stronger than in the other two seasons. It was proved by a higher degree of variability in the average cloud cover in particular circulation types – the difference between the types with the highest and the lowest cloud cover. This means that there were some circulation types that were clearly favourable and some types that were clearly unfavourable for the cloud cover development. During the polar day the difference in average cloud cover between N+NEa and S+Swa types reached on average 33.0% (Fig. 4), while during the polar night it equalled 53.7%. In the case of the cyclonic types (excluding S+Swa), clouds covered about 67.4% (the polar night) to 77.9% (the polar day) of the sky over Spitsbergen. For the majority of the cyclonic types (excluding W+NwC and N+NEc at polar night), the highest cloud cover occurred at Hornsund station. The station is frequently in the cloud zone induced by low pressure systems whose centres move south to the island (Marsz 2013). A decrease in the

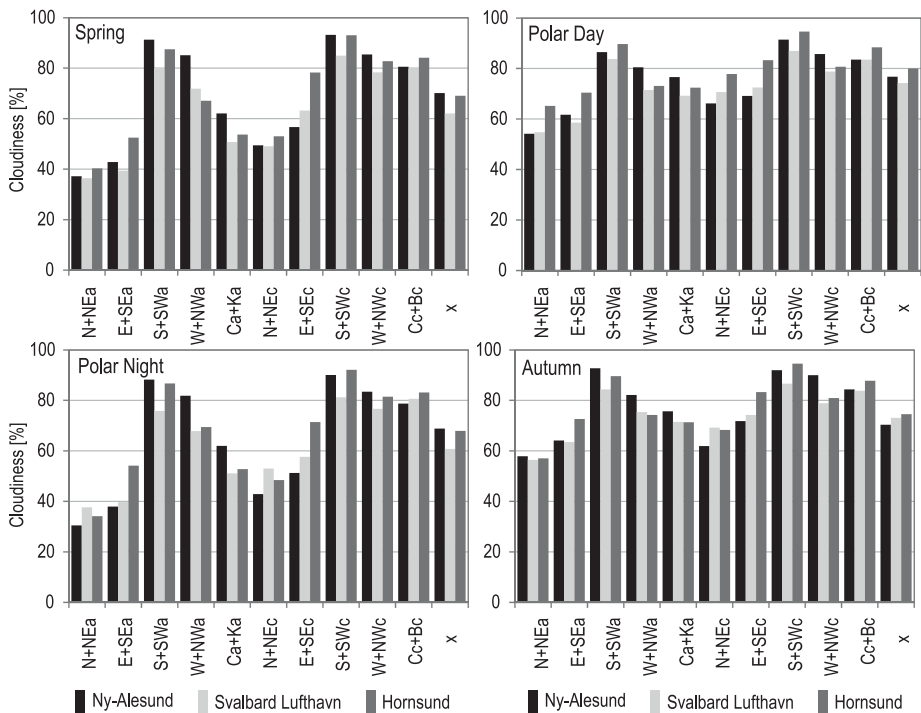


Figure 4. Average seasonal cloudiness [%] in circulation types in the period 1983-2015

cloud cover along with an increasing latitude was also noticed in the type E+S<sub>Ec</sub> in every season, e.g. from 78.2% (Hornsund) to 56.7% (Ny-Ålesund) in spring, and from 71.5% (Hornsund) to 51.3% (Ny-Ålesund) during the polar night. In the anticyclonic types (except for S+SW<sub>a</sub>), the average cloud cover varied between 51.6% (the polar night) and 68.5% (autumn). In the majority of the seasons and anticyclonic circulation types (S+SW<sub>a</sub> except for the polar day, W+NW<sub>a</sub> and Ca+Ka), the highest cloud cover was found at Ny-Ålesund station (from 62.0% to 92.7% depending on the season and type). The situation changed on days with air advection from the Barents Sea (E+S<sub>Ea</sub> type), when the highest cloud cover was noticed in Hornsund. The highest spatial variability in the cloud cover accompanied the type E+S<sub>Ec</sub>, when the cloud cover varied from 51.3% (Ny-Ålesund) to 71.5% (Hornsund) during the polar night, and from 56.7% (Ny-Ålesund) to 78.2% (Hornsund) during spring. No significant spatial and seasonal diversity was found in the cloud cover for Cc+Bc type. A low seasonal variability is also characteristic of S+SW<sub>a</sub>, S+SW<sub>c</sub>, W+NW<sub>c</sub> and Cc+Bc types in Hornsund, W+NW<sub>c</sub> in Svalbard Lufthavn and W+NW<sub>a</sub> and S+SW<sub>c</sub> in Ny-Ålesund. The differences between the seasonal cloud cover did not exceed 5.0%.

