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Spatiotemporal characteristics of seasonal snow cover in Northeast Greenland from in situ observations

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ABSTRACT

In this study, we quantified the spatiotemporal variability and trends in observations of multiple snow characteristics in High Arctic Zackenberg in Northeast Greenland through 18 years. Annual premelt snow-depth observations collected in 2005–2014 along an elevation gradient showed significant differences in snow depth between vegetation types. The seasonal snow cover was characterized by strong interannual variability in the Zackenberg region. Particularly the timing of snow-cover onset and melt, and the annual maximum accumulation, varied up to an order of magnitude between years. Hence, apart from the snow-cover fraction registered annually on 10 June, which exhibits a significant trend of −2.3% per year over the 18-year period, we found little evidence of significant trends in the observed snow-cover characteristics. Moreover, SnowModel results for the Zackenberg region confirmed that the pronounced interannual variability in snow precipitations has persisted in this High Arctic setting since 1979 and may have masked potential temporal trends. In exception, a significant difference in interannual variability of snow-cover onset timing was observed through the period 1997–2014, which in the recent period since 2006 was 7.3 times more variable.

Introduction

Within the last decades, the Arctic terrestrial snow cover has undergone changes, both in thickness and duration. The snow-cover extent (SCE) in the Arctic region has decreased by approximately 20% per decade during 1979–2013 (Blunden and Arndt, 2014). Moreover, the observed SCE reduction rate exceeds the simulated and projected rates of decreasing SCE, which are based on global climate model ensembles (Derksen and Brown, 2012; Blunden and Arndt, 2014). In addition, the timing of snowmelt onset has advanced 2 weeks on average in the pan-Arctic area since the start of the satellite era in 1979 (Tedesco et al., 2009). Snow model results for the terrestrial pan-Arctic region support in general an earlier snow-free date in spring and show that the maximum winter snow-water equivalent (SWE) decreased, the snow-cover onset occurred later in the autumn/early winter, and the length of the snow-covered period was reduced through the period 1979–2009 (Liston and Hiemstra, 2011). However, trends vary from positive to negative in regions across the Arctic area for the period 1979–2009 (Liston and Hiemstra, 2011) and 2001–2014 (Chen et al., 2015). Within North

America, Northern Eurasia, and the ice-free area of Greenland, there are regions with opposing trends in, for example, the annual snow precipitation, the timing of onset, and the end of core snow-covered period (Liston and Hiemstra, 2011).

In this study, we present a ground-based long-term time series of snow observations from Zackenberg in the High Arctic region of Greenland. Only a few ground-based studies using long-term snow observations have been conducted in the High Arctic (e.g., Zhang et al., 2000; Bulygina et al., 2011; Dyrrdal et al., 2013; Stuefer et al., 2013). However, these studies are valuable for mapping the diversity in changes and trends in snow variables within the pan-Arctic area. Furthermore, ground-based observations are requested as calibration and validation data sets for model simulations and remote sensing products and the development of such (Derksen et al., 2014; Bokhorst et al., 2016).

Finally, since the terrestrial snow cover is a key variable controlling Arctic ecosystem processes, these time series of snow observations are valuable in explaining changes seen in both biotic and abiotic components of the Arctic ecosystems (e.g., Jones, 1999; Post et al., 2009; Brooks et al., 2011; Callaghan et al., 2011; Cooper, 2014). The spatial distribution of snow depth is primarily driven by a combination of the dominant wind direction during and after snowfall (Liston and Sturm, 1998; Winstral et al., 2002), the topographic relief and slope orientation (Schirmer et al., 2011), and the vegetation cover, which traps wind-transported snow (Sturm et al., 2001). In addition, during the melt season, the snow-depth distribution is controlled by the availability of melt energy, which is governed by terrain elevation, slope, and aspect (Clark et al., 2011). Especially during the snow-covered season, when insulating properties of the snow cover (Goodrich, 1982; Sturm et al., 1997; Liston et al., 2002) provide stable thermal conditions in the below-snow environment, including the vegetation cover and soil (Schimel et al., 2004; Zhang, 2005; Bokhorst et al., 2011; Johansson et al., 2013). The soil thermal conditions moreover drive the microbial activity, the respiration rate, and the amount of soil organic carbon produced during winter (Elberling, 2007), and it controls the active-layer depth (Westermann et al., 2015). Hence, the snow-depth evolution through the autumn and winter governs the amount and timing of plant-available nutrients at the end of the winter and the following spring in tundra ecosystems (Schimel et al., 2004; Buckeridge and Grogan, 2008). The nutrient availability along with the meltwater released from the snowpack in spring (Jones, 1999) regulate, in turn, the vegetation growth far into the growing season (Blankinship et al., 2014) and thus the main food source for herbivores—for example, the muskoxen (*Ovibos moschatus*) (Kristensen et al., 2011; Schmidt et al., 2015; Mosbacher et al., 2016). Hence, the snow conditions in the preceding winter may have legacy effects on the following growing season(s), which makes snow observations essential in the understanding of ecosystem functions and feedbacks (Hollesen et al., 2015). Ultimately, due to the governing role of the snow, any observed changes, trends, and/or altered variability in snow conditions, may explain observed (inter-) seasonal effects, changes, and variability in the biotic components of the ecosystem. To identify significant trends and variability in ground-based snow observations, we examine an 18-year record comprising continuous observations of multiple, both point and spatially distributed, seasonal snow metrics collected as part of the Greenland Ecosystem Monitoring program (http://www.g-e-m.dk). We quantify the spatial variability, the temporal trends, and interannual as well as seasonal variation in a suite of ecologically relevant snow variables, which are all observed during the period 1997 through 2014. Additionally, we investigate whether the snow variables showed a change in interannual variability through the study period. Finally, modeled winter snow amounts for the period 1979–2014 allow us to explore whether the observed temporal variability and trends in the past 18 years of snow observations are unique in comparison to previous decades.

