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Air temperature variability in the vertical profile over the coastal area of Petuniabukta, central Spitsbergen

Klára AMBROŽOVÁ[1*] and Kamil LÁSKA[1,2]

[1] *Department of Geography, Faculty of Science, Masaryk University, Brno, Czech Republic <ambrozova.kl@mail.muni.cz>*

[2] *Centre for Polar Ecology, Department of Ecosystem Biology, Faculty of Science, University of South Bohemia, České Budějovice, Czech Republic <laska@sci.muni.cz>*

[*] *corresponding author*

Abstract: A two-year-long data set of air temperature from four different altitudes above Petuniabukta, central Spitsbergen, was analysed in order to assess the near-surface temperature lapse rates and the relative frequency of air temperature inversion occurrence. From August 2013 to July 2015, air temperatures at adjacent altitudes in Petuniabukta were strongly correlated. The near-surface lapse rates in all three layers differed significantly both from the average lapse rate in the international standard atmosphere (0.65°C 100 m^{-1}) and the lapse rate calculated by linear regression. A pronounced annual cycle was detected in the lowermost air layer (from 23 to 136 m a.s.l.) with a variable near-surface lapse rate in the winter months, while an annual cycle was not apparent in the air layers above 136 m a.s.l. The lowermost layer was also characterized by a notable daily cycle in near-surface lapse rate in spring and autumn. Air temperature inversions occurred in up to 80% of the study period in the air layer below 136 m a.s.l., with the relative frequency being much lower in the other two air layers. The air temperature inversions lasted as long as 139 hours. A case study revealed that one of the strongest air temperature inversions was connected to an area of lower pressure gradients at the 850-hPa pressure level.

Key words: Arctic, Svalbard, air temperature inversion, near-surface lapse rate.

Introduction

The atmosphere of Earth has been experiencing unprecedented warming in recent years. According to the IPCC, the land surface air temperature grew an average of 0.9°C per century in the period 1888–2012, and the growth was even faster since the 1970s (IPCC 2013). The warming is especially pronounced in the Arctic (*e.g.* Serreze *et al*. 2009), for instance the Svalbard Airport composite series revealed a current trend of 2.6°C per century for mean yearly data in the period 1898–2012 (Nordli *et al*. 2014). The complex orography and variable land cover of Svalbard cause high spatial variability of the air temperature field in the boundary layer, as was shown in numerous topoclimatic studies (*e.g*. Wójcik *et al*. 1998; Migała *et al*. 2008; Bednorz and Kolendowicz 2010; Araźny *et al*. 2012). The vertical distribution of air temperature in the atmospheric boundary layer was assessed as well in Svalbard, mostly in short-term spring campaigns (Argentini *et al*. 2003; Vihma *et al*. 2011; Mayer *et al*. 2012). In these studies, air temperature inversions were found to be a persistent feature, although there were many mechanisms causing their formation. In spite of regular atmospheric radiosounding performed at Ny-Ålesund since 1991 (Treffeisen *et al*. 2007), there is only one comprehensive study on air temperature inversions in free atmosphere that includes Svalbard (Serreze *et al*. 1992), which is based on data from Barentsburg for 1976–1987.

The results from radiosounding, however, might be imprecise and unable to catch air temperature inversions in the lowermost layer (Vihma *et al*. 2011). In such cases, the vertical change of air temperature at 2-m height above ground (the so-called near-surface lapse rate; Marshall *et al*. 2007) can be used for determining the vertical temperature profile, although it is more affected by ground surface properties. Near-surface lapse rates have been determined in some studies from Svalbard, however they were mostly calculated from summer measurements (Wójcik *et al*. 1998; Migała *et al*. 2008; Araźny *et al*. 2010; Bednorz and Kolendowicz 2010). The only existing study presenting year-long temperature data from altitudes up to 590 m a.s.l. from an ice-free area is the analysis by Araźny *et al*. (2012), who investigated air temperature data from the Forlandsundet region (NW of Spitsbergen) from July 2010 to August 2011 created within the AWAKE project (*e.g*. Przybylak *et al*. 2014).

The remarkable spatial temperature variability in Svalbard, ascertained by the AWAKE project, calls for enhanced comparison of vertical air temperature changes with other parts of the Svalbard archipelago. Specifically, information about air temperature-altitude dependence, the occurrence of air temperature inversions and the main mechanisms of their formation would be of utmost interest in the central part of Spitsbergen, where significant glacier retreat has been reported (Małecki 2013). Moreover, the notable effect of variable atmospheric circulation on air temperature (Niedźwiedź 2003) suggests that a longer study for determination of multi-year near-surface lapse rate variability and validation of numerical model outputs would be useful as well. The research is also important for understanding the impacts of climate change and interpreting air temperature increases in the extremely sensitive coastal areas of the Arctic.

The main aims of this study were i) to investigate the variation of air temperature with altitude in the central part of Spitsbergen, ii) to determine the annual and daily courses of near-surface temperature lapse rates from August 2013 to July 2015, and iii) to evaluate air temperature inversion frequency.

Study area

The study area lies in the central part of Spitsbergen, the largest island of Svalbard (Fig. 1a). The bay of Petuniabukta is oriented to the north and is part of the Billefjorden and Isfjorden fjords. The effect of ocean proximity is remarkably diminished, as is apparent for instance from the more severe sea-ice conditions in Petuniabukta in comparison with Svalbard Airport (Láska *et al*. 2012). Several valleys with their glaciers and glacial rivers join the bay to the northwest (Hørbyedalen), northeast (Rangardalen) and east (Ebbadalen). The vicinity of Petuniabukta is surrounded by mountain ranges with elevations up to 940 m a.s.l. The land cover grades with altitude from tundra vegetation in the coastal zone of Petuniabukta to bare soil and sedimentary rocks (Prach *et al*. 2012; Szpikowski *et al*. 2014). Snow covers the coastal zone from October to early summer (Láska *et al*. 2012) and seasonal sea ice, mainly as fast ice or open drift ice, usually occurs from December to May (Nilsen *et al*. 2008). The intensity of incoming solar radiation in Petuniabukta is close to zero from the end of October to the first part of February, while the average monthly temperature varies between -17 to 7°C (Láska *et al*. 2012).