Spatial variability in the cloud cover was complex and depended on both the circulation types and season. It was, however, noticed that in types with a relatively low cloud cover its spatial variability was also lower (e.g. N+NE<sub>a</sub>, particularly in transitional seasons and in the polar night) in comparison to the types favouring a high cloud cover (e.g. S+SW<sub>c</sub> and S+SW<sub>a</sub>), when the cloud cover is more prone to the impact of local factors.

### **Relations between days with characteristic cloud cover and atmospheric circulation**

Cloudless days (N=0%) were noted sporadically on Spitsbergen, however the highest probability of their occurrence was related to N+NE<sub>a</sub> and E+S<sub>Ea</sub> types (Tab. 4).

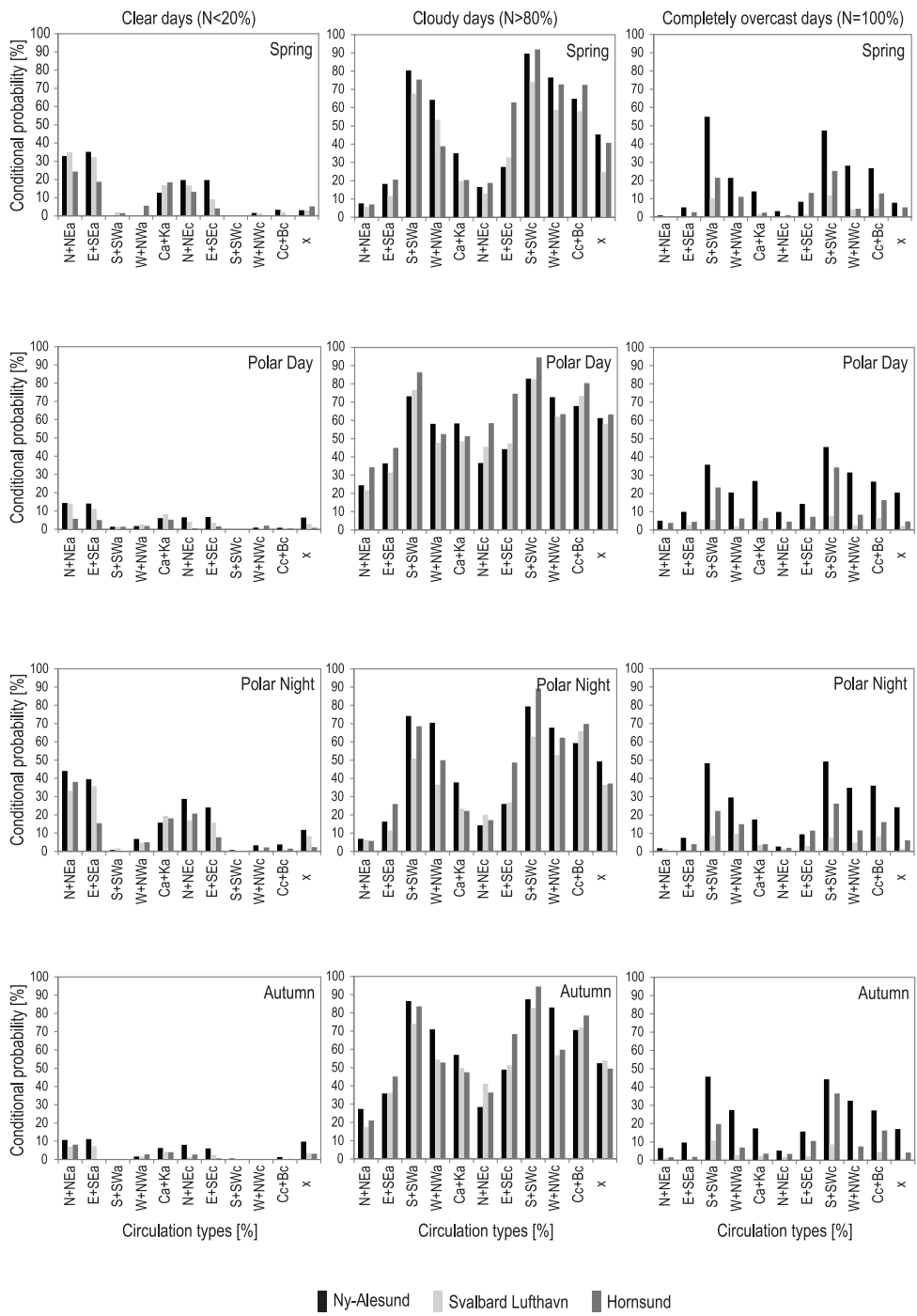
Considering seasonal relations, cloudless days were the most probable during the polar night at Ny-Ålesund station during days with air advection from the north-eastern sector (N+NE<sub>a</sub>, 17.8%) and south-eastern sector (E+S<sub>Ea</sub>, 13.7%). Hornsund was the only station where the highest probability of cloudless days was found in W+NW<sub>a</sub> (5.6%), which happened in spring. At Ny-Ålesund station the probability of the days in E+S<sub>Ea</sub> type (9.3%) was higher than in N+NE<sub>a</sub> type (4.9%). At Svalbard Lufthavn station, where cloudless days were the rarest, their probability exceeded 1% only during the polar night in N+NE<sub>a</sub> (2.0%) and E+S<sub>Ea</sub> anticyclonic types (1.0%).

