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The origin of pine pollen grains captured from air at Calypsobyen, Svalbard

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Abstract: Spitsbergen is the largest island in the Svalbard Archipelago (Norway) that has been permanently populated. The harsh Arctic climate prevents development of large vascular plants such as trees. A two-year aerobiological survey was conducted within the framework of two consecutive polar expeditions (2014 and 2015) in Spitsbergen (Calypsobyen, Bellsund). The air quality was measured continuously from June/July to August using a 7-day volumetric air sampler, Tauber trap and moss specimens. Collected air samples and gravimetric pollen deposits were processed following transfer to sterile laboratory conditions and analyzed with the aid of light microscopy. Days when pine pollen grains were detected in the air were selected for further analysis. Clusters of back-trajectories, computed using the Hybrid Single Particle Lagrangian Integrated Trajectory model in combination with ArcGIS software as well as the Flextra trajectory model, showed the movement of air masses to the sampling location at Hornsund, and thus indicated the likely origin of pollen grains. The GlobCover 2009 and CORINE Land Cover 2012 datasets were employed to establish the distribution of coniferous forests in the areas of interest. Conclusions were drawn based on the analyses of the circulation of air masses, using visualization of global weather conditions forecast to supercomputers. For the first time, we have demonstrated that pine pollen grains occurring in pine-free Spitsbergen, could originate from numerous locations, including Scandinavia, Iceland, Siberia and northern Canada. Pollen grains were transported via air masses for distances exceeding ~2000 km. Both air samples and gravimetric pollen deposits revealed the same pattern of *Pinus* pollen distribution.

Keywords: Arctic, Spitsbergen, pollen dispersal, *Pinus* spp., long distance transport.

Introduction

Many studies have suggested that Arctic areas are undergoing the fastest changes as a result of global warming (Yao *et al.* 2012 and references therein). A 30-year weather measurement record taken at Spitsbergen showed an increase in the mean air temperature of 2–3°C (Nordli *et al.* 2014). As a result of the increase in temperature, the limit of the occurrence of forest communities may shift to the north, as it happened in the mid-Holocene (Nichols 1967). Therefore research on the long-distance transport and deposition of tree pollen in the Arctic is important. The environmental conditions in Arctic areas facilitate studies of the long distance transport of bioaerosols, such as foreign pollen grains and spores (Nichols *et al.* 1978; Campbell *et al.* 1999; Rousseau *et al.* 2008; FAO 2010; Nichols and Stolze 2017).

A limited number of aerobiological surveys have been carried out at Svalbard Archipelago and in the Arctic areas in general. In 1957, Środoń (1960) examined pollen deposited on mosses during the scientific expedition to Hornsund (West Spitsbergen). He found *Pinus* spp. (hereafter *Pinus*) pollen to be the main component of long distance transport, which he connected to hurricane winds blowing from the direction where *Pinus* stands in Scandinavia were located (750 km away) (Figs. 1 and 2). *Pinus* occurred in all pollen spectra in various proportions ranging from *ca.* 0.5% at lower elevations (15 m a.s.l.) to *ca.* 34% in higher ones (500–730 m a.s.l.). In the 1980s, van der Knaap (1987, 1988) studied long distance transport of pollen in Spitsbergen and Jan Mayen, which resulted in a calculation of long distance pollen deposition at a rate equal to 2–6 grains cm^2 yr^{-1}. Other summer surveys took place at Ny-Ålesund, Spitsbergen (Johansen and Hafsten 1988), and at Nuuk, Greenland (Porsbjerg *et al.* 2003).

A long-term survey was conducted at Reykjavík, Iceland where the observations were recorded continuously from 1988 to 1997 (Hallsdóttir 1999). Johansen (1991) called for more studies that would determine different sources contributing to the total pollen spectrum at Svalbard. Since then, more than 20 years have passed, thus there is a need for a new investigation which could determine whether or not any changes in the air quality in Svalbard took place in

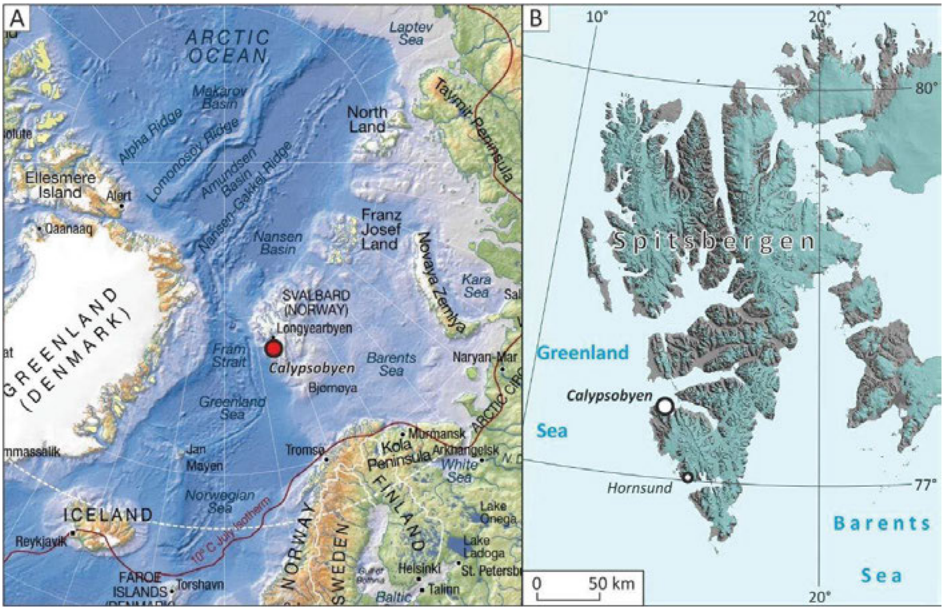

Fig. 1. Location of the test site in the Arctic (**A**), source: UNEP/GRID-Arendal) and in Svalbard (**B**).

parallel to changes in the global land cover. The most recent palynological studies, which were carried on in Svalbard, focused on the plant taxonomy and morphology of the pollen grains that were collected directly from the anthers.

To date, 184 plant species have been identified and described in Svalbard that are native to this Arctic archipelago. The vascular flora comprises in total of 164 species (FAO 2010; Yao *et al.* 2012, 2014). However, the number of species varies between different islands. According to the inventory that was carried out near Spitsbergen, *i.e.*, in Bjørnøya Island, 54 species were found (Engelskjøn 1986). Four woody species occur at Svalbard, and these are *Betula nana* subsp. *tundrarum* (dwarf birch), *Salix herbacea* (dwarf willow, snowbed willow), *Salix lanata* (woolly willow) and *Salix polaris* (polar willow). Although, these species have been classified to the group of trees taxonomically, they are in fact shrubs, *i.e.*, the maximum achieved heights are <1.2 m (*B. nana* subsp. *tundrarum*, *S. lanata*) and <10 cm (*S. polaris, S. herbacea*) and the Svalbard Archipelago in considered as non-forested (FAO 2010).

The aim of this work was to study the air quality regarding the presence of pollen grains and, when detected, to establish their origin. To ensure that the results of the monitoring covered the overall pollen spectrum available at Calypsobyen, Spitsbergen (2014–2015 summer seasons), the study included three types of samples: (*i*) Hirst type volumetric spore traps, (*ii*) gravimetric pollen deposits in Tauber traps and (*iii*) gravimetric deposits on moss specimens.