Study Area

The Zackenberg study area is located in the ice-free coastal part of Northeast Greenland (74°27′N, 20°34′W) (Fig. 1). The area has been covered by the Greenland Ice Sheet several times through geological history (Bennike et al., 2008). About 10,000 years ago, the lowland surrounding Zackenberg became ice-free, and today the ice sheet margin is located 70 km west of Zackenberg. The landscape in and surrounding Zackenberg is highly heterogeneous in terms of bedrock and sediment type,

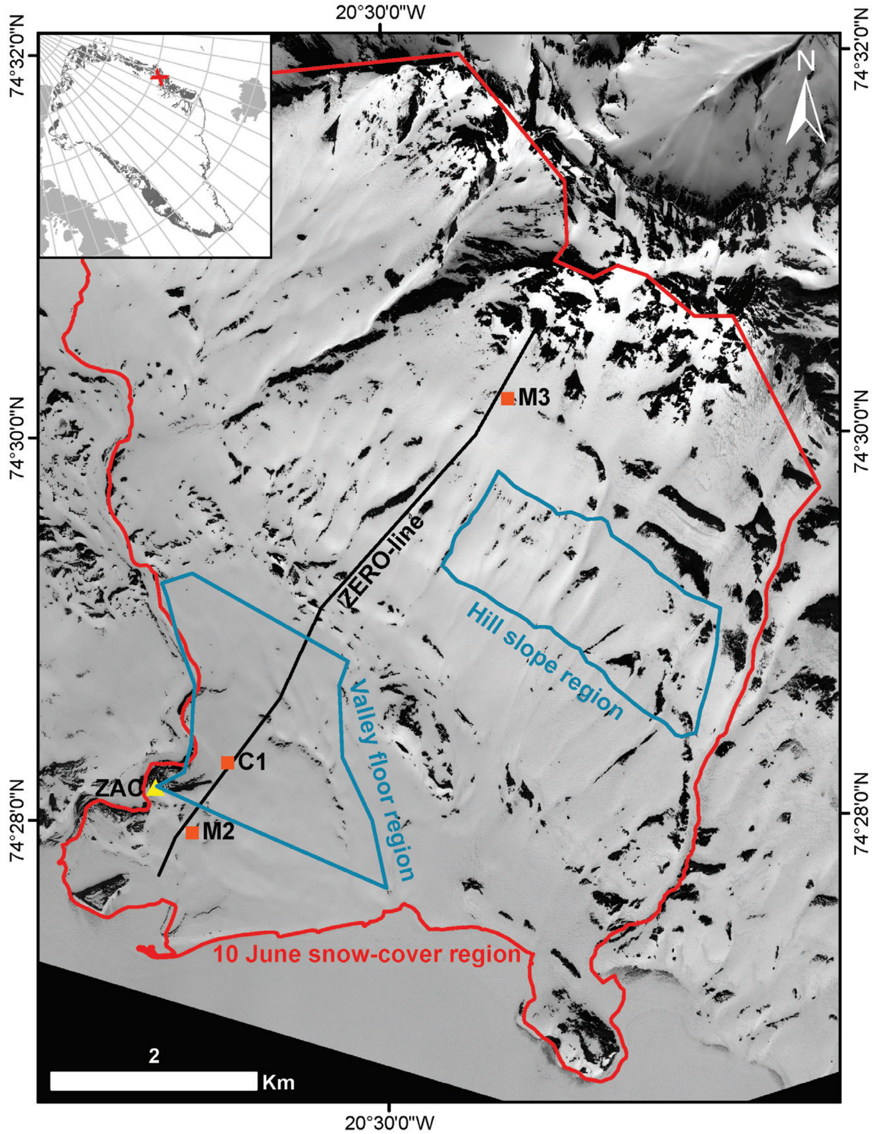

FIGURE 1. Zackenberg study area (QuickBird image from 31 May 2012) showing locations of climate stations C1, M2, and M3 (orange squares); ZERO-line transect (black line); the two regions Valley floor and Hill slope (blue line); the region for annual snow-cover estimations on 10 June (red line); and Zackenberg Research Station, ZAC (yellow triangle).

and the topography is characterized by deep fjords and valleys with elevations varying from sea level to mountain peaks reaching 1000–1400 meters above sea level (m a.s.l.). Zackenberg is located within the continuous permafrost zone, and the landscape development is thus dominated by periglacial processes (Westermann et al., 2015).

The Zackenberg study area is situated in the High Arctic zone (Bliss and Matveyeva, 1992) with a tundra climate (Kottek et al., 2006), which is mainly governed by the proximity to the Greenland Ice Sheet to the west and the Greenland Sea to the east. For the period 1997 through 2014, the monthly mean temperatures were between −19.8 °C (February) and 6.3 °C (July), and the yearly average temperature was −9.0 °C. There is polar night during 89 days and polar day during 106 days (refraction produces this asymmetry). The predominant wind direction is north during winter and southeast during summer, the latter mainly being triggered by the land-sea interaction. The annual average precipitation (snow and rain) for the hydrological years in Zackenberg (defined here to be 1 September to 31 August and denoted, e.g., "2012/2013") was 367 mm (1996–2014) varying between 222 mm (2003/2004) and 547 mm (2013/2014).

Methods

Snow Quantities and Snow-Cover Timing

The snow variables observed in Zackenberg include snow cover (i.e., presence or absence), snow

TABLE 1

Snow observations collected in Zackenberg by GeoBasis and ClimateBasis. All station locations are indicated in Figure 1. Data collection procedures are described by Sigsgaard et al. (2014). All data are available from http://www.zackenberg.dk, and data descriptions are given in ZERO Annual Reports 1–18 (http://www.zackenberg.dk/publications/annual-reports/).