The clear days (N < 20%) occurrence was strongly related to atmospheric circulation (Tab. 3). The highest probability was characteristic of the days with the air advection from the northern and eastern sectors under an influence of a high pressure system (N+NE<sub>a</sub> and E+S<sub>Ea</sub>). The probability in analogous cyclonic types (N+NE<sub>c</sub> and E+S<sub>Ec</sub>) and in Ca+Ka type was clearly higher than for the other cyclonic types. However, this pattern changed throughout the year and depended on the station. During the polar night the probability of the clear days occurrence in N+NE<sub>a</sub> type varied from 33.2% in Svalbard Lufthavn to 44.0% in Ny-Ålesund. On the days with similar air advection but under an influence of a low pressure system, the probability was much lower, i.e. from 17.0% (Svalbard Lufthavn) to 28.8% (Ny-Ålesund). Clear days were almost equally probable in the anticyclonic type of Ca+Ka and constituted between 15.7% in Ny-Ålesund to 19.3% of all the days with Ca+Ka type at the other stations. In the seasonal course the highest probabilities were found during the polar night and in spring (Fig. 5, Tab. 4). The probability of clear days in S+SW<sub>a</sub> type was low – it did not reach 2%, while in S+SW<sub>c</sub> type clear days did not occur at all at Svalbard Lufthavn and Hornsund stations. In the other seasons the pattern was similar, however the probability of clear days was vividly lower (Fig. 5, Tab. 4). Spatial variability in the probability of the clear days occurrence depended on the circulation types and was complicated.

**Table 4.** Conditional probability [%] of days with characteristic cloudiness in circulation types over Spitsbergen (1983-2015)