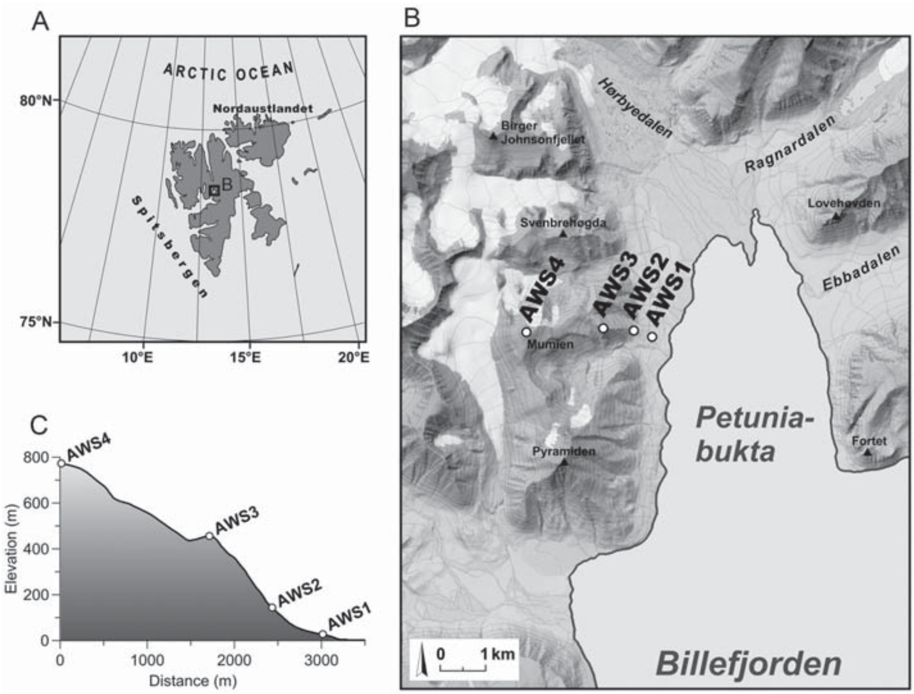

Fig. 1. Location of the study area: Svalbard (**A**) and Petuniabukta with selected automatic weather stations (**B**), also in vertical cross section (**C**). The modified map of Petuniabukta is based on the Svalbardkartet data (Norwegian Polar Institute).

Since August 2013, four AWS have been installed on the western coast of Petuniabukta (Fig. 1b–c). While AWS1 is situated on a marine terrace at 23 m a.s.l., the rest of the stations are on slopes (AWS2, AWS3) and the top of Mumien Peak (AWS4; Table 1). Considering that they are very close to each other (Fig. 1) and none of them is situated on a glacier, the difference in altitude should be the most important element influencing the spatial temperature variability.

Table 1

Selected topographic characteristics of the automatic weather stations (AWS) in Petuniabukta, central Spitsbergen.

station	surroundings description and location	latitude (°N)	longtitude (°E)	altitude (m a.s.l.)
AWS 1	tundra, marine terrace	78.6989	16.4325	23
AWS 2	regolith, ledge of Mumien Peak	78.7003	16.3164	136
AWS 3	regolith, spur of Mumien Peak	78.7008	16.3903	455
AWS 4	regolith, top of Mumien Peak	78.7003	16.4217	764

Data and Methods

Air temperature was measured from August 2013 to July 2015 with an identical set of Pt100/A resistance thermometers built-in the EMS33 and Minikin TH probes (EMS Brno, Czech Republic). The accuracy of the thermometers was ±0.15°C and the data were measured and stored at hourly intervals. The instruments were installed at the height of 2 m above the ground in a radiation shield and were calibrated before the installation as well as recalibrated every summer. During maintenance in summer 2014, 1–2 missing values were generated in all the AWS, which were filled in as arithmetic means. The temperature data were controlled for icing events by comparison with a nearby AWS located at 937 m a.s.l., where icing is common. The analysis proved that the effect of icing was negligible. Similarly, the temperature data were not affected by snow accumulation, since, according to time lapse camera monitoring, the snow depth in Petuniabukta rarely exceeded 50 cm (unpublished data). The wind speed and wind direction were used from an AWS located approx. 3 km to the north of AWS1, where it was measured at 6 m above the ground by wind instruments MetOne 034B (MetOne, USA) with an accuracy of ±0.1 m s^{-1} and resolution of the wind direction of 4°.

The air temperature data were used to calculate the near-surface lapse rates (Γ) in several atmospheric layers, most importantly Γ_1 between AWS1 and AWS2, Γ_2 between AWS2 and AWS3, and Γ_3 between AWS3 and AWS4. In this study, a positive difference in air temperature means higher temperature at the lower altitude AWS, while positive values of Γ indicate decreasing air temperature with height. Apart from tabular and graphical data processing, the correlation among air temperature data were determined, best fit relationships between the air temperature data and the acquired Γ were calculated by linear regression (Γ_{lr}) and differences among hourly Γ_1 to Γ_3 were tested (see Table 2). The null hypothesis was rejected when the statistical significance level was below 0.05. The hourly Γ_1 to Γ_3 were tested for similar variances by Levene's test, and since the variance of the three samples was not the same, Friedman's Test was used to test whether the samples differed from each other (McClave and Dietrich 1991). The average lapse rate in the international standard atmosphere (0.65°C 100 m^{-1}) was also compared to Γ_1 to Γ_3 in order to evaluate its applicability for subsequent studies (such as environmental modelling) instead of Γ derived from measured data (Brock and Richardson 2001).

The periods with negative Γ values were marked as air temperature inversions and were analysed in a separate section. The relative frequency of inversion occurrence was defined as the ratio of measurements with negative values of Γ to all measurements. The inversions were also sorted by length from one to more than 48 h, although it can be assumed that the longest inversions might have been generated and maintained by more than one mechanism of air temperature inversion generation. With respect to the aforementioned fact, a case study of the first part of one of the longest air temperature inversions was analysed at the end of this study in order to characterize the conditions leading to air termperature inversion formation and to suggest what is the main mechanism leading to development of very strong inversions in central Spitsbergen. Large-scale atmospheric motion was assessed according to the geopotential height of 850 hPa pressure level obtained from the National Centre for Environmental Prediction/National Center for Atmospheric Research Reanalysis (NCEP/NCAR) (Kalnay *et al*. 1996).