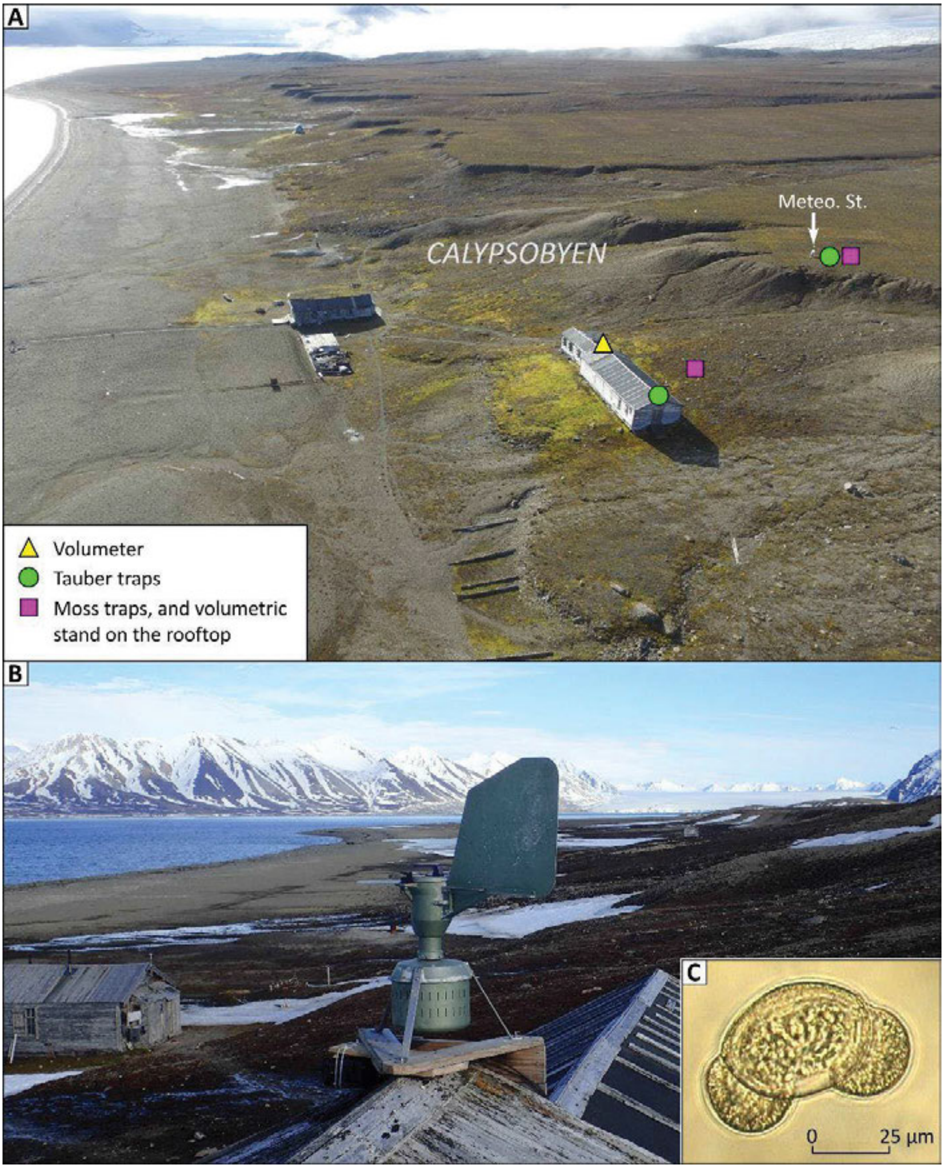

Fig. 2. **A–B -** Location of pollen traps in Calypsobyen (Photo: P. Zagórski and J. Rodzik); **C -** *Pinus* pollen (Photo: B. Żuraw).

Study site

Spitsbergen is the largest (39 000 km^2) and most mountainous (up to 1717 m a.s.l.) island in the Svalbard Archipelago (Fig. 1). Its western coast is surrounded by the waters of the Greenland Sea, the eastern coast by the Barents Sea, the southern coast by the Norwegian Sea, and the north by the Arctic Ocean.

Spitsbergen is also the northernmost inhabited land in the world with a population of 2600. The climate of the Svalbard Archipelago is subarctic maritime, more mild on the western coast. Thermal and precipitation patterns are mostly shaped by the Icelandic low pressure system, as well as the "warm" West Spitsbergen Current. The eastern part of Spitsbergen is under influence of cool air masses blown from the Arctic Ocean in the North Pole Basin (Johansen and Hafsten 1988; Zagórski *et al.* 2013).

The Stanisław Siedlecki Polish Polar Station in Hornsund reported an annual mean temperature of −4.3°C and annual precipitation of 434 mm. Monthly mean temperatures in January and July equal to −10.9°C and 4.4°C, respectively. East winds prevail, being especially strong in winter, usually with the characteristics of foehn wind, but in the summer months air masses mostly flow from the south and west directions (Marsz and Styszyńska 2013; Osuch and Wawrzyniak 2016). Snow cover begins to form in the end of August (Yao *et al.* 2012).

The survey was conducted at the Polar Station of Maria Curie-Skłodowska University in Calypsobyen. It is located on the west coast of Spitsbergen, in the north-western part of Wedel Jarlsberg Land, where the Bellsund connects three internal fjords with the Greenland Sea (Fig. 1). This area is shielded by mountainous ridges (500–800 m a.s.l.) from the south-west direction, from where moist air masses usually blow. The distance to the northernmost point of the mainland of Norway (Cape Nordkinn) is *ca.* 800 km.

Materials and methods

Pollen survey. — Air quality measurements were taken simultaneously using a 7-day volumetric air sampler of the Hirst design (Hirst 1952) (Fig. 2B). This device enables a continuous record of both organic and non-organic particles suspended in the air, which can be further analysed using an hourly, bi-hourly or 24 h time scale under a light microscope. The air sampler was co-located with the weather station (77°33'30" N, 14°31'01" E) and it was placed at 5 m above ground, and 23 m a.s.l. The airborne particle sampling was carried out over two consecutive summers; from 8 July to 18 August, 2014 and from 16 June to 5 August, 2015.

Particles were actively collected with an airflow of 10 L min^{-1} on to a tape coated with adhesive, which was fastened around the drum and placed inside the sampler. A clock mechanism ensured the drum rotated at a constant speed of 2 mm h^{-1} with a full drum rotation completed every 7 days. The drum was changed on weekly basis, at the same day and hour and further processed under sterile laboratory conditions, after return from the expedition. The collection tape was cut into 48 mm long segments, each corresponding to 24 h periods of time, and stained using basic fuchsin. This stain aids in the discrimination of pollen grain wall structures based upon which plant taxa can be identified. Pollen grains were identified at the genus level and counted on 2 longitudinal transverses, under ×400 magnification. Subsequently, daily pollen counts were multiplied by a microscope specific Correction Factor (Lacey and West 2006) in order to determine the pollen concentration, *i.e.*, number of pollen grains per cubic meter of air, abbreviated to pg m^{-3}.

Additionally, pollen deposition was monitored using two Tauber-style traps (plastic 5 L containers with a 4 cm diameter) according to the method described by Hicks *et al.* (1996). One of them was placed on the roof of the Research Station building, close to the Hirst volumetric sampler and operated for a 2-year summer periods (2014 and 2015). The other one was buried in the ground, so that the opening was slightly above the ground surface, in the patchy tundra plant community close to the meteorological station, and operated in 2015. Studies were conducted according to the guidelines of the Pollen Monitoring Programme (Hicks *et al.* 1996). The annual pollen deposited in the trap was subjected to laboratory treatment: filtering, heating in 10% KOH, and acetolysis. In each year, a moss sample of *ca.* 5 cm diameter was collected from tundra adjacent to each of the traps. The moss samples were boiled in 10% KOH, shaken and sieved through a coarse sieve to release pollen. Pollen grains, suspended in the solution, were extracted using the same techniques as for the trap samples.

Coniferous tree distribution, source of pollen. — The first distribution map of the coniferous forest was produced based upon the GlobCover 2009 dataset (v. 2.3). The applied resolution was equal to 300 m (Fig. 3A). A better resolution map, available for the European countries only, was produced using the CORINE Land Cover (CLC) 2012 dataset (EC 2013) (Fig. 3B). Two classes were extracted from this dataset: #312 representing distribution of coniferous forest (*green*), and #313 representing the mixed forest areas (*red*). The applied grid was equal to 100 m. Finally, the distribution map of *Pinus sylvestris* was made available thanks to the European Forest Institute (Brus *et al.* 2011) (Fig. 3C).

With regard to the national forest inventories, there are two common species of pine in Sweden, *i.e.*, *P. sylvestris* (Scots pine) and *P. contorta* (Lodgepole pine) (Swedish Forestry Agency 2016). In the case of Norway, the Scots pine is a native species in this country, while the Lodgepole pine, originally growing in the western part of North America, has been introduced by foresters. Another alien species is *Pinus mugo* subsp. *mugo* (mountain pine), which came from the mountainous areas in southern Europe (Gederaas *et al.* 2012). In the case of Iceland, all pine species, *i.e.*, *P. albicaulis*, *P. cembra*, *P. flexilis*, *P. mugo*, *P. sibirica*, *P. sylvestris* have been artificially introduced since the only native species to this country are *Betula pubescens* and *Betula nana* (Dammert 2001; Guðjohnsen pers. comm.). Out of all listed pine species, *P. contorta* has been planted all over the lowlands of Iceland over the past 60 years (*ca*. 15–20% of the 1000–2000 ha annually afforested). Other pine species have long been a minor component of the annual planting effort (Sigurgeirsson pers. comm.).