TC	Ny-Ålesund				Svalbard Lufthavn				Hornsund			
	PN	S	PD	A	PN	S	PD	A	PN	S	PD	A
Cloudless days (N = 0%)												
N+NEa	17.8	4.9	2.3	0.7	2.0	0.8	-	-	5.4	0.7	0.3	-
E+SEa	13.7	9.3	2.9	0.7	1.0	0.4	0.5	-	1.5	0.7	-	-
S+SWa	-	-	-	-	-	-	-	-	-	-	-	-
W+NWa	4.5	-	-	-	-	-	-	-	2.5	5.6	-	-
Ca+Ka	4.9	2.5	0.5	0.5	0.8	0.5	0.3	-	0.5	1.5	0.3	-
N+NEc	9.1	2.3	1.3	0.3	-	0.3	0.2	-	1.3	-	-	-
E+SEc	8.4	2.5	1.0	-	0.2	-	-	-	0.5	-	-	-
S+SWc	0.3	-	-	-	-	-	-	-	-	-	-	-
W+NWc	0.7	-	-	-	-	-	-	-	-	-	-	-
Cc+Bc	0.8	0.4	-	-	-	-	-	-	0.2	-	0.2	-
x	3.7	-	-	1.2	0.8	-	-	-	-	-	-	-
Clear days (N<20%)												
N+NEa	44.0	32.9	14.3	10.7	33.2	34.7	14.0	7.0	38.0	24.4	5.7	8.1
E+SEa	39.5	35.1	14.1	11.2	35.8	32.0	11.2	7.4	15.4	18.7	5.0	-
S+SWa	0.8	-	1.3	-	1.8	1.7	1.4	-	-	1.5	1.4	-
W+NWa	6.8	-	1.7	1.6	4.9	-	2.7	1.5	5.0	5.6	1.8	2.8
Ca+Ka	15.7	12.7	6.1	6.3	19.3	17.0	8.3	4.1	18.1	18.4	5.2	4.0
N+NEc	28.8	19.7	6.5	8.0	17.0	17.0	4.1	1.3	20.6	13.2	0.5	2.7
E+SEc	24.1	19.7	6.6	6.0	15.7	8.9	3.6	2.5	7.7	4.1	1.6	0.7
S+SWc	0.8	-	-	0.5	-	-	-	-	-	-	-	-
W+NWc	3.4	1.6	0.9	-	-	1.4	0.6	-	2.2	-	1.9	-
Cc+Bc	3.8	3.3	0.8	1.3	1.2	1.6	-	-	1.5	-	0.4	0.3
x	11.8	3.1	6.3	9.8	8.3	2.9	2.9	3.3	2.3	5.3	0.8	3.2
Cloudy Days (N>80%)												
N+NEa	6.9	7.6	24.5	27.3	6.3	5.6	21.7	17.5	5.8	7.0	34.3	21.1
E+SEa	16.3	18.2	36.4	35.8	11.5	11.6	31.3	36.5	26.0	20.6	45.0	45.1
S+SWa	74.2	80.4	73.2	86.4	50.9	67.8	76.7	74.1	68.5	75.4	86.3	83.5
W+NWa	70.5	64.3	58.1	71.0	36.6	53.3	47.8	54.4	50.0	38.9	52.5	52.8
Ca+Ka	37.8	35.0	58.3	57.0	23.5	19.8	48.5	49.8	22.2	20.4	51.4	47.5
N+NEc	14.3	16.5	36.7	28.4	20.0	12.9	45.6	41.2	17.1	18.8	58.5	36.3
E+SEc	26.0	27.5	44.2	48.9	26.9	32.8	47.3	51.4	48.7	62.9	74.6	68.4
S+SWc	79.4	89.6	82.8	87.4	62.9	74.1	82.6	82.8	89.2	91.9	94.5	94.4
W+NWc	67.8	76.6	72.7	82.9	52.7	58.9	62.0	56.7	62.3	72.7	63.5	59.7
Cc+Bc	59.4	64.9	67.9	70.6	65.9	58.0	73.4	71.9	69.9	72.5	80.4	78.5
x	49.3	45.9	61.3	52.4	36.4	24.6	58.1	53.8	37.2	40.8	63.3	49.5
Overcast days (N = 100%)												
N+NEa	1.8	0.9	5.1	6.7	1.6	-	0.7	1.2	0.4	-	3.9	1.6
E+SEa	7.5	5.3	10.0	9.7	1.0	0.4	2.8	0.7	4.0	2.6	4.5	1.9
S+SWa	48.3	54.9	35.7	45.7	8.8	10.2	5.5	10.6	22.2	21.5	23.3	19.8
W+NWa	29.5	21.4	20.5	27.4	9.8	-	1.8	2.9	15.0	11.1	6.3	6.9
Ca+Ka	17.6	14.0	26.9	17.4	3.7	1.6	5.1	2.5	4.1	2.4	6.5	3.6
N+NEc	2.7	3.2	9.8	5.2	1.5	0.3	1.2	1.6	2.1	1.1	4.5	3.4
E+SEc	9.5	8.3	14.3	15.7	3.1	1.3	1.3	2.2	11.5	13.2	7.2	10.5
S+SWc	49.2	47.4	45.4	44.2	7.5	11.9	7.6	8.6	26.2	25.2	34.2	36.5
W+NWc	34.9	28.1	31.5	32.6	4.8	4.1	2.4	0.7	11.6	4.5	8.3	7.5
Cc+Bc	36.1	26.8	26.5	27.2	8.3	4.7	6.6	4.5	16.2	12.9	16.3	16.3
x	24.3	7.8	20.4	17.1	1.5	-	2.2	1.1	6.2	5.3	4.7	4.2