Results

Air temperature. — The variability of daily and monthly mean air temperatures and the differences between all AWS from August 2013 to July 2015 are presented in Fig. 2. The air temperature in the study period ranged from -29.8°C, measured at AWS4 on 10 and 11 February 2015, to 17°C, which was recorded at AWS1 on 30 July 2015 (Table 3). The warmest month was July 2015 with an average air temperature of 7.3°C at AWS1, while the coldest month was February 2015 (-16.2°C on average at AWS1). July was also the warmest month of the year in 2014, however, the lowest mean air temperature of 2014 occurred in April with an average temperature of -12.5°C at AWS1.

Table 2

Summary of the statistical tests (McClave and Dietrich 1991) used in this paper: the data used for each task (Data), specification of the task (Task definition), null and alternative hypotheses (Null hypothesis and Alternative hypothesis) and the name of the statistical test used for each task (Test).

Data	Task definition	Null hypothesis	Alternative hypothesis	Test
Daily minimum, average and maximum temperature at AWS1 to AWS4	e.g. minimum temperature at AWS1 against minimum temperature at AWS2	T at AWS1 and AWS2 are stochastically independent.	T at AWS1 and AWS2 are not stochastically independent.	Pearson product-moment correlation coefficient, t-test for its significance
Minimum, average and maximum temperature at AWS1 to AWS4	e.g. minimum temperature from AWS1 to AWS4 is fitted by the linear model	The model of constant value is sufficient to approximate the data.	The model of constant value is not sufficient to approximate the data.	F-test for regression model
Hourly Γ_1 to Γ_3 for the whole period	Difference among Γ_1, Γ_2 and Γ_3	The medians of the three groups are identical.	At least one of the medians is different.	Friedman's Test and Post-hoc Analysis
Hourly Γ_1 to Γ_3 against 0.65°C/100 m	e.g. average Γ_1 against 0.65°C/100 m	$\Gamma_1 = 0.65$	$\Gamma_1 \neq 0.65$	One sample t-test
Hourly Γ_1 to Γ_3 against Γ_{lr} derived from average temperature at AWS1 to AWS4	e.g. hourly Γ_1 against Γ_{lr}	$\Gamma_1 = \Gamma_{lr}$	e.g. $\Gamma_1 \neq \Gamma_{lr}$	One sample t-test
Hourly Γ_1 to Γ_3 for each season	e.g. difference among Γ_1, Γ_2 and Γ_3 in spring	The medians of the three groups are identical.	At least one of the medians is different.	Friedman's Test and Post-hoc Analysis
Hourly Γ_1 to Γ_3 for each season	e.g. Γ_1 in spring, summer, autumn and winter	The medians of the four groups are identical.	At least one of the medians is different.	Friedman's Test and Post-hoc Analysis

Compared to AWS1, there were slightly higher air temperatures observed on the slope of Mumien Peak (AWS2) with the lowest mean air temperature occurring in February 2015 (-15.1°C) and the highest in July 2015 (6.7°C). The mean daily temperature differences between AWS1 and AWS2 (Fig. 2b) were within ±0.5°C for 52% of the measurements with these differences generally being on average negative from September 2013 to April 2014 and again from January to April 2015. There was a strong linear relationship between the air temperatures at AWS1 and AWS2 (Fig. 3), with the corresponding temperature at

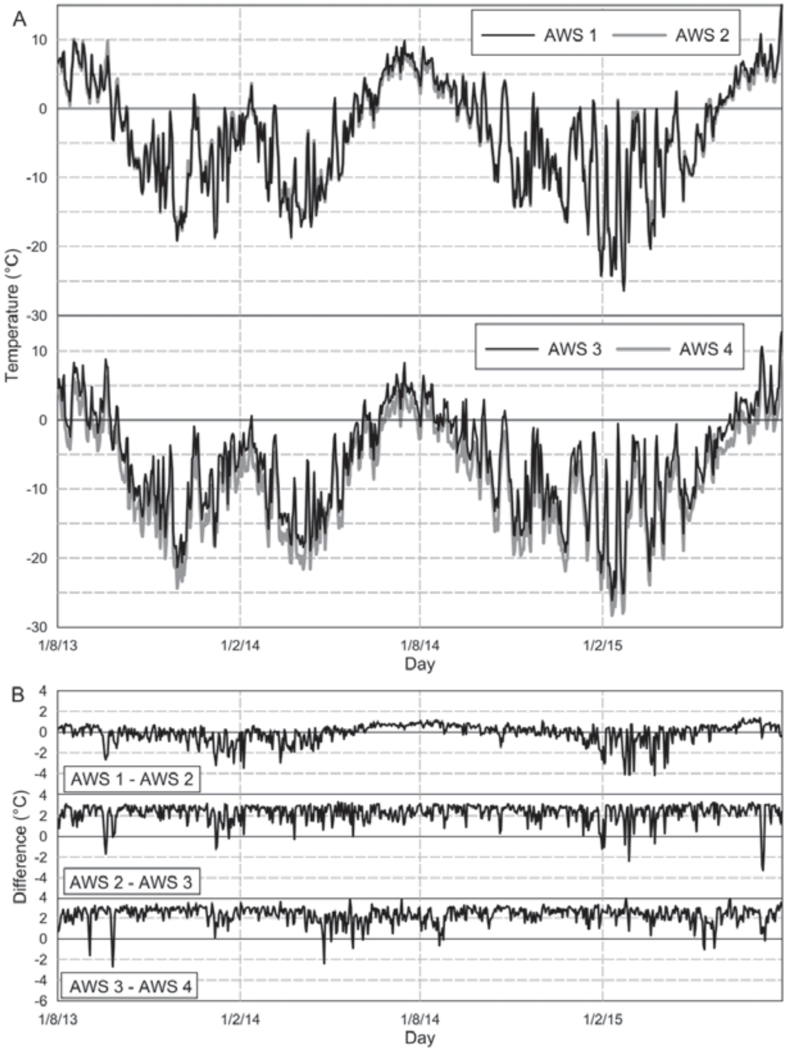

Fig. 2. Variation of mean daily air temperature at selected automatic weather stations (AWS) in Petuniabukta (**A**), and the mean daily temperature difference between two adjacent stations (**B**) from August 2013 to July 2015.