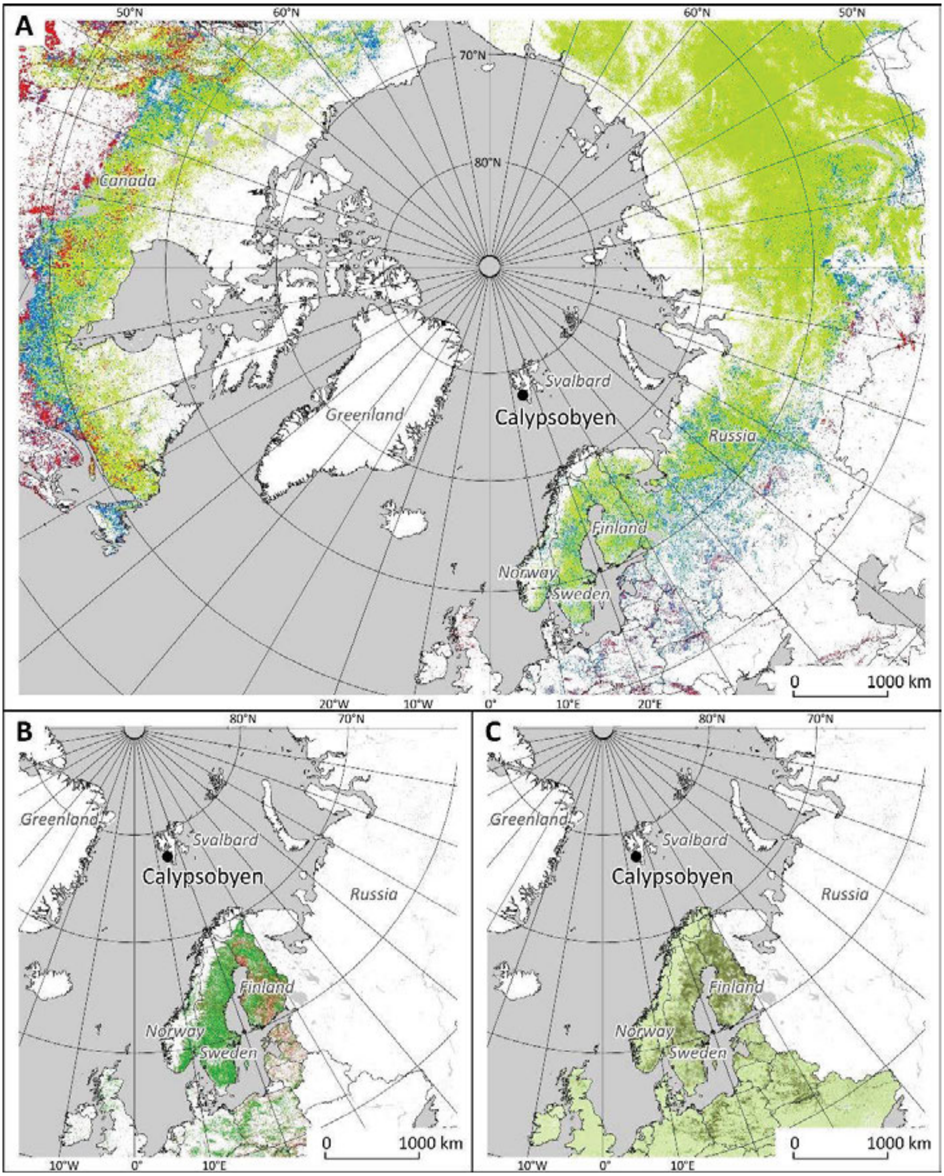

Fig. 3. **A** - distribution of coniferous forest in the northern hemisphere (GlobCover 2009). Selected classes are shown: open (15–40%) needleleaved deciduous or evergreen forest (green), closed (>40%) needleleaved evergreen forest (red), closed to open (>15%) mixed broadleaved and needleleaved forestand (blue), and water bodies (grey); **B** - distribution of coniferous (green) and mixed forest areas (red) based upon the CORINE Land Cover (CLC) 2012 dataset; **C** - distribution map of *Pinus sylvestris* (Scots pine) produced by the European Forest Institute (Brus *et al.* 2011).

Back-trajectory analyses. — The analysis of the movement of air masses to the sampling point was carried out using both the NOAA HYSPLIT Trajectory Model and the FLEXTRA trajectory model (Fig. 4). Kinematic 3D backward

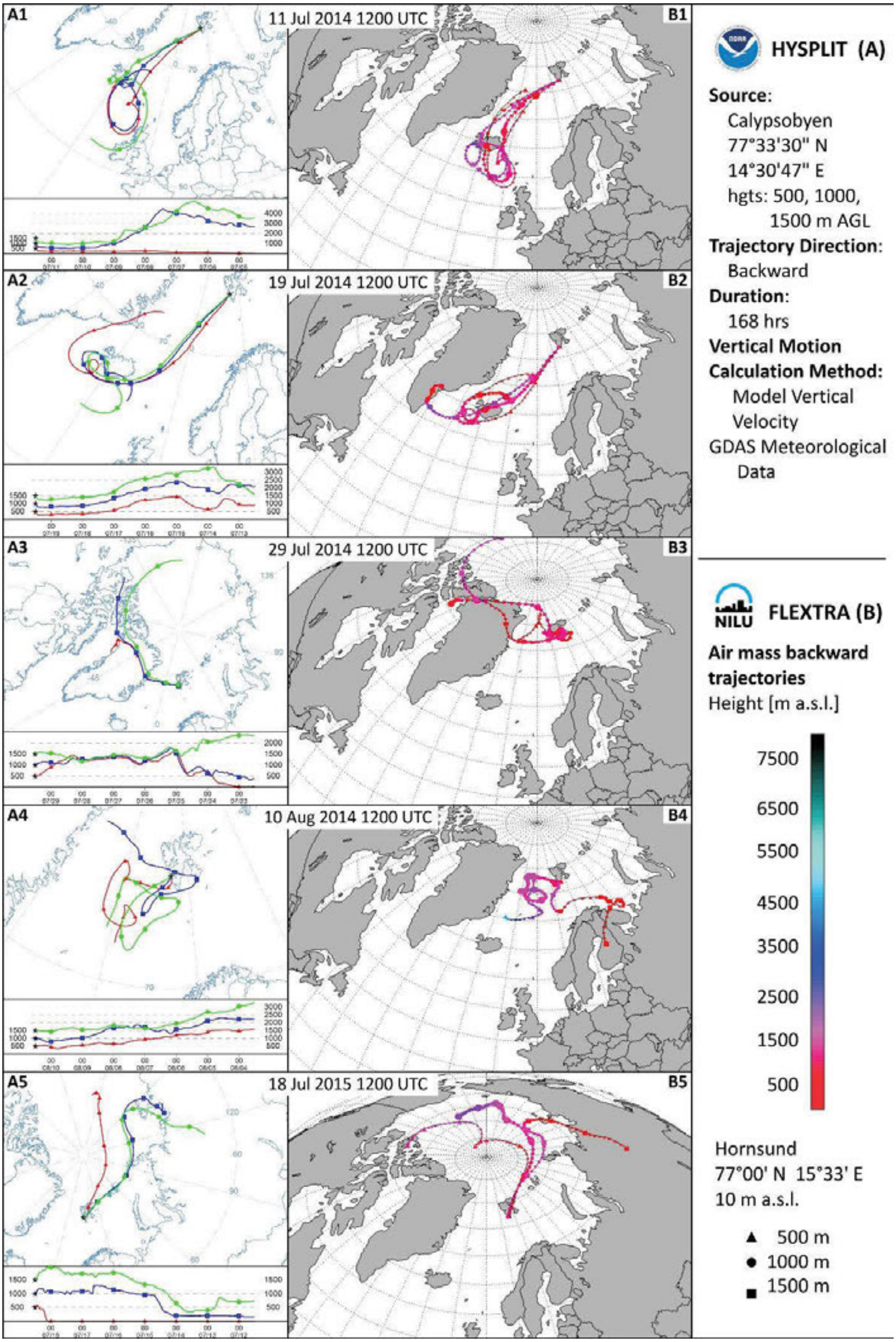

Fig. 4. Back trajectory simulation for separated events at Calypsobyen: **A1–A5** - according to HYSOLIT; **B1–B5** - according to FLEXTRA.

trajectories were generated to examine the origin of the air masses on the days, when *Pinus* pollen grains were detected in the air at Calypsobyen. Thus, the following days in July 2014 (11–12, 18–20, 28–29, 31), in August 2014 (6, 9–11) and in July 2015 (18) were subjected to analysis (Fig. 5A).

The HYSPLIT model (http://ready.arl.noaa.gov/HYSPLIT.php) enables a simple evaluation of the source–receptor dependencies by drawing pathways, which reflect the flow of air masses in time (Stein *et al.* 2015 and references therein).