Snow variable	Unit	Accuracy	Time series	Sampling method
Snow depth (sensor)	m	±0.01	1997–2014 (C1) 2003–2014 (M2) 2003–2014 (M3)	3-hourly measurements by automated sonic ranging snow-depth sensor (Campbell SR50a) located at the climate stations: C1 (74°28′20″N, 20°33′08″W, 38 m a.s.l.), M2 (74°27′56″N, 20°33′47″W, 19 m a.s.l.), and M3 (74°30′11″N, 20°27′35″W, 410 m a.s.l.).
Snow density	kg m^{-3}	*	2004–2014	Estimated in snow pits through layers using a RIP cutter, 250 cm^3 (http://www.snowmetrics.com), density cutter, 100 cm^3 (http://www.snowhydro.com) or ring samples (100–300 cm^3), and for full depth snow packs using Standard Federal Snow Sampler (Clyde, 1932). The density samples were collected only in March–November, when Zackenberg Research Station was manned.
Snow-water equivalent	m w.e.	*	2004–2014	From snow pit total depth and bulk snow density or from snow core length and snow density collected with Standard Federal Snow Sampler.
Snowfall events	#	—	1997–2014	Snow-depth increase from snow-depth sensor at C1.
Snow depth (ZERO-line)	m	±0.02	2005–2014	Premelt snow depth point measurements along the ZERO-line transect (Fig. 1) with GPS/MagnaProbe (http://www.snowhydro.com) every 10 m, or ground penetrating radar with a 500 MHz shielded antenna (http://www.malags.com).
Snow-cover fraction	%	—	1997–2014	Based on georeferenced, orthorectified, and snow-classified photos from automatic cameras (Buus-Hinkler et al., 2006). 10 June snow cover was estimated for a 47 km^2 region (Fig. 1).

*Accuracy varies with, e.g., snowpack stratigraphy and density cutter (Proksch et al., 2016).

depth and snow density, hence snow-water equivalent (SWE), and snowfall events. The metadata and sampling methods for these variables are described in Table 1, and the data are given in Tables 2 and 3. All observations are made by the climate and geophysical monitoring programs, ClimateBasis and GeoBasis, respectively. The spatial analysis of snow cover and topographic features was performed for two separate regions, Valley floor and Hill slope, where the snow-cover monitoring was conducted by GeoBasis (Fig. 1). The sampling methods were kept constant throughout the time series to allow for interannual comparison (Sigsgaard et al., 2014). The statistical methods, which are used for the quantification of the temporal trends and interannual variability, are described in the section Statistical Analysis.