AWS2 being higher than at AWS1. Air temperature at AWS2 was also the least variable in the whole study period with a standard deviation of 4°C, although the difference between the standard deviations at AWS1 to AWS4 was negligible.

Mean air temperature on the ledge of Mumien Peak (AWS3) was 2.3°C lower than at AWS2 with positive temperature differences between AWS2 and AWS3 in more than 97% of the study period (Fig. 3). The temperature at AWS3 varied between -27.3°C and 16.3°C and the mean daily air temperatures closely

Table 3

Average, minimum and maximum air temperatures (T) and their standard deviations (σ) at selected automatic weather stations (AWS) in Petuniabukta from August 2013 to July 2015.

T (°C)	AWS 1				AWS 2				AWS 3				AWS 4			
	min	mean	max	σ	min	mean	max	σ	min	mean	max	σ	min	mean	max	σ
Winter	-28.3	-8.9	4.8	7.1	-25.0	-8.3	5.1	6.7	-27.3	-10.4	2.0	6.4	-29.8	-13.0	-0.7	6.4
Spring	-23.3	-7.5	6.2	5.9	-20.7	-7.2	5.6	5.4	-23.1	-9.5	3.2	5.4	-25.8	-11.6	4.0	5.5
Summer	-2.9	5.4	17.0	2.9	-3.8	4.8	16.7	2.9	-7.0	2.5	16.3	3.4	-9.6	0.3	12.5	3.4
Autumn	-20.6	-3.7	10.0	6.1	-19.8	-3.8	12.1	6.1	-22.2	-6.2	10.7	6.3	-25.2	-8.7	8.0	6.4
Whole period	-28.3	-3.7	17.0	8.0	-25.0	-3.6	16.7	7.5	-27.3	-5.9	16.3	7.5	-29.8	-8.3	12.5	7.6

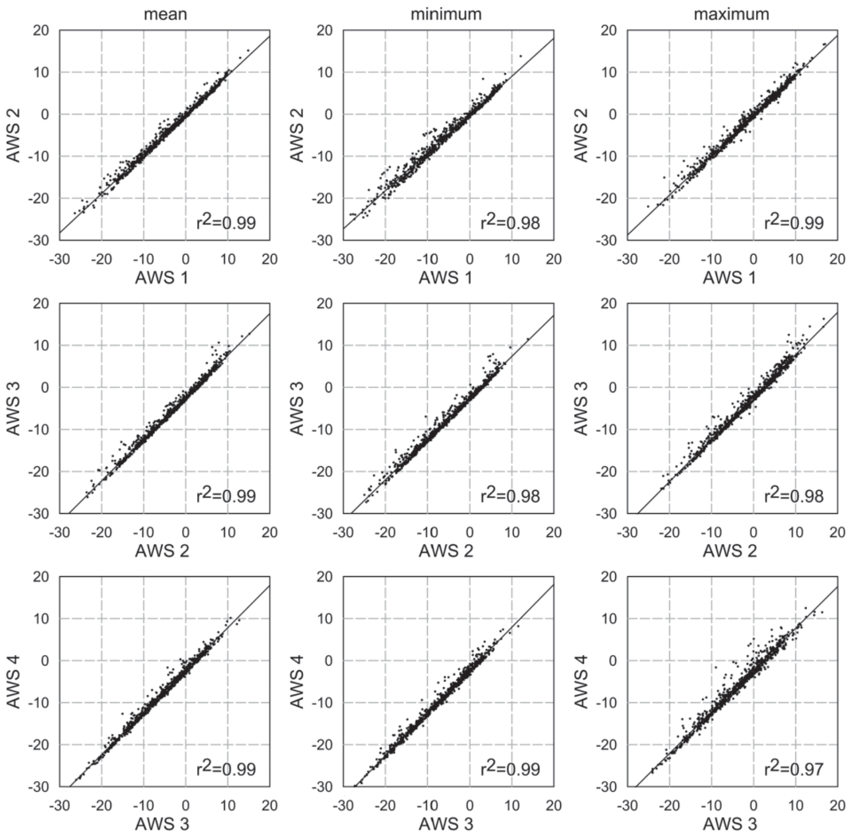

Fig. 3. Scatter plot of daily average, minimum and maximum temperatures between selected automatic weather stations (AWS) in Petuniabukta from August 2013 to July 2015.

resembled the values observed at the other stations (Fig. 2–3). The station at the top of the mountain (AWS4) was the coldest with the lowest monthly mean air temperatures over the whole study period (Fig. 2). The maximum air temperature at AWS4 was 12.5°C, measured on 11 July 2015. The linear relationship between daily air temperatures at AWS3 and AWS4 is again very strong, despite the lower correlation coefficient (0.98) for maximum daily temperatures.

Near-surface lapse rates. — The near-surface lapse rates of air temperature (Γ) in Petuniabukta were derived for several air layers for the period from August 2013 to July 2015. Of the three adjacent layers (Γ_1 to Γ_3), the Γ in the two higher layers were quite similar (Table 4) with average values of 0.7°C 100 m^{-1} for Γ_2 and 0.8°C 100 m^{-1} for Γ_3. The lowest layer, however, was significantly more stable than the other two, as indicated by an average value of -0.1°C 100 m^{-1} for

Table 4

Average, minimum and maximum lapse rates (Γ) and their standard deviations (σ) in air layers from 23 to 764 m a.s.l. in Petuniabukta from August 2013 to July 2015. The table also includes the lapse rate calculated by linear regression (Γ_{lr}) and its correlation coefficient (r).

Γ (°C/100 m)	min	mean	max	σ
Γ_1 (AWS1 to AWS2)	-8.6	-0.1	4.0	1.0
Γ_2 (AWS2 to AWS3)	-1.8	0.7	1.8	0.3
Γ_3 (AWS3 to AWS4)	-3.2	0.8	2.2	0.4
Γ_4 (AWS1 to AWS3)	-2.4	0.5	1.7	0.4
Γ_5 (AWS2 to AWS4)	-1.1	0.7	1.5	0.3
Γ_6 (AWS1 to AWS4)	-1.3	0.6	1.3	0.3
Γ_{lr}	0.37	0.65	0.57	.
r	0.60	0.99	0.90	.

the study period, but was also more variable (standard deviation 1.0°C 100 m^{-1}). The mean Γ for thicker air layers (Γ_4 to Γ_6) ranged between 0.5–0.7°C 100 m^{-1}.