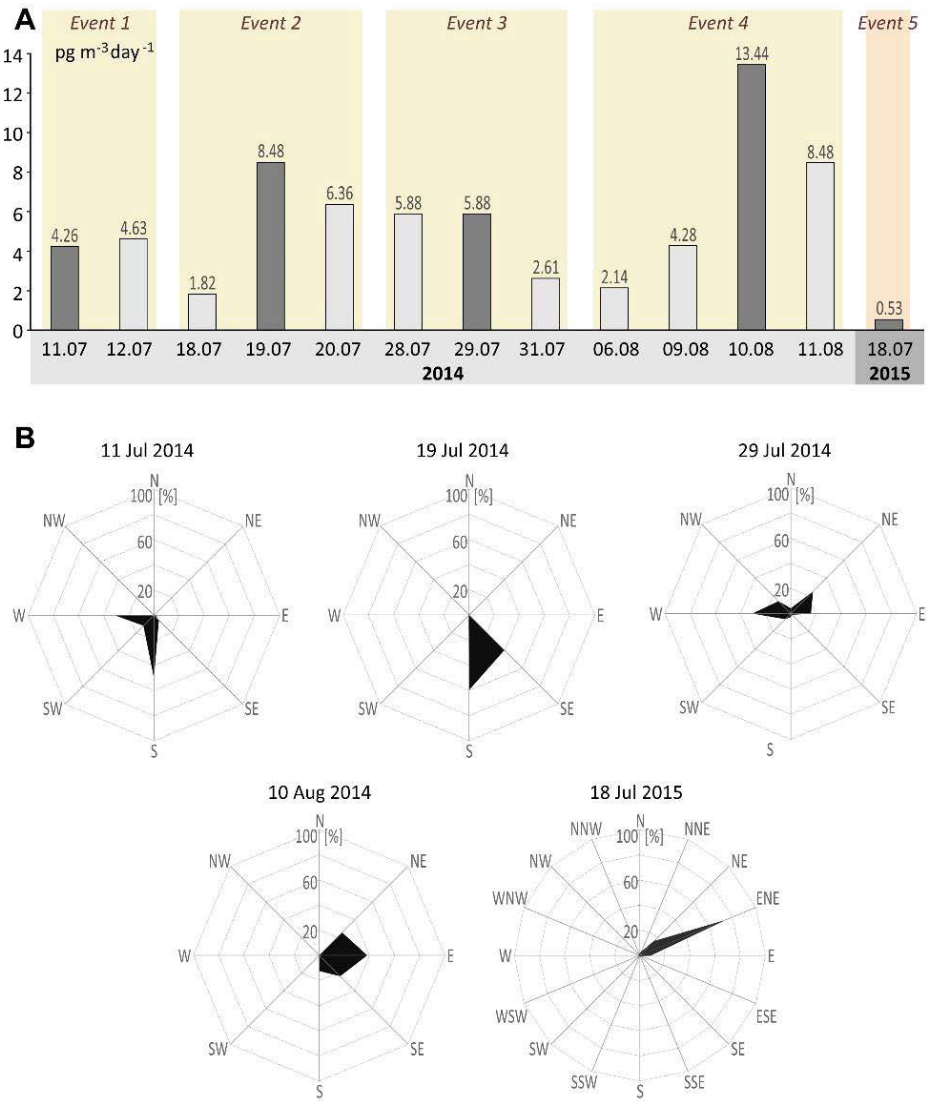

Fig. 5. Concentration of all *Pinus* pollen in Calypsobyen in 2014 through 2015 (**A**), shaded areas show different events. **B** - wind rose diagrams for selected days.

Since a single trajectory may not accurately show the turbulent mixing processes, which air parcels experience during transit, all the computed trajectories were aggregated and analysed jointly. This results in a reduction of the uncertainty regarding the determination of the atmospheric transport passage (*e.g.*, Hernández-Ceballos *et al.* 2011). The weather data used for the trajectory calculation was derived from the Global Data Analysis System (GDAS) archives, which are maintained by the National Oceanic and Atmospheric Administration (NOAA) and the Air Resources Laboratory (ARL). Air mass trajectories for Calypsobyen were plotted 168 hours back in time (starting from 12:00 h UTC), with 1 h intervals, at 500, 1000, 1500 m height above ground level (a.g.l.) (Figs. 4A1 to 4A5).

The origin of air masses arriving in Svalbard were examined using the FLEXTRA trajectory model which also enables tracking the paths of pollen produced by coniferous forests (Stohl *et al.* 1995; Stohl and Seibert 1998). The model was accessed using the webpage (www.nilu.no/trajectories) of the Norwegian Institute for Air Research (NILU). The FLEXTRA model produced backward trajectories of air mass based on meteorological data from European Centre for Medium Range Weather Forecasts (ECMWF). Trajectories were computed every 6 h for the location nearest to the air sampler, in Hornsund (about 70 km SSE of Calypsobyen), Spitsbergen with a spatial resolution of 1.25 degree (Figs. 4B1 to 4B5). The accuracy of the trajectories is typically of the order of *ca*. 20% of the travel distance (Stohl 1998), but uncertainties in individual models can be also much larger due to turbulence in the boundary layer. To overcome this and to minimize the possible error, three trajectories arriving at different elevations (500 m, 1000 m and 1500 m) are computed simultaneously for the same location. Depending on the weather conditions present at that time, their range can either underestimate or overstate the potential area of the air mass origin, however it provides a good estimate of the overall air mass passageway.

Circulation of air masses. — The direction and height of movement of air masses that were able to carry pollen grains over long distances (*ca.* 1500 m a.s.l.) depend on the prevailing pressure system (Appendix 1). This type of analysis, based on visualization of global weather conditions updated at intervals of three hours, was elaborated by Cameron Beccario (https://earth.nullschool.net/). A seven-day back analysis was compiled for selected events.

Meteorological data. — Weather data were collected using an Aster/VAISALA METmini 5 weather station in 2014 and Davis weather station in 2015, located on a flat marine terrace at the level of 23 m a.s.l. (77°33’30”N, 14°30’47”E). The following meteorological parameters were measured: air temperature and relative humidity at 0.2 m a.g.l., air temperature at 0.05 m a.g.l., rainfall at 1 m a.g.l., wind speed and wind direction at 7 m a.g.l. In addition, presence of mist, visibility and degree of cloudiness were recorded. However, in this study only the measurements of wind speed and wind direction were used for the analysis. More information on the weather data collected during the summer campaign in 2014 can be found in Mędrek *et al.* (2014).

Statistical evaluation. — The relationship between pollen concentration and wind direction and wind speed was examined using Spearman's rank test (Fig. 6). In addition, the Seasonal Pollen Index (SPI) was calculated, which comprises a sum of daily mean pollen concentrations measured throughout one year of survey. The SPI is reported without units.

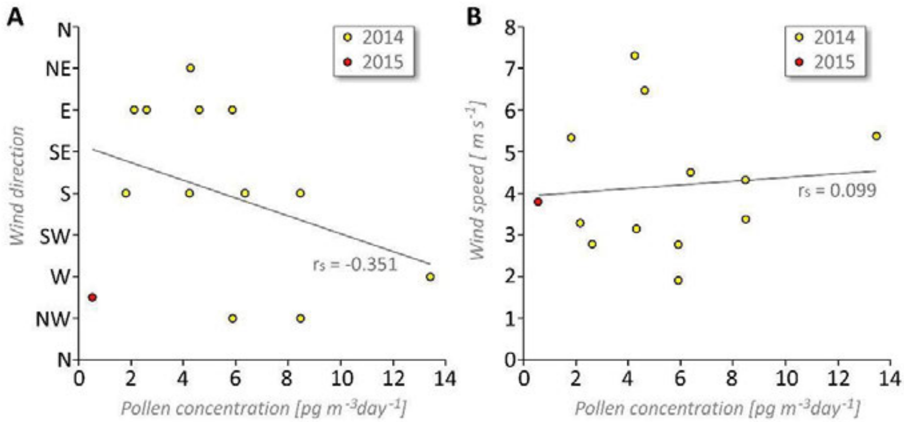

Fig. 6. *Pinus* pollen concentration in a response to changes in (**A**) wind direction and (**B**) wind speed measured during summer campaigns in 2014 and 2015 at Calypsobyen.

Results

Pollen occurrence at Calypsobyen. — Out of a total of six identified pollen taxa in the aeropalynological spectrum of Spitsbergen, the *Pinus* genus was found to be the most prevalent (51%) (Table 1). Other significant contributions, equal to 41%, comprised jointly pollen of *Oxyria* and *Saxifraga*, which represented local vascular flora (Table 2). During the first year of the study, *Pinus* pollen was detected on 12 days, while in the following year only on a single day (Fig. 5A). In 2014, pollen was detected over a one-month period, between 11 July and 11 August, with 2–3 day gaps between observed occurrences. The total SPI in 2014 was equal to 68.23, while in the following year it was 0.53. The maximum pollen concentration throughout the entire survey occurred on 10 August, 2014 reaching 13.44 grains m^{-3} (Fig. 5A).