To quantify the changes, trends, and temporal variability in the observed snow variables, we have calculated several snow metrics. Snowfall events (large snowfall events) were defined as times with a snow-depth increase (at climate station C1, Fig. 1) of more than 0.05 m (0.20 m) from one day to the next. In this way, snowfall events also include the large snowfall events. The thresholds (0.05 m and 0.20 m) were set according to the local snow conditions, where the snow depth varied up to ±0.05 m from day to day because blowing snow was de-

TABLE 2

Snow variables observed in Zackenberg from 1997 through 2014.

Hydrological year (1 Sep–31 Aug)	10 June snow cover (%)	Snow-cover duration (days)	Snow-cover end (DOY)	Snow-cover onset (DOY)	Snowfall events (#)	Large snowfall events (#)	Mean snow depth (C1) (m)	Maximum snow depth (C1) (m)
1997/1998	80	219	176	322	10	2	0.36	0.89
1998/1999	92	250	184	299	11	4	0.48	1.30
1999/2000	54	166	166	365	6	1	0.17	0.49
2000/2001	82	221	175	319	8	0	0.27	0.69
2001/2002	77	214	171	322	15	2	0.50	1.33
2002/2003	83	191	165	339	7	0	0.07	0.60
2003/2004	49	203	165	327	5	0	0.24	0.69
2004/2005	37	163	158	360	7	0	0.19	0.74
2005/2006	77	195	182	352	16	1	0.40	1.09
2006/2007	43	148	159	11	8	1	0.15	0.55
2007/2008	65	243	176	298	15	2	0.48	1.30
2008/2009	28	85	136	51	4	0	0.04	0.18
2009/2010	44	265	167	267	11	1	0.30	0.73
2010/2011	46	136	161	25	9	0	0.11	0.45
2011/2012	78	257	178	286	11	2	0.47	1.30
2012/2013	3	74	138	64	0	0	0.05	0.13
2013/2014	77	187	175	353	7	1	0.42	0.90

DOY = day of year. C1 = climate station.

posited and eroded from the snow surface and not because of snowfall. The snow-depth threshold for determining whether the ground was continuously snow-covered or snow-free was defined to be 0.10 m. This height equaled the maximum vegetation height and microtopographic relief in the Valley floor region surrounding the snow-depth sensor at C1 (Fig. 1). Further, the snow-cover fraction for the Valley floor region (described in the section Spatial Distribution of Snow) of 90%–100% coincided in time with snow depths above 0.10 m being measured at the automated snow-depth sensor at C1. Snow-cover onset is, herein, defined as the first day of a period, where the snow depth at C1 is continuously above 0.10 m. Snow-cover end is the last day in this period—that is, the day when the snow depth decreases below 0.10 m. The core snow-covered period corresponds to the period between snow-cover onset and end and is the longest continuous period in a winter when the snow depth is larger than 0.10 m. All metrics are calculated for the longest snow-depth time series from C1 (Table 1) in the observational data set. These point measurements are considered representative for the Valley floor region (Fig. 1), because it is a flat and homogeneous area, and also in terms of vegetation type and cover.

Spatial Distribution of Snow

To describe the spatial distribution of snow in the landscape in Zackenberg, we investigated the snow-depth temporal and spatial variability along an elevation gradient on a mountain slope (ZERO-line) and the spatial snow-cover depletion in the two confined regions, Valley floor and Hill slope. The monitoring transect, ZERO-line (Fredskild and Mogensen, 1997; Meltofte et al., 2008a), was established in 1992 on a southwest-facing slope covering an elevation gradient from sea level to 420 m a.s.l. (Fig. 1). In order to get an estimate of the snow accumulation during the preceding winter, snow-depth observations have been annually collected since 2005 along ZERO-line at the end of winter or early spring before

TABLE 3

Timing and duration of the snowmelt periods in the Valley floor region and Hill slope region.