Linear regression was also used in order to acquire mean, minimum and maximum values of the lapse rate (Γ_{lr}) for the study period from all four AWS (Table 4), but the linear model was not appropriate to fit the temperature data for the minimum and maximum temperatures. The Γ_{lr} derived from mean air temperature was close to the average lapse rate in the international standard atmosphere (0.65°C 100 m^{-1}). Nevertheless, Γ_1, Γ_2 and Γ_3 significantly differed from the average lapse rate in the international standard atmosphere and Γ_{lr} (Table 4).

Annual cycle of near-surface lapse rates. — The largest range in mean monthly Γ (Fig. 4) was observed in the lowest layer, with the lowest Γ_1 value in January 2014 (-1.1°C 100 m^{-1}) and the highest Γ_1 of 0.7°C 100 m^{-1} in August 2014. For Γ_2 and Γ_3, the mean monthly values were between 0.5 and 0.9°C with several local minima and maxima during the year. The importance of the annual cycle in the lowest layer was confirmed by Friedman's ANOVA and posthoc analysis, which showed that none of the two seasonal medians in hourly Γ_1 (*e.g.* average spring against average summer Γ_1) were identical. For Γ_2, however, the medians in summer and autumn did not differ significantly, as neither did the Γ_3 spring and summer medians nor the autumn and winter medians.

Friedman's ANOVA and its posthoc analysis also confirmed that Γ_1 differed significantly from Γ_2 and Γ_3 in all seasons of the year. When the two years

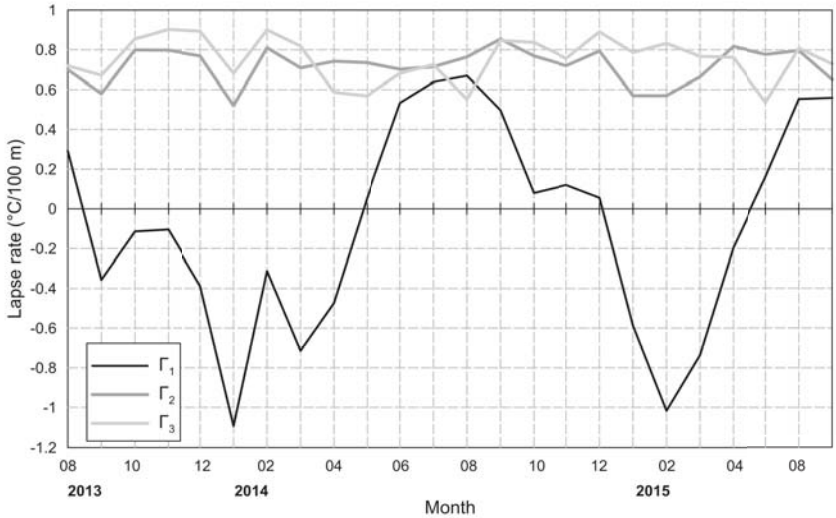

Fig. 4. Variation of mean monthly lapse rates in three adjacent layers (Γ_1 to Γ_3) in Petuniabukta from August 2013 to July 2015.

were compared, it was clear that especially the winter values of Γ differed remarkably. For instance, while February 2015 had the lowest mean Γ_1, the value was -0.3°C 100 m^{-1} with a local maximum for 2014. For Γ_2 and Γ_3, the two years seemed to be distinctly different with almost no similarities as for local minima and maxima.

Daily cycle of near-surface lapse rates. — The daily variation of Γ in the three adjacent layers was examined for different seasons from August 2013 to July 2015 (Fig. 5a) and the aforementioned results are also supplemented by mean air temperature for the same period at all four AWS (Fig. 5b). The most pronounced daily cycle in Γ_1 was detected in spring with maximum values between 12:00 and 14:00 UTC and the minimum at 04:00 UTC. A similar pattern was also distinguished in summer Γ_1. It is apparent that the marked daily cycles in spring and summer were caused by a slightly larger air temperature range at AWS1 in comparison with AWS2. Daily variation of Γ_1 was negligible in autumn and winter, which was confirmed by the fact that the difference between the maximum and minimum air temperatures at AWS1 and AWS2 was less than 0.6°C for autumn and 0.3°C for winter. For Γ_2 and Γ_3, only a very gentle daily cycle was detected in spring and summer, however, the values were within 0.2°C 100 m^{-1} the whole day and so the daily cycle in these two layers is not described further.