Pollen spectra collected by Tauber traps were very meagre (Table 1). *Pinus* pollen was the main component of foreign origin both in Tauber traps and in moss samples. In 2015, no *Pinus* pollen was collected by the Tauber traps. Moss samples yielded from 36 to 38 pollen grains in 2015, but the spectra represented mainly local herbaceous vegetation. The largest number of pollen taxa was recorded in moss near the meteorological station, adjacent to the trap buried at soil level. The prevailing pollen taxa were *Saxifraga oppositifolia*, *Salix polaris*, *Cerastium* spp. and *Silene* spp., which are abundant in the surrounding tundra.

Table 1.

Pinus pollen grains in the total amount of pollen and spores collected by Tauber traps and moss samples in Calypsobyen, Spitsbergen in 2014–2015.

Trapping medium	Year / Location	Number of *Pinus* pollen grains	Total number of pollen grains and spores
Tauber trap	2014/ roof of the research station building	5	8
	2015/ roof of the research station building	0	0
	2015/ meteorological station	0	5
Moss samples	2014/ close to the research station building	1	3
	2015/ close to the research station building	4	36
	2015/ meteorological station	0	38

Table 2.

Pollen and spore types collected by moss samples in the Calypsobyen in 2014–2015.

Pollen/plant spore type	Number of grains/spores		
	2014 close to the research station	2015 close to the research station	2015 meteorological station
Alnus		1	
Betula undifferentiated		2	
Caryophyllaceae undifferentiated			1
Cerastium type			8
confer *Cerastium* type (destroyed)			1
Cyperaceae		1	
Pinus sylvestris type	1	4	
Poaceae		1	
Polygonum viviparum		5	
Salix polaris type		6	2
Salix undifferentiated (destroyed or crumpled)		5	16
Saxifraga granulata type			2
Saxifraga oppositifolia type		1	6
Silene type			1
Musci spores	2	4	
Indeterminable		6	1
Total	3	36	38

Back trajectory analysis modelling. — At Calypsobyen, pine pollen was recorded essentially in 4 events in 2014 and one in 2015 (Fig. 5A). Five days were selected for spatial analysis, for which the source areas of the inflow of air masses were determined using HYSPLIT and FLEXTRA modelling. The determination of their trajectory was supported by the analysis of the variability of the atmospheric circulation up to 7 days ago and the meteorological data from the Calypsobyen Polar Station. Back trajectory analysis (Fig. 4) was conducted for five time-intervals: 4–11 July 2014, 12–19 July 2014, 22–29 July 2014, 2–10 August 2014 and 11–18 July 2015, representing events 1 through 5, as follows.

Event 1; 4–11 July 2014. — On 4 July and 5 July, high-pressure systems were present over Greenland, the Barents Sea and the European part of the Russian Arctic. A well-developed cyclone occurred south of Iceland and east of Novaya Zemlya, while a weaker centre of low pressure was found over Scandinavia (Figs. 4A1, 4B1; Appendix 1). On 7 July, extensive high-pressure area (HPA) anticyclone from the Russian Arctic moved over Scandinavia. At the same time in the south of Iceland there was a low-pressure area (LPA) cyclone, which persisted until 8 July and dissipated on 9 July. On the same day, in the south of Svalbard, the HPA was noted in effect, which drew the air masses from Scandinavia and Iceland. On the following day (10 July), the system moved to the south over Scandinavia, but two more LPAs began to develop. On 10 July, an extensive HPA was observed over Scandinavia, which directed air masses westwards, and then northwards, when air masses arrived over the Norwegian Sea. At this time, there were two centres of LPA: over Iceland and NE of Svalbard. On the next day (11 July), the LPA expanded in area and moved over southern Iceland and NE of Svalbard. Concurrently, the HPA over Scandinavia moved towards the SE of Finland. With this arrangement the air masses were pushed northwards from Scandinavia towards Svalbard. Summarising, during this period of observation, the main air masses were moved from Island and the British Isles, possibly also from southern Scandinavia, and then, through the Norwegian Sea on its W side to the N, and finally via the Greenland Sea over Svalbard. Meteorological data from 11 July for Calypsobyen indicates that two dominant wind direction of S (50.0%) and W (31.3%) and its daily average speed was 4.1 m s^{-1} and the maximum of 6.3 m s^{-1} (Fig. 6). The probable sources of pine pollen grains on this day would have been southern Scandinavia (Figs. 4A1 and 4B1).

Event 2; 12–19 July 2014. — Between 12 July and 14 July, the HPA areas stretched over Greenland, the Greenland Sea and the White Sea, and the European part of the Russian Arctic. In contrast, the LPAs occurred over Ireland and north of Novaya Zemlya (Figs. 4A2, 4B2; Appendix 1). After them, on 15 July, a strong HPA formed over Svalbard, while on Iceland and the Norwegian Sea LPAs were prevailing, consequently, air masses were directed from northern Scandinavia to Spitsbergen. On subsequent days (16–17 July), an HPA moved towards the south, over northern Scandinavia. In turn, the Icelandic LPA diminished and dispersed into several smaller areas of low pressure. Starting from 18 July, a vast and relatively stable HPA developed over the entire Scandinavia and parts of the Barents and Norwegian seas. Small LPAs formed westwards of the British Isles and Iceland but were of marginal impact. It was not until 19 July when a more substantial system was observed west of Iceland. Meteorological data from 19 July for Calypsobyen indicate that two dominant wind directions were S (59.7%) and SE (39.6%) with a daily average speed of 5.4 m s^{-1} and the maximum of 10.2 m s^{-1} (Fig. 6). With such atmospheric pressure systems, air masses were moved from the areas of north-eastern Canada and from Iceland, the Norwegian Sea and Greenland Sea to Spitsbergen. It is also possible that a significant part of the captured pollen grains was incorporated into this main stream of air from the air mass originating from Scandinavia (Figs. 4A2 and 4B2).

Event 3; 22–29 July 2014. — In the period preceding the detection of the majority of pollen grains, the trajectories indicate movement of air masses originating from Greenland and northern Canada. The atmospheric conditions in this period was complex (Figs. 4A3, 4B3; Appendix 1). On 22 July, the centres of HPA were developed over Scandinavia, Svalbard and on Greenland. A strong LPA developed over Svalbard and to the north of it, and a smaller centre appeared to the west of Iceland. In this situation, air masses were coming to Svalbard from the north, north-west and south. On 25 July, the situation was similar with the exception that the LPA located north of Svalbard was weaker. On the following days (26–28 July), the Scandinavian HPA moved to the SE and was replaced by an LPA. In turn, the LPA over Iceland expanded and moved eastwards. Svalbard and the area south of it was encompassed by the zone of an HPA. Starting on 29 July, the LPA migrated from the NE towards Svalbard. Meteorological data from 29 July for Calypsobyen indicates that two dominant wind directions were W (30.6%) and NE (25.0%) with daily average speed of 1.9 m s^{-1} and the maximum of 4.2 m s^{-1} (Fig. 6). In this situation, the air masses were pushed to Svalbard from the NW and W. Summarising, the most likely origin of pine pollen grains were northern Canada and Siberia (Figs. 4A3 and 4B3).

Event 4; 2–10 August 2014. — Starting from 2 August, the air pressure system was quite stable. Two strong HPAs occurred over Scandinavia and Greenland while a much weaker centre was observed at first over Iceland and then, after moving northwards, over the Greenland Sea (Figs. 4A4, 4B4; Appendix 1). A very strong LPA was located NE of Svalbard. It lasted until 6 August and then it was initially driven eastward and later on pushed northwards, due to an Arctic wedge of HPA. The other two centres of LPA occurred in the west of Iceland and over the British Isles. In the next days, these both moved to the north. Summarising, with this configuration of pressure systems influencing the air masses over Svalbard, pollen grains most likely originated from Scandinavia. In the period before successful sampling of pine pollen grains, two strong centres of LPAs were found. The first was initially located in the south of Iceland and then it expanded. On 10 August, it covered the area of the North Sea and the southern part of the Norwegian Sea. The second LPA occurred east of Svalbard and the Novaya Zemlya, with its centre located over Taymyr Peninsula. From 6 August, the areas from Greenland, via the Greenland Sea and up to Scandinavia were under the influence of an HPA. In the following days, however, this HPA gradually diminished in magnitude, at first over Scandinavia (8 August) and then over Greenland (10 August). Soon after, an HPA started to develop over Svalbard. Meteorological data from 10 August for Calypsobyen indicate tree dominant wind directions of E (38.2%), NE (25.7%) and SE (23.6%) with a daily average speed of 3.2 m s^{-1} and the maximum of 7.0 m s^{-1} (Fig. 6). The main air masses carrying pine pollen grains were moved from Scandinavia (Fig. 4B4). However, the Hysplit Model shows, ambiguously the direction (Fig. 4A4).