Hydrological year (1 Sep–31 Aug)	Valley floor timing of 20% snow cover (DOY)	Valley floor timing of 50% snow cover (DOY)	Valley floor timing of 80% snow cover (DOY)	Hill slope timing of 20% snow cover (DOY)	Hill slope timing of 50% snow cover (DOY)	Hill slope timing of 80% snow cover (DOY)	Valley floor snowmelt duration (days)	Hill slope snowmelt duration (days)
1997/1998	—	173	—	212	186	173	—	39
1998/1999	187	184	180	228	188	181	7	47
1999/2000	168	162	160	178	168	160	8	18
2000/2001	177	175	174	196	186	181	3	15
2001/2002	177	170	164	197	178	160	13	37
2002/2003	165	164	158	165	161	147	7	18
2003/2004	164	158	157	174	158	156	7	18
2004/2005	160	155	154	171	163	153	6	18
2005/2006	186	170	175	210	196	177	11	33
2006/2007	165	162	157	174	165	156	8	18
2007/2008	178	174	167	185	171	163	11	22
2008/2009	151	149	143	174	164	159	8	15
2009/2010	168	167	162	175	167	156	6	19
2010/2011	166	162	158	179	168	160	8	19
2011/2012	180	177	170	195	179	166	10	29
2012/2013	150	148	139	150	148	139	11	11
2013/2014	178	169	165	203	180	167	13	36

DOY = day of year.

substantial melting had occurred in the snowpack. One premelt snow-depth transect per year was included in the analysis for the period 2005–2014. To verify that no or only limited melting had occurred previous to the snow-depth measurements, we defined two requirements: (1) the positive degree-day (PDD) sum during spring in Zackenberg should be less than 5 PDDs, and (2) the cumulated snow-depth decrease should be less than 0.07 m from the day of maximum snow depth to the day when the ZERO-line observations were made. The 0.07 m threshold corresponded to our observed maximum premelt snowpack settling. For these estimates, we used air temperature and snow-depth observations recorded at station C1 (Table 1, Fig. 1). All years in the period 2005–2014 met these requirements.

To investigate variations in the snow distribution amongst vegetation types and along the altitudinal gradient, we used the ZERO-line end-of-winter snow depths (Table 1). For each snow-depth measurement point along the ZERO-line in the period 2005–2014, we extracted the corresponding vegetation type from a vegetation map by Elberling et al. (2008), including *Dryas* heath, fell-field, fen, *Cassiope* heath, grassland, and *Salix* snowbed. Likewise, we extracted the elevation from a digital elevation model (DEM) with a 10-m horizontal resolution (originally rescaled from a DEM with 0.10-m horizontal and vertical resolution based on digital photos taken from drone flights over Zackenberg Valley in summer 2012). This 10-m resolution adequately described the Zackenberg area landscape features.

The temporal evolution of the snow-cover fractions for the Valley floor and Hill slope regions was estimated during the snowmelt season, to derive the timing of the spatially distributed spring snowmelt and to investigate its change and variability through the study period. For this, we used digital photos, which were daily acquired from April through August by an automated camera. These photos were geo-referenced and orthorectified by applying the method of Buus-Hinkler et al. (2006) and also used by Mernild et al. (2007), and subsequently we performed a snow-classification in the image-processing program ENVI (http://www.exelisvis.com). Similarly, the snow-cover fraction was estimated on 10 June within a region covering 47 km^2 of the Zackenberg Valley and the eastern mountain slopes from sea level to 880 m a.s.l. (see region marked in red in Fig. 1). The annual 10 June snow-cover fraction was referred to as "spring snow cover." Previous studies have demonstrated that this date can be linked to a range of ecological processes in the tundra ecosystem in Zackenberg (e.g., Forchhammer et al., 2005; Schmidt et al., 2006; Meltofte et al., 2008b; Pellissier et al., 2013). The timing of 80%, 50%, and 20% snow cover marked the onset, middle, and end of the core snowmelt season, respectively, for the regions Valley floor and Hill slope (Fig. 1). Hence, the duration of the core snowmelt period was defined as the difference in days between 80% and 20% snow cover.

In order to obtain a measure of the topographic variability that may influence the spatial snow distribution within each region, the mean terrain slope was calculated using the ArcMap GIS 10.1 "Spatial Analyst Surface Slope" tool and is defined as the average of slopes for all grid cells within a region. The terrain ruggedness (TR) was estimated using a method by Riley et al. (1999) and the GIS terrain analysis tool "Spatial Analyst Neighborhood Focal Statistics." TR is the summed change in elevation between a grid cell and the eight-cell neighborhood (Riley et al., 1999). The mean TR is the average TR of all grid cells within a defined region. Both the terrain slope and TR analysis was conducted on the 10-m horizontal resolution DEM, and the terrain slope was calculated over areas of 100 m by 100 m.