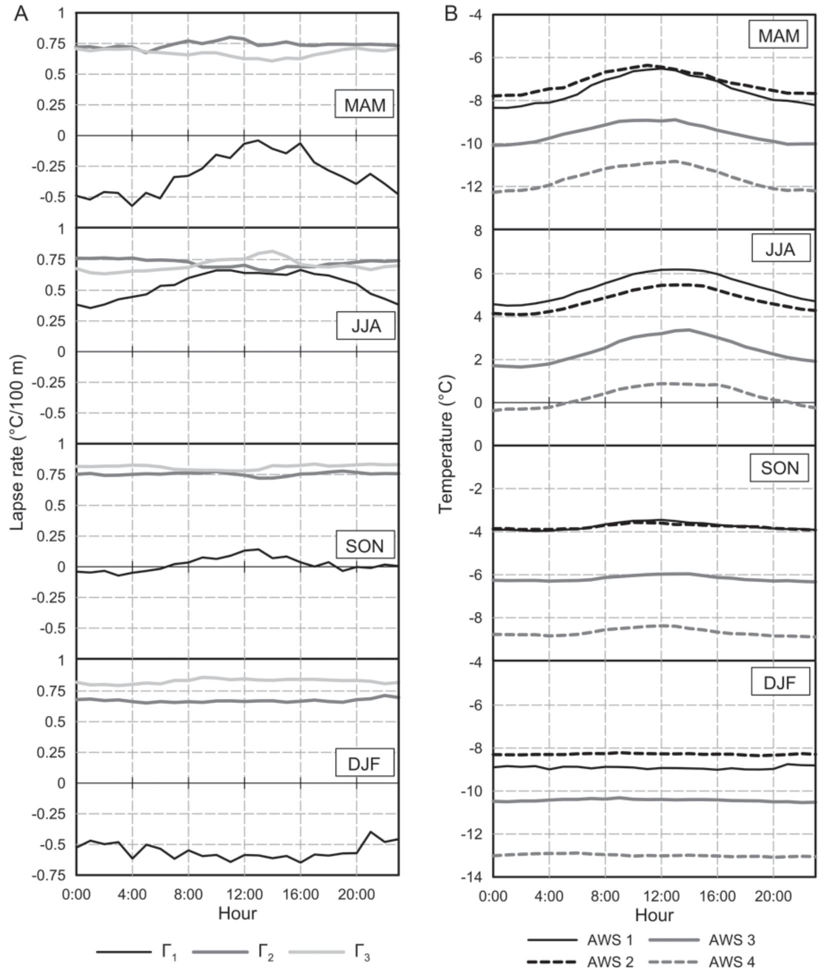

Fig. 5. Variation of mean hourly lapse rates in three adjacent layers (**A**) and air temperatures at selected automatic weather stations (AWS) in Petuniabukta (**B**) for different seasons of the year (MAM = spring, JJA = summer, SON = autumn, DJF = winter) from August 2013 to July 2015.

Air temperature inversions. — Air temperature inversion frequency was determined in three adjacent air layers for the whole study period. The mean relative frequency of air temperature inversions reached 41% in the lowest layer (Fig. 6a), while it was much smaller for the middle (5%) and the highest (4%) layers. There was a clear annual cycle detectable in the lowest layer with the air temperature inversion frequency ranging from 5% in July 2014 to 83% in January 2014. On the other hand, air temperature inversions were not observed in October 2013 (both in the middle and the highest layers) and in January 2015 (the highest layer). Besides, air temperature inversions in the highest air

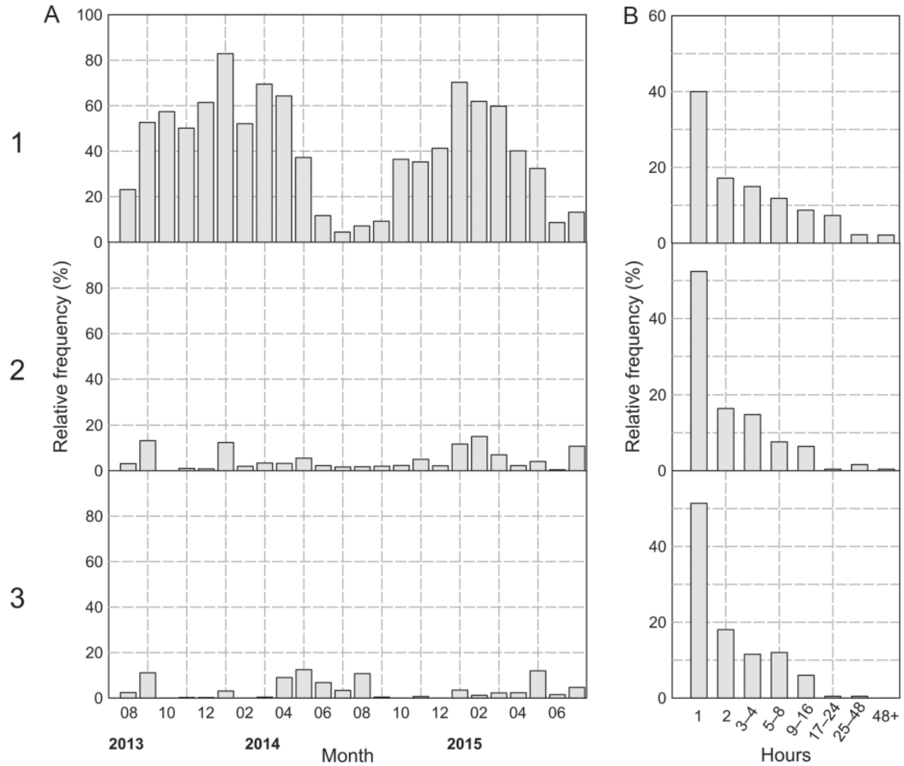

Fig. 6. Variation of air temperature inversion relative frequency (**A**) and relative frequency of duration of the inversions (**B**) in three adjacent layers (1 = the lowest layer, 2 = middle layer, 3 = the highest layer) in Petuniabukta from August 2013 to July 2015.

layer were most frequent in May 2014 (13%) and May 2015 (12%), so it seems that the annual cycle in this layer was shifted with respect to the lowest layer.

The air temperature inversions lasted up to more than 48 hours (Fig. 6b), with the longest one lasting from 19 March 2014 10:00 UTC to 25 March 2014 06:00 UTC. The 1-hour lasting inversions were always the most frequent with relative frequencies of 40% (the lowest air layer), 52% (middle air layer), and 51% (the highest air layer). Although the relative frequency of inversion duration decreased in all the layers, it is apparent that the decrease of the relative frequency was slower for the lowest layer. For instance, air temperature inversions lasting more than 24 hours accounted for 4% of all inversions in the lowest layer, while it was only 2% in the middle layer and less than 0.5% in the highest layer.

Air temperature inversions in the three layers also coincided occasionally. With the statistical population defined as the measurements where an air temperature inversion was detected in at least one of the two layers, the coincidence of inversions was 9% (for the lowest and middle layers), 3% (for the lowest and highest layers), and 6% (for the middle and highest layers). For the lowest and middle layers, co-occurence was the most common in winter with a relative frequency of 12% and the least frequent in spring (6%). On the other hand, for the lowest and highest layers there was almost no annual cycle observed (relative frequency of 4% in spring and summer, and 2% in autumn and winter). The annual cycle was most pronounced for the middle and highest layers with the maximum relative frequency in autumn (10%) and the minimum in winter (2%).