Event 5; 11–18 July 2015. — At the start of this period (11 July) there were HPAs west of Svalbard, centred over Greenland (Figs. 4A5, 4B5; Appendix 1). In contrast, an LPA dominated to the east of Svalbard. On 14 July, a large LPA, with its centre located over Novaya Zemlya, caused movement of air masses from the north to Svalbard. On the following days (18 July), it was fragmented into several smaller LPAs. The largest one, located south of Svalbard, was moving from NE to SW. Meteorological data from 18 July for Calypsobyen indicate dominant wind direction of ENE (71.2%) with a daily average speed of 3.8 m s^{-1} and the maximum of 8.5 m s–^{1} (Fig. 6). Such a pressure system caused movement of air masses from the arctic regions of Russia towards Svalbard. There were no winds from Iceland in this period of time. Pine pollen grains may have come from Siberia and/or from Canada (Figs. 4A5 and 4B5).

Figure 6 shows the pattern of *Pinus* pollen deposition, whose concentration was plotted against wind speed and wind direction. The results indicate that *Pinus* pollen was largely detected on days when wind speed did not exceed 5 m s^{-1}. However, with regard to the impact of wind direction, the majority of pollen occurred in the air of Calypsobyen when the wind was blowing from the south, although this was in lower concentrations (Fig. 5). The Spearman rank test showed no statistically significant correlation between *Pinus* pollen concentration and wind direction (r_s= −0.351) or wind speed (r_s= 0.099) variables (Fig. 6).

Discussion

Long-distance pollen transport in the polar conditions. — Our results indicated that *Pinus* pollen travelled a distance of almost 2000 km from Iceland to Spitsbergen (Fig. 4). Other studies provided evidence for a distance of 300–400 km that separates Sweden from countries on the south side of the Baltic Sea (Lindgren *et al.* 1995), and 3000 km for transport from Quebec to Repulse Bay in Canada (Campbell *et al.* 1999). Changes in the air temperature induce turbulence and an increase in wind speed that facilitates release and uplift of particles, such as pollen grains, into 2000 m and their further transport (Lindgren *et al.* 1995; Jackson and Lyford 1999).

Morphological features enabling successful long dispersal of particles include: wall structure, special appendages, size, weight and overall aerodynamic shape. In the case of *Pinus*, pollen grains are equipped with two saccis located on the sides of the grain, which have an overall elliptical shape. Eisenhut (1961; after Jackson and Lyford 1999) reported that although *Pinus* and *Picea* pollen grains were very similar in size and overall shape, they differed in their weight. This resulted in contrasting settling velocities for each genus. Fall speed of *Pinus* pollen was estimated at 3.1–4.5 cm s^{-1} (*Pinus sylvestris* 3.7 cm s^{-1}), while for *Picea* pollen at 5.6 cm s^{-1}. These traits have implications for dispersal range. With the given settling velocity and the maximum height to which pollen could be lifted, it would take 15 h for *Pinus sylvestris* pollen grains to be deposited on the ground. Hicks (2001) suggested that a value of <300 *Pinus* pollen grains cm^{-2} yr^{-1} can be estimated as the threshold value for the absence of *Pinus* trees within 10 km range from the trapping site. In still air conditions, it has been established, through empirical testing, that *P. sylvestris* pollen could be dispersed at a distance of 75 km (Dyakowska 1959). However, under favourable weather conditions, *Pinus* pollen is very likely to be transported at much greater distances.

Tracing pollen-climate relationship. — In our research, the difference in numbers of *Pinus* pollen grains detected in years 2014 and 2015 appeared. Long-term observations on the occurrence of *Pinus* pollen in Sweden showed a very high correlation with the air temperature, number of sunshine hours, wind speed and changes in the air pressure (Atkinson and Larsson 1990). Similarly, Jackson and Lyford (1999) indicated that majority of the *Pinus* pollen was released between midday and afternoon hours on dry and warm days. With respect to pollen production, Hallsdóttir (1999) reported that this was greatly related with the air temperature toward the end of summer in the previous year. Furthermore, a 10-year pollen survey conducted in Sweden showed a 3-year cycle in distribution of *Pinus* pollen in the air (Atkinson and Larsson 1990). A similar pattern was also observed in *Betula* pollen concentration measured in Iceland, although a 2-year cycle was previously reported for the same genus in the European mainland (Hallsdóttir 1999). The highest maximum pollen count captured in Iceland also occurred at different years than in the continental Europe. Thus, Hallsdóttir (1999) suggested that delay in the biological cycles of both coniferous and deciduous trees was related with the polar climate rather than genetic variability. On the other hand, Weryszko-Chmielewska and Piotrowska (2007) stated that *Pinus* trees can make breaks of up to 6 years between flowering seasons. This would also explain the difference in numbers of *Pinus* pollen grains detected in years 2014 and 2015 in Calypsobyen. In countries of temperate climate, *Pinus* blooms from May to June (Weryszko-Chmielewska and Piotrowska 2007). Similar observations were reported by Guðjohnsen (personal communication) who conducts airborne pollen monitoring in Akureyri and Gardabaer, Iceland. However, further north, the same taxon may flower later, from the second or third week of June to the beginning of August (Johansen 1992; Lindgren *et al.* 1995). Since we trapped pollen in July and August, this would implicate the origin of pollen from areas of a cooler climate, such as northern Norway.

Differences in the pollen collection by various trapping media. — In our samples, *Pinus* pollen dominated and constituted 51% of total number of pollen grains. We also detected pollen of *Betula* and *Alnus*. Porsbjerg *et al.* (2003) did not detect a single grain of *Pinus* pollen throughout a 3-year survey in Greenland. The location of the air sampler at a height of 1.5 m above ground level could be a possible explanation, since in continental Europe traps are usually placed on rooftops at 10−30 m height. However, at 4 different locations in Greenland, Rousseau *et al.* (2008) trapped *Pinus* pollen in 2004 and 2005 that originated from North America. Trapping experiments were performed at the ground level. Overall, *Pinus* pollen constituted 32% of total observed exotic pollen. Further north, after a 4-month summer monitoring at Jan Mayen Island, Johansen (1991) identified 10 pollen taxa, of which *Betula* pollen constituted the largest proportion. With regard to *Pinus*, only a single grain was collected, on 4 July. The author suggested that *Betula*, *Castanea* and *Pinus* pollen must be delivered through a long-distance transport, most likely from Iceland, North America or Greenland. Previous airborne pollen survey at Spitsbergen (Ny-Ålesund) noted 4 pollen taxa of foreign origin: *Pinus*, *Betula*, *Juniperus* and *Alnus* (Johansen and Hafsten 1988). The contribution of *Pinus* pollen was 4.3%.

Annual pollen sums of *Pinus* collected in Calypsobyen by mosses are comparable with values obtained by van der Knaap (1988), where the number of long distance transported pollen grains was 2–6 grains cm^{-2} yr^{-1}. However, *Pinus* pollen production exhibits dramatic year-to-year variations, controlled largely by July temperatures of the previous year (Hicks 2001; van der Knaap *et al.* 2001; Pidek *et al.* 2010). Modelling approaches to pollen-vegetation relationships in SE Poland revealed that a major proportion of *Pinus* pollen collected by Tauber traps was deposited up to 4.5 km from the source area (Poska and Pidek 2010). This was also observed in samples collected using volumetric air samplers (Pidek *et al.* 2010). Thus, the results of the present study, where *Pinus* was the main component of foreign pollen, confirm the above mentioned findings on the exceptional ability of pine pollen to be long-distance transported and support the results of Środoń (1960) and van der Knaap (1987, 1988), whose research led to similar conclusions. Furthermore, when comparing two trapping media, *i.e.*, Tauber traps and mosses, results reported by Pardoe *et al.* (2010) showed that pollen deposition in mosses compared best to average pollen deposition in pollen traps throughout a 2-year period of pollen deposition. The same authors observed a tendency for bisaccate pollen, including *Pinus*, to reach higher percentages in moss samples compared to adjacent pollen traps (Pardoe *et al.* 2010). This fact can explain the higher number of *Pinus* pollen grain numbers in mosses in 2015. Due to very low number of *Pinus* pollen grains in the present study, it is hard to support the statement made by Levetin *et al.* (2000) that the results obtained by volumetric air sampler agree well with the ones obtained by Tauber traps, although such a coincidence was previously reported also by Ranta *et al.* (2007).