TC – circulation type, PN – the polar night, S – the spring transitional period, PD – the polar day, A – the autumn transitional period



**Figure 5.** Conditional probability of the occurrence of selected days with characteristic cloudiness (clear days:  $N < 20\%$ , cloudy days,  $N > 80\%$ , completely overcast days,  $N = 100\%$ ) from seasonal perspective in Spitsbergen in the period 1983-2015

Despite that, it is noticeable that in the majority of the seasons and circulation types clear days were most probable at Ny-Ålesund station.

Cloudy days, ( $N > 80\%$ ) in contrast to the other days with characteristic cloud cover, may occur in Spitsbergen in every circulation type. However, their highest probability (at least 50%) was related to S+SEc, S+SWa, W+NWc and Cc+Bc circulation types (Tab. 4). The probability of cloudy days in the cyclonic types at Hornsund, and at the other stations similarly, reached its maximum during the polar day (72.5% in Hornsund, 60% at the other stations); at Svalbard Lufthavn and Ny-Ålesund stations it was also quite high in autumn. During the polar night and in spring the chance of the cloudy days occurrence was lower, thus the average probability of their occurrence in the cyclonic situations was also lower, i.e. from ca. 44.1% in Svalbard Lufthavn to 54.1% in Hornsund during the polar night, and from 43.6% in Svalbard Lufthavn to 59.9% in Hornsund in spring. At every station cloudy days were the least frequent in N+NEa type during the polar night (from 5.8% in Hornsund to 6.9% in Ny-Ålesund) and in spring (from 5.6% in Svalbard Lufthavn to 7.6% in Ny-Ålesund). The chance of the cloudy days occurrence in the other anticyclonic situations (E+SEa, W+NWa, Ca+Ka) varied from 11.5% (the polar night) to 54.4% (autumn) at Svalbard Lufthavn station, from 20.6% (spring) to 52.8% (autumn) at Hornsund station and from 16.3% (the polar night) to 71.0% (autumn) at Ny-Ålesund station (Tab. 4).

Completely overcast days may occur in almost every circulation type. However, the probability of their occurrence was the highest during air advection from the southern sector (S+SWa and S+SWc). It particularly applies to Ny-Ålesund station (S+SWa: from 35.7% to 54.9%; S+SWc: from 44.2% to 49.2%) and Hornsund station (S+SWa: from 19.8% to 23.3%; S+SWc: from 25.2% to 36.5%) (Tab. 4). The least chance of completely overcast days characterised Svalbard Lufthavn station, located deep into the island where the probability did not exceed 10%, except for S+SWa type in spring (10.2%)

and autumn (10.6%) and S+SWc type in spring (11.9%). This may be related to the topography – the station is sheltered by a high orographic barrier that stops the moist air flowing from the south. Seasonal differentiation in the probability of completely overcast days did not exceed 10% at Hornsund and Svalbard Lufthavn stations, while at Ny-Ålesund station it was higher than 12% in anticyclonic types S+SEa, W+NWa and Ca+Ka. Completely overcast days were the least probable in N+NEa situation, the probability of their occurrence in that circulation types exceeded 5% only at Ny-Ålesund station during autumn and the polar day