SnowModel 1979–2014

In order to investigate whether the observed temporal variability and trends in the past 18 years of snow observations have changed with respect to the previous decades, we used modeled SWE to extend the observational time series. The spatially distributed snow modeling tools, MicroMet (Liston and Elder, 2006a) and SnowModel (Liston and Elder, 2006b), were applied in the Zackenberg Valley using reanalysis data from ERA-Interim (Dee et al., 2011). This model setup, including a precipitation correction by assimilating observed SWE using SnowAssim (Liston and Hiemstra, 2008) for a terrestrial Greenland domain, is described in detail by Pedersen et al. (2015). For the period 2004–2014, modeled SWE was extracted from the grid cell corresponding to the location of the ground observations of SWE from snow pits dug in the end of winter (within the Valley floor region in all years) and at the same date as the ground observations were made. We compared the variability of the observed and modeled end-of-winter SWE to validate the ability of SnowModel to reproduce the interannual variability. To quantify if the variability in annual snow amounts had changed through the period 1979–2014, we compared the temporal variability in modeled end-of-winter SWE in both 5-year and 11-year periods within the 35-year modeled time series.

Statistical Analysis

For the trend analysis we used linear regression (ordinary least squares) between a given variable and time in order to quantify the direction of the trend (positive or negative) as well as the statistical significance of the trend (different from 0.0, i.e., $p < 0.05$). Furthermore, linear regression was also used for finding relationships between snow characteristics. Linear relationships between snowmelt duration in the two regions were quantified with correlation coefficients (r) as well as the covariance between annual maximum snow depths observed at the three Zackenberg meteorological stations (Table 1). F-tests were used to evaluate whether the variances of a variable (e.g., timing of onset or end of snow cover) in two periods were significantly different. We used an ANOVA to examine if snow depth varied among vegetation types and with elevation. Snow-depth data were logarithmic transformed—that is, log(snow depth + 0.01m)—to stabilize the variances to allow the application of the ANOVA. To account for the interannual variation in snow depth, we included the "year" as an explanatory variable in the model. As post hoc test we used Tukey's Honest Significant Differences for multiple comparisons of means ($p < 0.01$) to identify for which vegetation-types the mean snow depth were significantly different at a 95% confidence level. We used the software R (http://www.r-project.org/) for the statistical analysis.

Results

Snow Quantities and Temporal Variation

Snow-Covered Period

The 17 winters of snow depth from C1 in Zackenberg showed variable duration of the core snow-covered period (Fig. 2). The maximum snow-cover duration of 265 days was observed in winter 2009/2010 and the minimum duration was observed in winter 2012/2013, where the snow depth was above 0.10 m for only 74 consecutive days. In 2008/2009, the second shortest snow-cover duration of 85 days was registered (Figs. 2 and 3). Snow-poor winters (e.g., 2008/2009 and 2012/2013) had several shorter periods (2–17 days) with snow-covered ground before or after the core snow-covered period. The onset of the snow-covered period was also highly variable, ranging between 24 September and 5 March, through the 17-year period and thus contributed to the high interannual variability in the snow-cover duration (Fig. 3, Table 2). However, the end of the snow-covered period (snow-cover end) varied less—that is, between 16 May (2009) and 3 July (1999). The variance in timing of snow-cover onset in the early period (1997/1998–2005/2006) was significantly different ($F = 0.124$, $p < 0.001$) from the variance in the most recent period (2006/2007–2013/2014), and the variance was 7.3 times larger in the latter. This difference was not found for snow-cover end ($F = 0.274$, $p = 0.090$) between the same two periods. Likewise, the variances in the timing of 50% snow cover during spring in the Valley floor and Hill slope areas were not significantly different in the two periods 1997/1998–2005/2006 and 2006/2007–2013/2014 ($F = 0.730$, $p = 0.664$ and $F = 1.914$, $p = 0.408$, respectively). Additionally, the variance in snow-cover onset was approximately an order of magnitude (ratio = 8.7) higher than the variance in snow-cover end during the 17 winters. A trend analysis of the snow-cover timing through the period 1998–2014 showed no significant trends in snow-cover onset, snow-cover end, snow-cover duration, or timing of 50% snow cover (Table 4). However, the timing of 50% snow cover in Valley floor was tightly linked with snow-cover duration ($R^2 = 0.84$, $F = 60.87$, $p < 0.001$) (Fig. 3, Tables 2 and 3).

Snow Depth

Across years, the 10% highest snow depth (above 90th percentile for each winter) occurred between February and late May. No temporal trends were observed in either the mean snow depth or the annual maximum snow depth or the timing of the latter through the study period (Table 4). The annual maximum snow depth had a pronounced interannual variation ranging from 0.13 m in winter 2012/2013 to 1.33 m in 2001/2002 (Fig. 2). Measured maximum snow depth showed an interannual covariance in the period from 2003 through 2014 between C1 and M3 (*covariance* (C1, M3) = 0.12, $t = 2.533$, $p = 0.035$, $r = 0.667$), but no correlation with M2 (data not shown). The highest annual maximum snow depth (2.53 m in 2013/2014) was found at M2, which is installed in a snowdrift, and the lowest (0.09 m in 2012/2013) at M3, installed on a southwest-facing slope at 410 m a.s.l. (Fig. 1, Table 1).