A small amount of pollen collected by our trapping media in Calypsobyen does not pose an allergic risk, but it can be expected that toxic air pollutants from industrial centres located near the polar circle may be transported in a similar way. This fact leads to another field of the future studies.

Conclusions

Based on the analysis of pollen material collected by various methods, *i.e.* volumeter, Tauber traps and collecting from the moss surface, at Calypsobyen in the SW Spitsbergen of the Svalbard Archipelago, the distribution of pine forests in subpolar regions as potential sources of pollen and analysis of air mass circulation illustrating the pollen transport routes, we conclude that under favourable circulation conditions, *Pinus* pollen grains can be transported in small amounts by air masses, even over 2000 km. Determination of the source of pollen is possible through the analysis of retrograde trajectories, as the concentration of pollen grains does not correlate with the local speed and direction of the wind, as well as with the direction of direct inflow of air masses over Svalbard. *Pinus* pollen captured in Spitsbergen may come from many locations, including Scandinavia, Iceland, Siberia and even northern Canada.

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Appendix 1. Seven-day back analyses based on visualization of global weather conditions forecast elaborated by Cameron Beccario (https://earth.nullschool.net/), compiled for Event 1 through Event 5.

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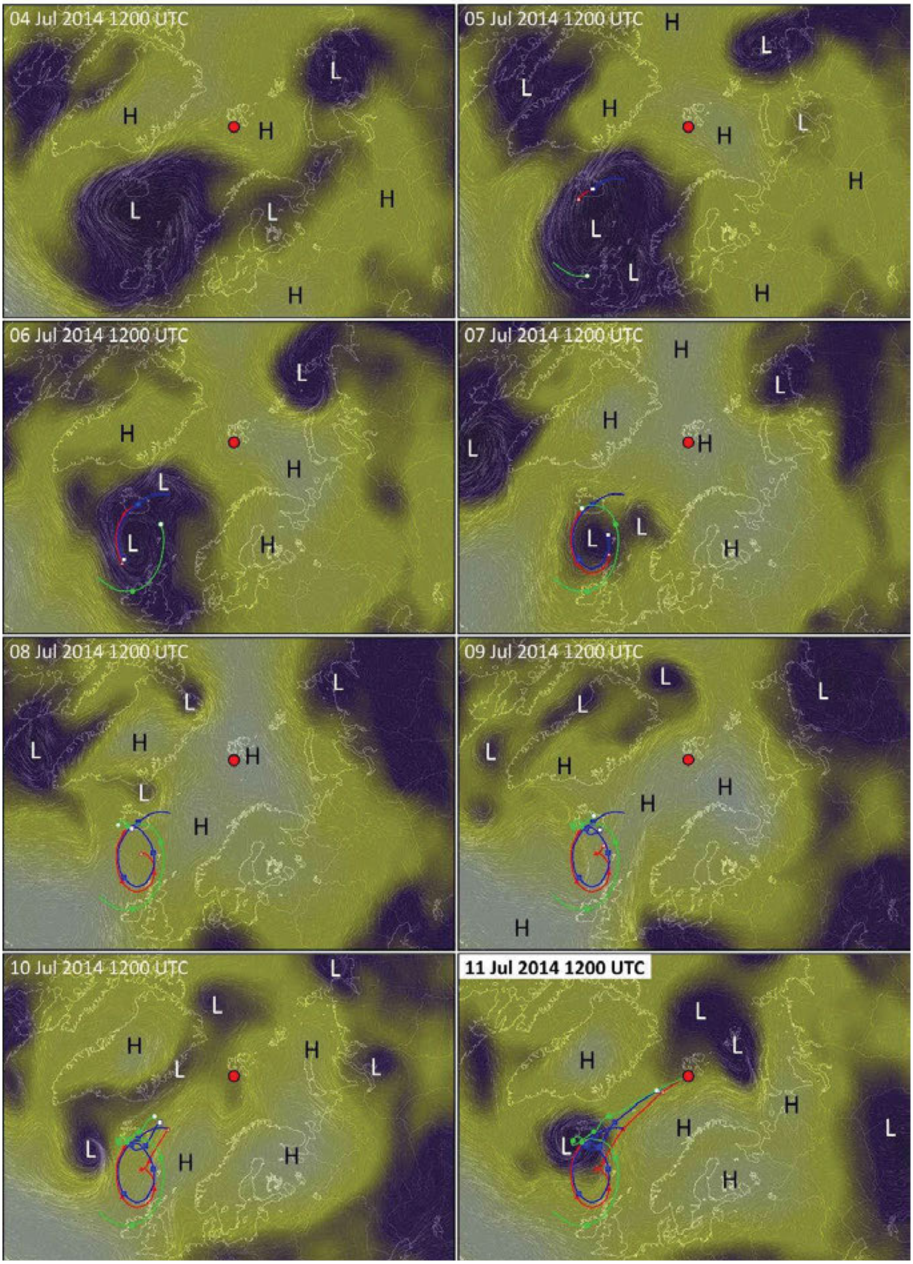
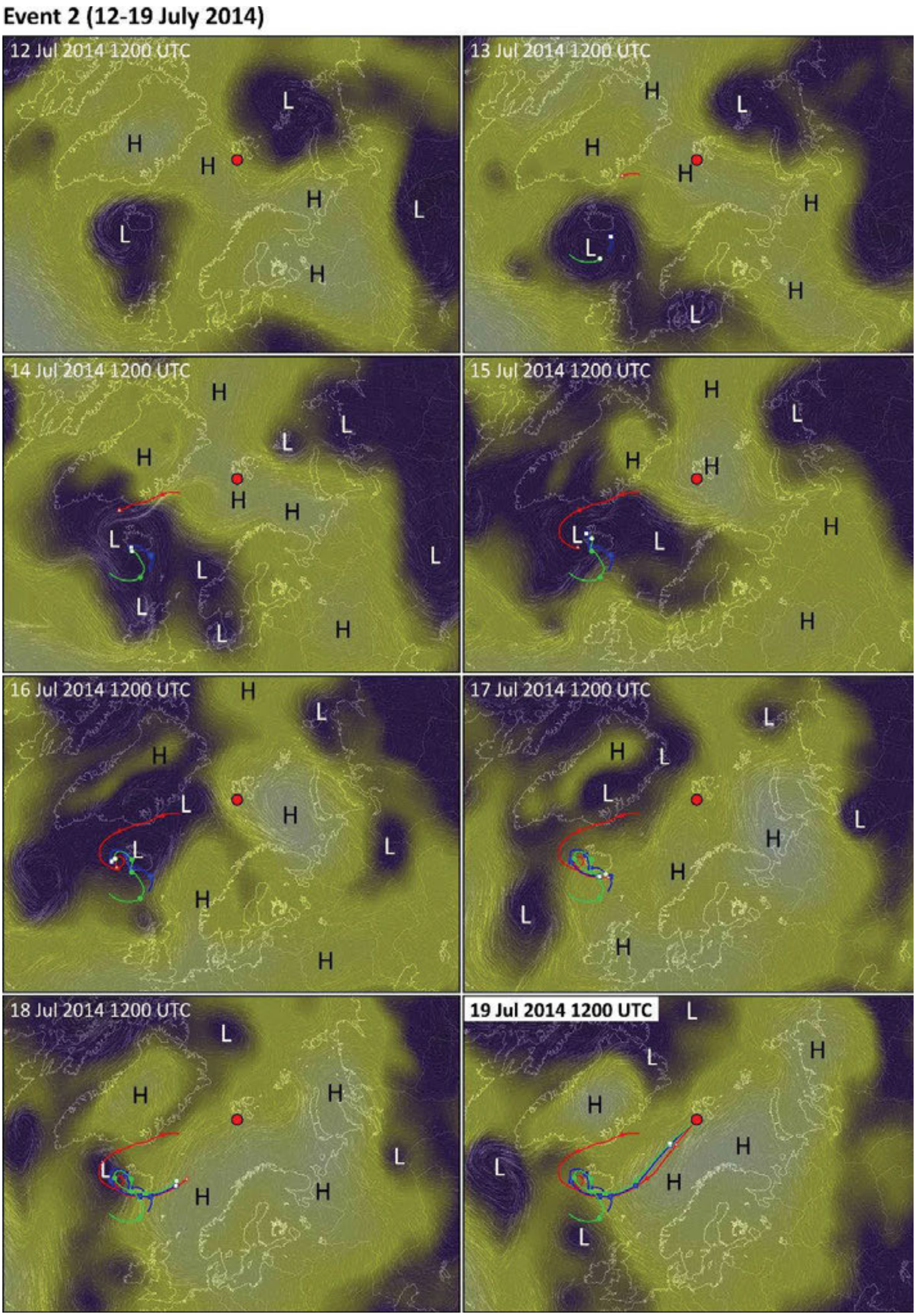
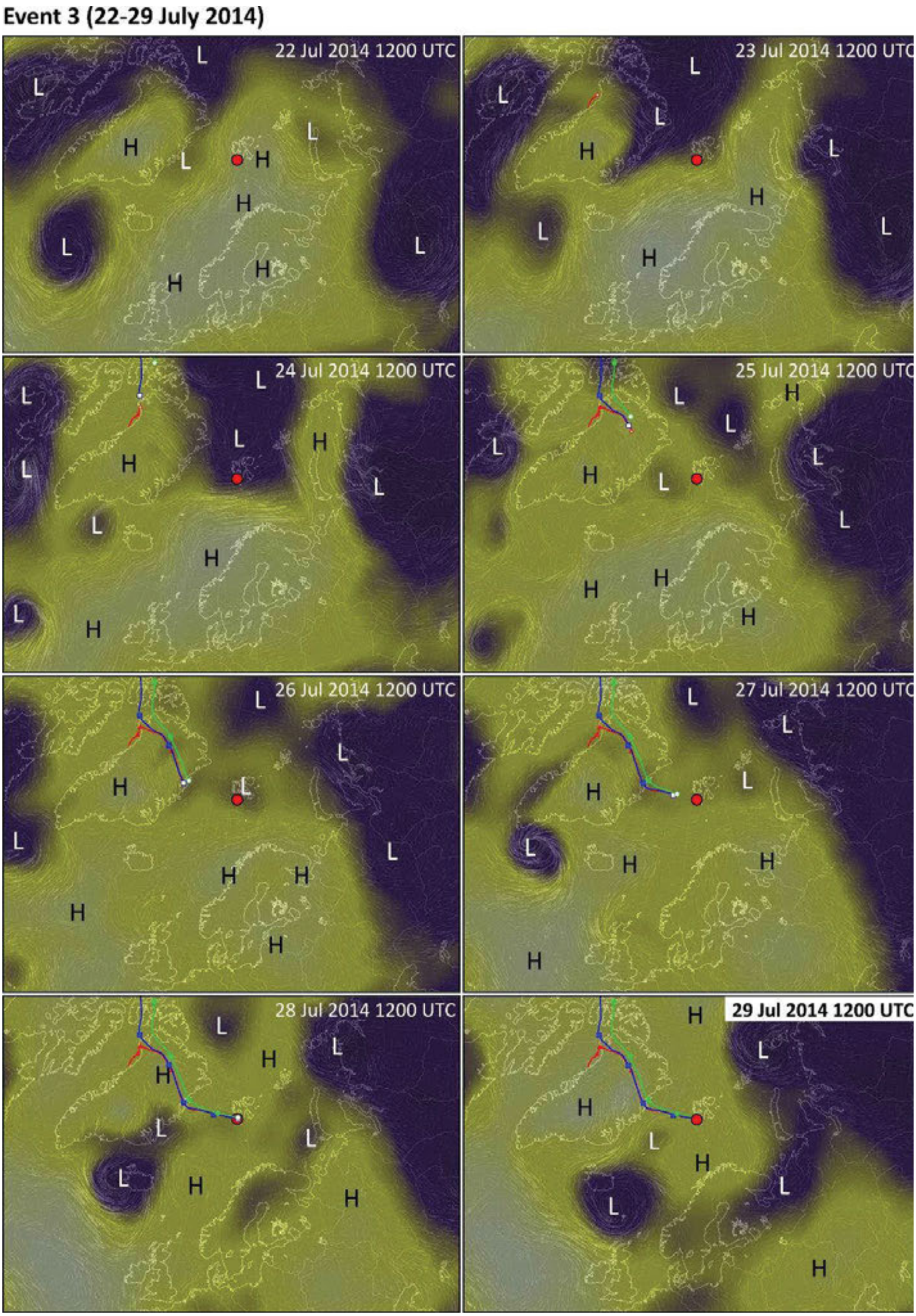
Appendix 1.