Case study. — In order to ascertain which mechanisms lead to the generation of air temperature inversions in the coastal zone of Petuniabukta, one of the inversions was thoroughly examined. The selected air temperature inversion was one of the strongest inversions with respect to duration and the value of Γ. The inversion took place between 12 and 14 March 2014, when Petuniabukta was covered by fast ice (Norwegian Meteorological Institute 2016b) and continuous snow cover occurred in the study area (J. Kavan, personal communication). The air temperature inversion started at noon on 12 March and a decrease in Γ_1 at an average rate of 0.2°C 100 m^{-1} per hour was followed by a period of remarkable Γ_1 oscillations (Fig. 7a) with Γ_1 reaching -5.8°C 100 m^{-1} in the end of this period. Finally, Γ_1 grew again to around -0.6°C 100 m^{-1} from 19:00 UTC 14 March onwards. It is apparent from Fig. 7a that the Γ in the middle and highest layers oscillated slightly within the interval from -0.1 to 1.5°C 100 m^{-1}.

The air temperature inversion came into being during a concurrent decrease in air temperature (Fig. 7b), which was the most intense at AWS1. The subsequent air temperature rise was not well pronounced at AWS1, where the temperature fluctuated. The final drop of Γ_1 at 09:00 UTC 14 March was the result of a sharp reduction of air temperature at AWS1 and a simultaneous air temperature rise at AWS2. Eventually, the air temperature rose also at AWS1, bringing Γ_1 close to zero.

Formation of the air temperature inversion was promoted by a specific atmospheric circulation and local topography. The retreat of a high pressure ridge from the southeast resulted in an area of lower pressure gradients settling above Svalbard on 13 March 2014 (Fig. 8b), which agreed well with the decrease in surface wind speed to 2 m s^{-1} (Fig. 7c), being predominantly a northerly wind (Fig. 7d), and cloudless conditions in the central part of Spitsbergen (NASA/GFS/ESDIS 2016). On 14 March (Fig. 8b), another high pressure ridge was gradually formed in the area, which increased the pressure gradients at the 850 hPa level as well as the wind speed, and led to disintegration of the air temperature inversion. It appears that the key factor in the evolution of the air temperature inversion was the attenuation of the large-scale atmospheric motion and clear-sky conditions, which enhanced radiation loss from the snow- and ice-covered surface at the coastal zone of Petuniabukta.

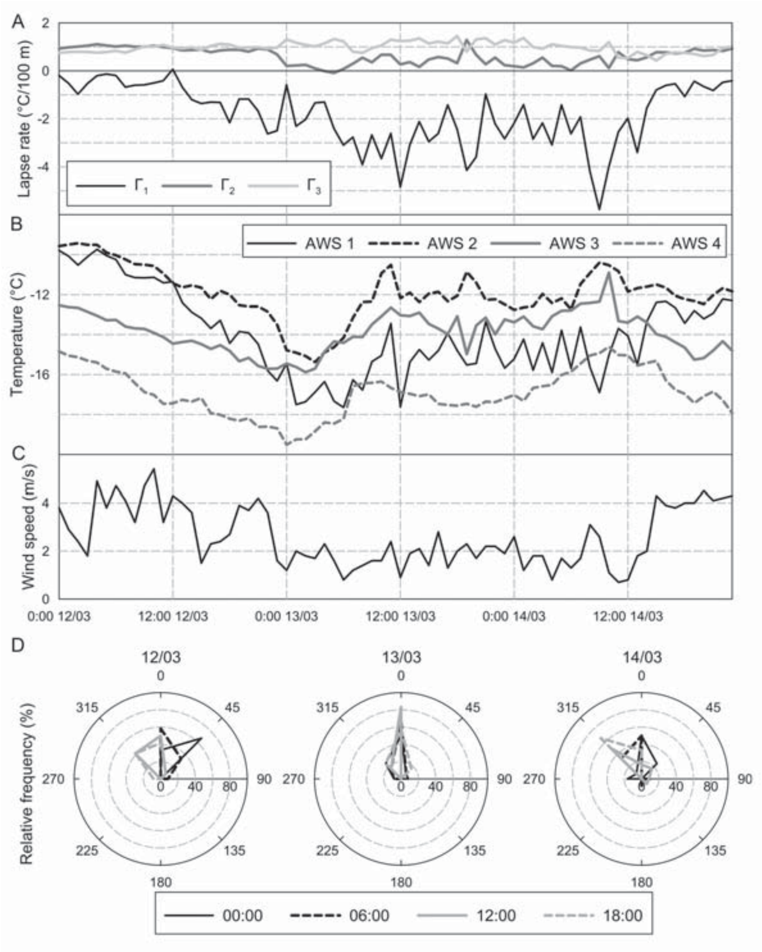

Fig. 7. Variability of near-surface lapse rate (**A**), air temperature (**B**), wind speed (**C**) and wind direction (**D**) from 12 to 14 March 2014 in Petuniabukta.

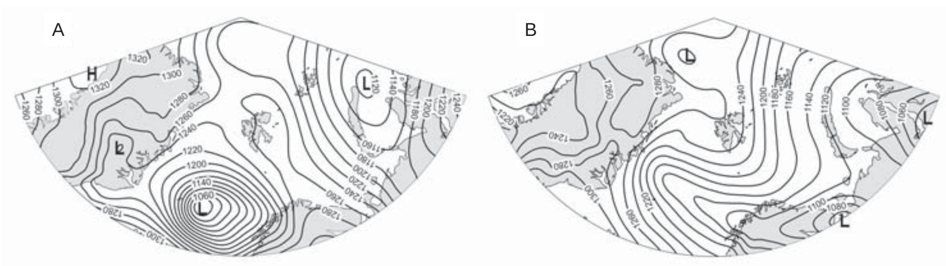

Fig. 8. 850 hPa pressure level height (m) on 13 March 2014 12:00 UTC (**A**) and 14 March 2014 18:00 UTC (**B**) in the North Atlantic region.

Discussion

In this study, air temperature variability with altitude was assessed at Petuniabukta in central Spitsbergen from August 2013 to July 2015. The average air temperature at Svalbard-Lufthavn, as well as the rest of the western coast of Spitsbergen, in the study period was above normal of the period 1980–2010 (Norwegian Meteorological Institute 2016a; Nordli *et al*. 2014; Gjelten *et al*. 2016). In spite of the fact that long-term measurements for Petuniabukta are not available, it is clear that the western coast of Petuniabukta was warmer during the study period than August 2008–June 2010, as analyzed by Láska *et al*. (2012).