Snow Density and Snow-Water Equivalent

The snow densities observed during the period 2004–2014 ranged between 173 kg m^{-3} (September 2009) and 685 kg m^{-3} (June 2005) and the mean density was 398 kg m^{-3} ± 104 kg m^{-3}, which compared with the bulk density of 380 kg m^{-3} for the tundra snow-cover class defined by Sturm et al. (1995). The mean monthly snow density showed an increase through the snow-covered season from September through June. The densities in June were in some years collected from melting snowpacks that may have contained liquid and/or refrozen meltwater causing the density increase in June (Fig. 4). SWE, estimated from all available bulk density observations and corresponding snow depths, had a median of 0.22 m of water equivalent (w.e.) in the period 2004–2014, and the maximum SWE observed in the period was 2.13 m w.e. in a 5-m-deep snowdrift (11 April 2008).

Snowfall Events

Snowfall events occurred from September through May and totaled 150 snowfall events in

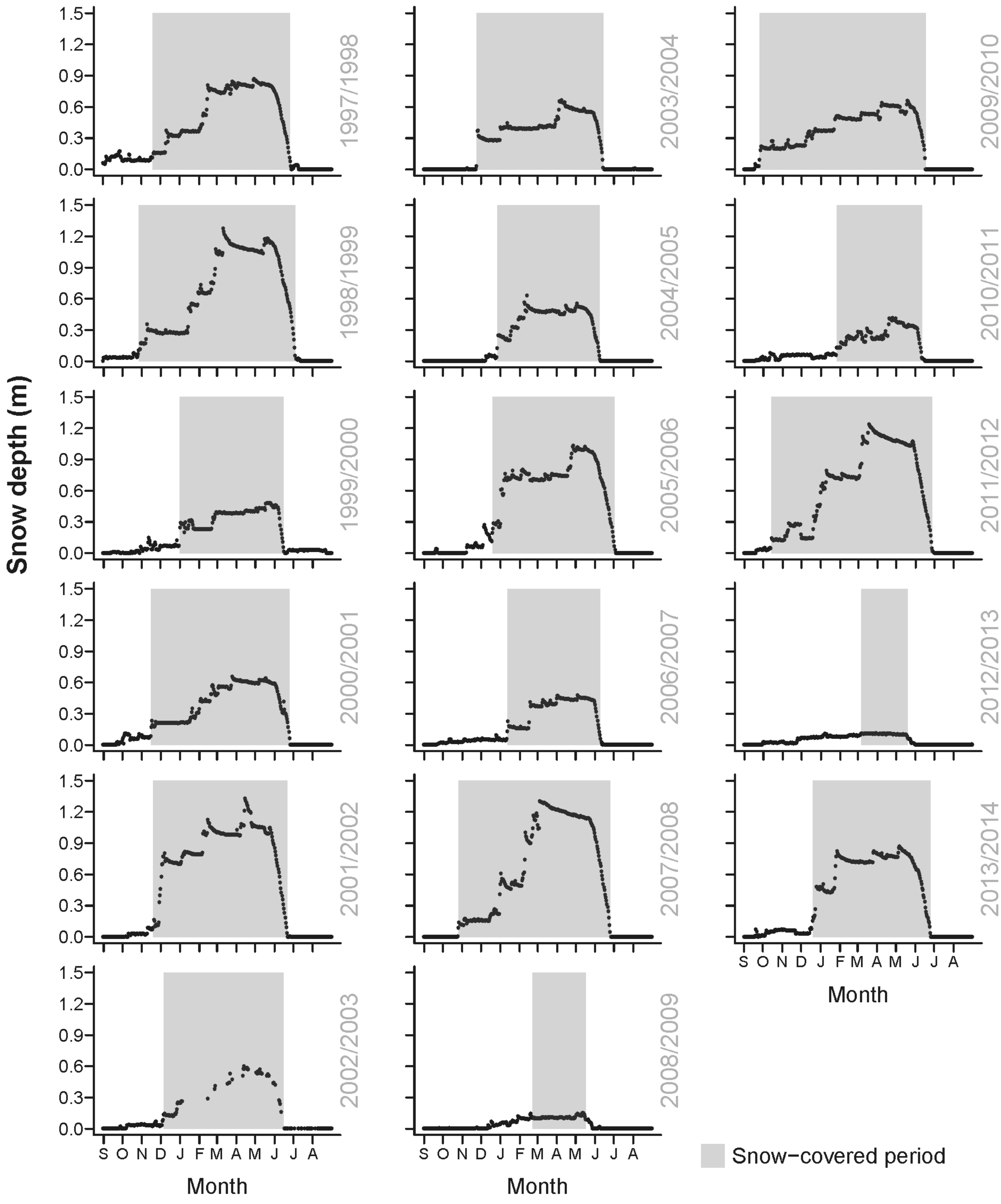