Seven-day back analyses based on visualization of global weather conditions forecast elaborated by Cameron Beccario (https://earth.nullschool.net/), compiled for Event 1 through Event 5.

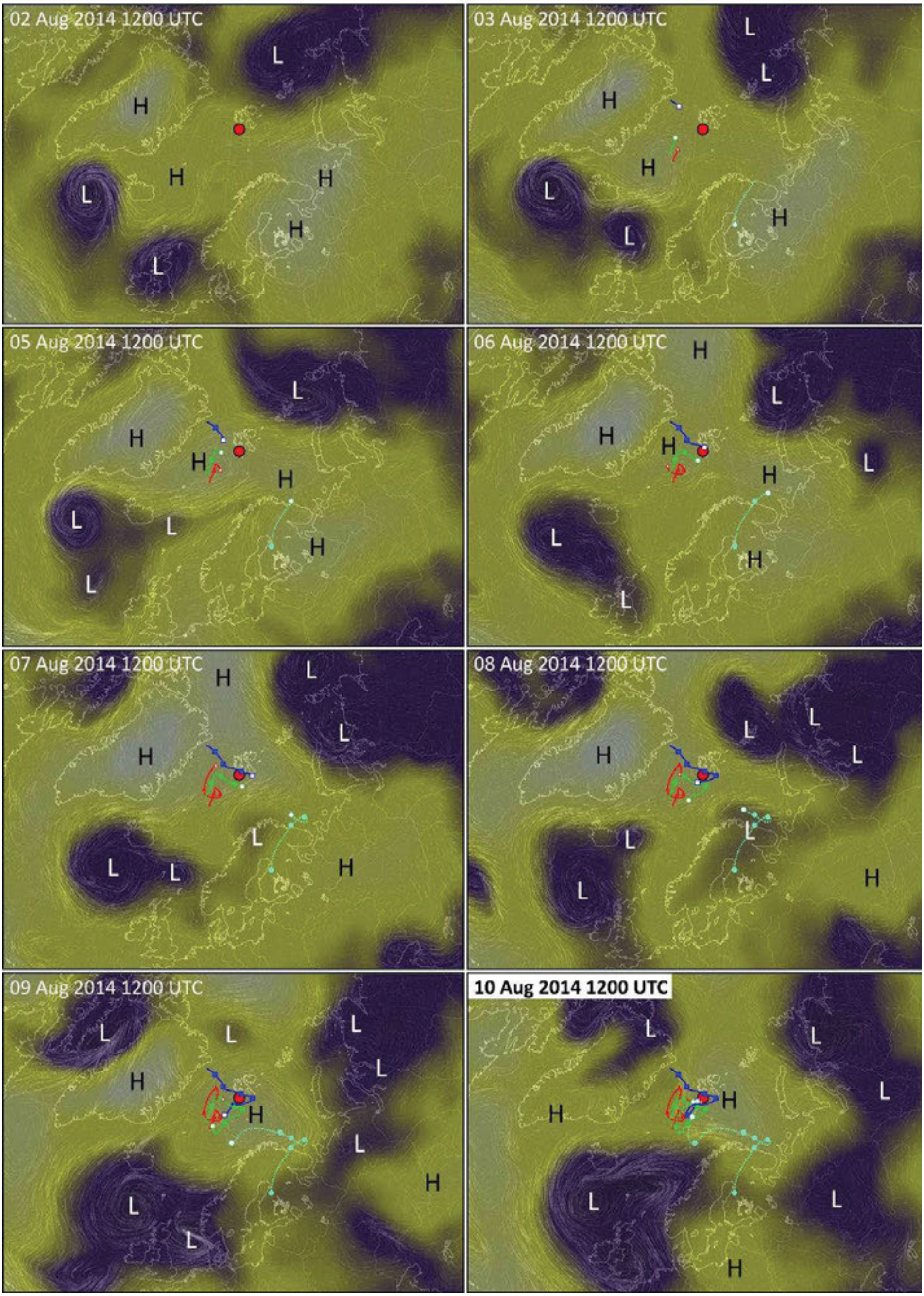
Event 1 (04-11 July 2014)




Event 2 (12-19 July 2014)
12 Jul 2014 1200 UTC
13 Jul 2014 1200 UTC
14 Jul 2014 1200 UTC
15 Jul 2014 1200 UTC
16 Jul 2014 1200 UTC
17 Jul 2014 1200 UTC
18 Jul 2014 1200 UTC
19 Jul 2014 1200 UTC


Event 3 (22-29 July 2014)
22 Jul 2014 1200 UTC
23 Jul 2014 1200 UTC
24 Jul 2014 1200 UTC
25 Jul 2014 1200 UTC
26 Jul 2014 1200 UTC
27 Jul 2014 1200 UTC
28 Jul 2014 1200 UTC
29 Jul 2014 1200 UTC

Event 4 (02-10 August 2014)



Event 5 (11-18 July 2015)