### Correlation between variability in cloud cover characteristics and variability in circulation types frequency

The calculated correlation coefficients indicate a significant impact of the some circulation types on the long-term variability in the cloud cover characteristics. The relation patterns found for the cloud cover and cloudy days were similar. However, the variability in the cloudy days frequency depends more on atmospheric circulation than the variability in cloud cover. The strongest relations were found in spring when increased frequency of S+SWc and W+NWc types resulted in the development of the cloud cover and greater frequency of cloudy days. In this season the cloudiness characteristics were also significantly correlated with the non-advection type of Cc+Bc (Tab. 5). In other seasons, particularly in autumn and during the polar days, increased cloud cover and the cloudy days frequency are related to increased frequency of only S+SWc type. During the polar night atmospheric circulation seems to have a much weaker impact on cloud cover since single correlation coefficients were statistically significant. The opposite effect was found for N+NEa type, which was recognized as uncondusive to the occurrence of cloudy days and high cloud cover. Apart from spring, the negative correlation between N+NEa type and the cloud cover characteristics were also found in autumn at every

**Table 5.** Spearman correlation coefficients between days with characteristic cloudiness and circulation types frequency over Spitsbergen (1983-2015)

SZ	ST	N+NEa	E+SEa	S+SWa	W+NWa	Ca+Ka	N+NEc	E+SEc	S+SWc	W+NWc	Cc+Bc	x
Cloud cover												
PN	NA	<b>-0.502</b>	-0.198	+0.286	-	-0.177	-0.093	+0.051	+0.220	-0.048	+0.486	-0.015
	SL	-0.232	-0.271	+0.075	-	-0.256	-0.082	+0.136	+0.297	-0.108	+0.336	-0.041
	H	-0.192	<i>-0.347</i>	+0.188	-	-0.292	+0.030	+0.121	<b><u>+0.563</u></b>	-0.009	+0.236	+0.151
S	NA	<b><u>-0.563</u></b>	<i>-0.359</i>	+0.123	-	-0.288	+0.015	+0.006	<b><u>+0.497</u></b>	<i>+0.357</i>	+0.530	+0.309
	SL	<b><u>-0.569</u></b>	-0.243	+0.028	-	-0.143	-0.204	-0.064	<b><u>+0.563</u></b>	<b><u>+0.522</u></b>	<b><u>+0.592</u></b>	<b><u>+0.461</u></b>
	H	<b><u>-0.711</u></b>	-0.170	+0.018	-	-0.135	-0.155	-0.024	<b><u>+0.504</u></b>	<b><u>+0.643</u></b>	<i>+0.431</i>	<b><u>+0.446</u></b>
PD	NA	<i>-0.424</i>	-0.068	+0.221	-0.004	-0.197	-0.017	-0.131	+0.358	+0.243	+0.297	+0.095
	SL	<i>-0.458</i>	-0.148	+0.332	-0.149	-0.225	-0.099	+0.012	<b><u>+0.555</u></b>	+0.128	<b><u>+0.422</u></b>	+0.088
	H	-0.316	-0.226	+0.148	-0.258	<i>-0.358</i>	+0.091	+0.290	<i>+0.421</i>	+0.018	+0.318	+0.104
A	NA	<i>-0.448</i>	-0.192	+0.282	+0.149	-0.068	-0.324	+0.157	+0.305	+0.041	-0.092	+0.080
	SL	<b><u>-0.583</u></b>	+0.017	+0.184	+0.146	-0.010	<i>-0.346</i>	+0.162	<b><u>+0.503</u></b>	-0.046	+0.126	+0.292
	H	<b><u>-0.653</u></b>	-0.101	+0.123	-0.152	-0.112	-0.254	+0.103	<b><u>+0.526</u></b>	+0.300	+0.298	-0.040
Clear days (N<20%)												
PN	NA	<i>+0.446</i>	+0.163	-0.198	-	<i>+0.376</i>	-0.049	-0.024	-0.180	+0.069	<i>-0.412</i>	+0.014