The Γ in the three adjacent air layers Γ_1 to Γ_3 were found to be significantly different from the average lapse rate in the international standard atmosphere as well as the lapse rate calculated by linear regression. This implies that, for future studies in Svalbard focusing on topoclimate investigation and environmental modelling, the use of Γ calculated from measured air temperature data would lead to more accurate results, although it is recommended to confirm the results for a longer period of time. Analysis of the daily cycle revealed notable daily variations of both air temperature and Γ in spring, which agrees well with the results by Vihma *et al*. (2011) from the vicinity of Ny-Ålesund. The Γ in the lowest air layer was also found to have a strong annual cycle, however with marked differences between the two years. Therefore, it seems that the year-to-year differences in atmospheric circulation as well as sea ice conditions (Láska *et al*. 2012; Vihma *et al*. 2014) influence Γ and noticeably alter the regular annual cycle.

The difference in Γ between the layers is connected to the air temperature inversion frequency. As the case study indicates, surface cooling from snow and sea ice due to a negative radiation budget (Vihma *et al*. 2011; Mayer *et al*. 2012) seems to be the most likely mechanism for surface-based air temperature inversions in Petuniabukta. This conclusion is supported by the sharp decrease in air temperature inversion frequency in the period April–June with May being the last month with permanent snow cover in Petuniabukta (Láska *et al*. 2012). Moreover, the air temperature inversions in the lowest layer mostly coincided with low near-surface wind speed (result not shown in this study). Araźny *et al*. (2012) also connected the occurrence of elevated air temperature inversions from May to July to the presence of low-level clouds. Howerever, the typical height of the cloud condensation level is hard to determine for Petuniabukta, since Bednorz and Kolendowicz (2010) observed summer *Stratus* clouds base within a height of 100–300 m, but Láska *et al*. (2013) detected *Stratus* and *Stratocumulus* cloud-base height up to 700 m a.s.l. The air temperature inversion frequency in Petuniabukta had similar elementary characteristics as those analyzed by Serreze *et al*. (1992), who used radiosonde data from Barentsburg: an increase in the occurrence of inversions from summer to winter and a simultaneous decrease of the ratio of elevated and all inversions. The relative frequency of all inversions was approximately 15–30% lower in Petuniabukta, which could have been expected considering that Serreze *et al*. (1992) determined inversions up to the 700-hPa pressure level. The observed difference between the two studies is likely due to elevated air temperature inversions, as the greatest difference between the two studies occurred in summer.

The change of air temperature with altitude and Γ is comparable to the results of other short-term studies. The mean Γ in Hornsund in July–September 2005 (Migała *et al*. 2008) in the whole analysed air layer (from 26 to 133 m a.s.l.) was more than 0.2°C 100 m^{-1} higher than mean Γ_1 in Petuniabukta, which was also apparent from the air temperature inversion frequency being more than 10% higher in Petuniabukta. The results also indicate that the lowest very stable air layer is not as deep in Hornsund as in Petuniabukta, since the air temperature inversion frequency in the two study regions is comparable when the lowermost air layer is defined as being between the two AWS at the lowest altitudes. On the other hand, in the summer experiment of Bednorz and Kolendowicz (2010) conducted in part of July 2009 from inside the Ebba valley on the east coast of Petuniabukta, the Γ in the lowest 500 m a.s.l. was lower than for the corresponding air layer in this study. This difference could be connected to the bottom of the valley being heated more intensively in summer than the west coast of Petuniabukta, and so the temperature drop with altitude is more intensive in the valley (Barry 2008). Comparison of the present results with the yearlong study by Araźny *et al*. (2012), who derived mean monthly temperatures from six AWS situated between 11 to 590 m a.s.l. in the Forlandsundet region (NW Spitsbergen), reveals that, unlike in Petuniabukta, negative mean monthly Γ in Forlandsundet were observed even in higher air layers (*e.g*. 345–500 m a.s.l.). Another remarkable difference between the two sites was that the very low annual range of Γ detected in Petuniabukta above 126 m a.s.l. was not found in any other air layer in Forlandsundet. The possible reasons for the dissimilarities are: a) different land cover and geomorphological settings (some AWS in Forlandsundet region were situated on glacial moraines at the mouth of the valley), b) a shorter horizontal distance between AWS in Petuniabukta and c) different orientation of the study areas, as the valley in Forlandsundet was oriented to the west and the profile in Petuniabukta was on the eastern side of the mountain. Since most of these premises could also be applied to the studies of Migała *et al*. (2008) and Bednorz and Kolendowicz (2010), the topoclimatic differences seem to be the most important factor in the explanation of dissimilar Γ in various parts of Svalbard.

Conclusions

In this study, a two-year-long data set of air temperature from four different altitudes (23, 136, 455 and 764 m a.s.l.) from the coastal zone of Petuniabukta was presented and used for calculation of Γ as well as air temperature inversion frequencies. The most important conclusions are as follow.

1. The air temperature was very similar at the two lowest AWS with mean temperatures of about -3.7°C, but decreased with height at higher altitudes. The decrease of air temperature with height in Petuniabukta was larger than in Forlandsundet but smaller than in Hornsund.
2. The Γ differed significantly from the average lapse rate in the international standard atmosphere (0.65°C 100 m^{-1}) as well as from each other, with the lowest mean value in the lowermost layer. There was an annual cycle distinguished in Γ_1; however, the corresponding monthly mean values differed between the two analysed years, especially in winter. A slight daily cycle in Γ_1 was also apparent in spring and summer with the lowest values around 04:00 UTC.
3. The relative frequency of air temperature inversions was found to be up to 80% in the lowermost layer with an average value of 41% and a marked seasonal cycle. The relative frequencies of air temperature inversions in central Spitsbergen were always lower in 2013–2015 than in the study by Serreze *et al*. (1992), although both studies reported a similar annual cycle of air temperature inversions.

The near-surface temperature lapse rate approach used to study the air temperature-altitude dependence has brought new knowledge about local climate variations and a pronounced topographic effect in central Spitsbergen. However, for future experiments, we recommend to combine measurements of permanent AWS and special in-situ instrumentation, *e.g*. unmanned aerial vehicles or tethered balloons that give a more detailed picture about boundary layer processes and vertical temperature profiles over the study area.

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