	SL	<i>+0.358</i>	+0.180	-0.147	-	+0.350	+0.099	-0.155	<i>-0.454</i>	+0.221	-0.314	-0.049
	H	+0.234	+0.296	-0.344	-	+0.315	+0.016	-0.148	<b><u>-0.573</u></b>	-0.020	-0.068	-0.069
S	NA	<b><u>+0.503</u></b>	+0.297	+0.132	-	+0.333	-0.205	-0.091	-0.052	-0.306	<i>-0.421</i>	-0.282
	SL	<b><u>+0.509</u></b>	+0.316	+0.335	-	+0.188	+0.029	-0.172	-0.264	<b><u>-0.520</u></b>	<i>-0.435</i>	-0.326
	H	<b><u>+0.608</u></b>	+0.271	+0.126	-	+0.147	+0.048	-0.070	-0.294	<b><u>-0.627</u></b>	-0.285	-0.423
PD	NA	+0.105	+0.072	-0.076	+0.000	+0.253	-0.326	+0.240	+0.059	-0.159	-0.344	+0.056
	SL	+0.255	+0.224	-0.348	+0.012	+0.286	-0.166	+0.158	-0.234	-0.116	<i>-0.452</i>	-0.051
	H	<b><u>+0.500</u></b>	-0.012	-0.188	+0.053	+0.279	-0.071	-0.001	-0.146	-0.158	<i>-0.370</i>	-0.215
A	NA	-0.292	-0.228	-0.332	+0.237	<i>-0.367</i>	+0.215	+0.326	-0.084	+0.055	<i>+0.389</i>	<i>-0.020</i>
	SL	<b><u>+0.566</u></b>	+0.208	+0.016	-0.035	+0.161	+0.091	-0.169	<i>-0.352</i>	-0.095	-0.210	<i>-0.354</i>
	H	+0.288	-0.044	-0.140	+0.132	+0.270	+0.038	+0.093	<i>-0.352</i>	-0.335	+0.116	-0.037
Cloudy days (>80%)												
PN	NA	<i>-0.403</i>	-0.163	+0.253	-	+0.014	-0.140	+0.029	+0.194	+0.088	<b><u>+0.408</u></b>	-0.003
	SL	-0.103	-0.311	+0.065	-	-0.008	-0.120	+0.003	+0.142	+0.063	<b><u>+0.399</u></b>	-0.039
	H	+0.004	-0.234	+0.092	-	-0.129	-0.025	+0.017	<b><u>+0.489</u></b>	+0.117	+0.243	+0.122
S	NA	<b><u>-0.558</u></b>	-0.184	+0.254	-	-0.193	-0.175	-0.137	<b><u>+0.683</u></b>	<b><u>+0.474</u></b>	<b><u>+0.459</u></b>	<i>+0.358</i>
	SL	<i>-0.396</i>	-0.054	<b><u>+0.387</u></b>	-	+0.089	-0.329	-0.308	<b><u>+0.710</u></b>	<b><u>+0.472</u></b>	+0.332	<i>+0.396</i>
	H	<b><u>-0.655</u></b>	-0.065	+0.077	-	-0.132	-0.221	-0.037	<b><u>+0.578</u></b>	<b><u>+0.539</u></b>	<b><u>+0.386</u></b>	<i>+0.347</i>
PD	NA	<i>-0.438</i>	-0.145	+0.297	-0.117	-0.140	-0.036	+0.013	<b><u>+0.468</u></b>	+0.215	+0.183	+0.103
	SL	<i>-0.368</i>	-0.245	<b><u>+0.377</u></b>	-0.154	-0.232	-0.092	+0.004	<b><u>+0.640</u></b>	+0.148	+0.297	+0.088
	H	-0.261	-0.272	+0.130	-0.307	-0.336	-0.021	<b><u>+0.377</u></b>	<b><u>+0.487</u></b>	+0.042	+0.269	+0.059
A	NA	<i>-0.426</i>	-0.143	<b><u>+0.357</u></b>	+0.164	-0.011	-0.372	+0.087	+0.330	+0.012	-0.069	+0.000
	SL	<b><u>-0.635</u></b>	-0.233	+0.051	+0.169	-0.201	-0.132	+0.221	<b><u>+0.390</u></b>	+0.040	+0.192	+0.315
	H	<b><u>-0.513</u></b>	-0.140	+0.244	-0.023	-0.101	-0.327	+0.219	<b><u>+0.447</u></b>	+0.161	+0.212	+0.002

SZ – season, PN – the polar night, S – the spring transitional period, PD – the polar day, A – the autumn transitional period, ST – station, NA – Ny-Ålesund, SL – Svalbard Lufthavn, H – Hornsund, +0.089 – insignificant correlation, **+0.408** – significant correlation at  $\alpha < 0.05$ , **+0.468** – significant correlation at  $\alpha < 0.01$ , **+0.640** – significant correlation at  $\alpha < 0.001$ , “-” correlation not calculated due to low frequency of circulation type

station and during the polar day at Ny-Ålesund and Svalbard Lufthavn stations. During the polar night, the correlation was significant only at Ny-Ålesund station (Tab. 4).

The relation between the long-term course of clear days and atmospheric circulation are reverse to that found for cloud cover and cloudy days. Again the strongest correlations were noted in spring (Tab. 5). In that season an increase in the frequency of N+NEa type resulted in the higher number of clear days. Similar effect was found in autumn at Svalbard Lufthavn station, during the polar night at Svalbard Lufthavn and Ny-Ålesund stations, and during the polar day at Hornsund station. The cyclonic types of S+SWc, W+NWc and Cc+Bc were negatively correlated with the clear days frequency. Their impact on the variability in clear days differs depending on the season. The impact of S+SWc types is significant in autumn and during the polar night, while of Cc+Bc type – mainly in spring and during the polar day. A strong correlation was also found between clear days and S+SWc types at Hornsund and Svalbard Lufthavn station, however only in spring.

## Conclusions

The undertaken research of the annual course and seasonal variability in the cloud cover at selected stations located on the Western coast of Spitsbergen in 1983-2015 showed that atmospheric circulation is an important factor affecting the cloud cover. Despite relatively short distances between the stations, the cloud cover was diverse. Hornsund was the cloudiest station. At Ny-Ålesund and Svalbard Lufthavn stations the cloud cover was similar. The maximum cloud cover was found during the polar day and in autumn. The minimum cloud cover was characteristic of the polar night. However, it must be stressed that the assessment of cloud cover during that season is the most difficult.

The number of days with a characteristic cloud cover also varies depending on the station. The highest number of cloudless ( $N=0\%$ ) and clear ( $N<20\%$ ) days was found in Ny-Ålesund. The same applies to completely

overcast days ( $N=100\%$ ). The highest number of cloudy days ( $N>80\%$ ) was noticed in Hornsund, located furthest to the south.

The research of the relation between cloud cover and atmospheric circulation points to the following conclusions:

- The cloud cover depended on the direction of air advection. The type of pressure system was of minor relevance. The highest cloud cover over Spitsbergen was related to air advection from the southern sector regardless of a pressure system (S+SWc and S+SWa). At each station and in all seasons the lowest cloud cover was related to the types of N+NEa and N+NEc.
- In the majority of the cyclonic types, the highest cloud cover was found in Hornsund (except for W+NWc type during the polar day and in autumn). In the anticyclonic situations of S+SWa (except for the polar day at Hornsund station), W+NWa and Ca+Ka, the highest cloud cover was noticed in Ny-Ålesund. At Svalbard Lufthavn station the highest cloud cover during the polar night was related to the air advection from the northern sector.
- The impact of atmospheric circulation on the cloud cover was the strongest during the polar night (Svalbard Lufthavn and Ny-Ålesund) and in autumn (Hornsund), while the weakest – during the polar day, when the solar radiation is a crucial climate factor.
- In Spitsbergen cloudy days ( $N>80\%$ ) were dominant. These days, and completely overcast days likewise ( $N=100\%$ ), were the most probable during the air advection from the southern sector regardless the pressure system.
- The number of cloudless days over Spitsbergen was relatively low, particularly at Hornsund and Svalbard Lufthavn stations. The highest probability of these days was found at Ny-Ålesund station during the polar night and in spring during the air advection from the north-eastern and south-eastern sectors (N+NE and E+SE) regardless of the type of pressure system. These circulation types also favoured the occurrence of clear days over the whole research area.

- Atmospheric circulation significantly influences the variability in the cloud cover characteristics, and the relations change throughout the year being the strongest in spring and the weakest during the polar night. The frequency of N+NEa type is positively correlated with clear days, and negatively with cloudy days and cloud cover, while the opposite relations were found with S+SWc, W+NWc and Cc+Bc types.

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