FIGURE 2. Daily snow depth (m) measured at C1 in the hydrological year (1 September–31 August) for the period 1 September 1997 through 31 August 2014. The gray shaded area marks the core snow-covered period from snow-cover onset (snow depth at C1 is above 0.10 m) to snow-cover end/snowmelt (snow depth at C1 is below 0.10 m), that is, the timing of the longest continuous period with snow depth above 0.10 m for each hydrological year.

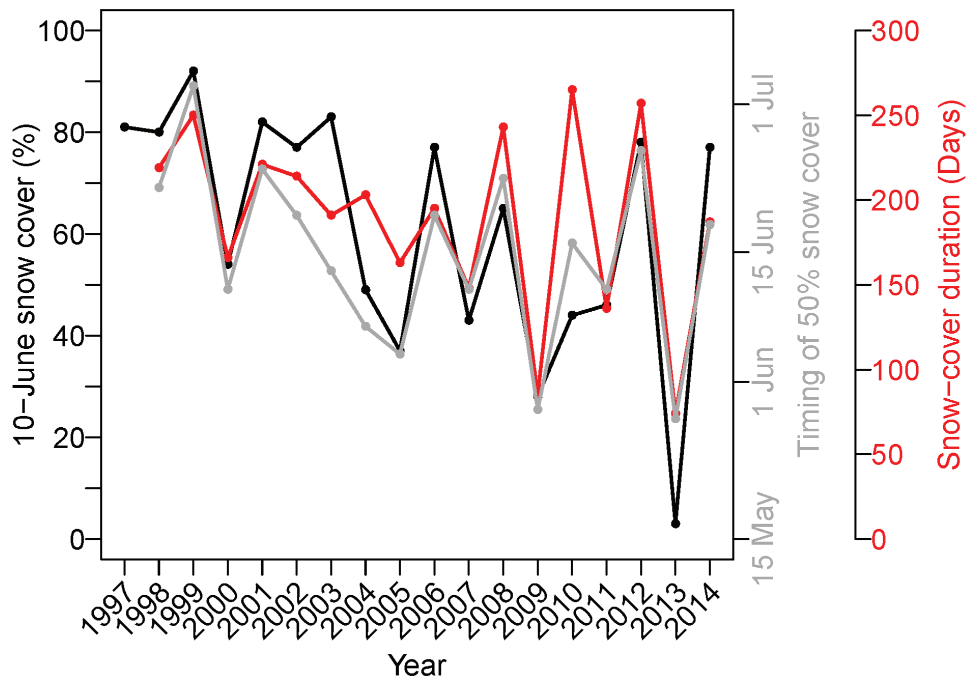

FIGURE 3. Snow-cover fraction estimated from georeferenced, orthorectified, and snow-classified photos taken at 10 June in years 1997–2014 (black points). Linear fit (dashed black regression line) statistics: slope = –2.3, R^2 = 0.27, F = 5.803, p = 0.028. Timing of 50% snow cover in Valley floor region, estimated from georeferenced, orthorectified, and snow-classified photos in years 1997–2014 (gray points). Snow-cover duration (days) for each hydrological year defined as the length of the period between snow-cover onset and end, where snow depth was consistently above 0.10 m at C1 (red points).

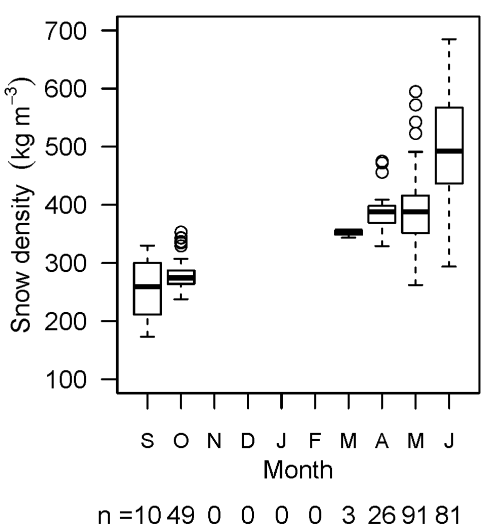

FIGURE 4. Snow bulk density (kg m^{-3}) collected in 2004–2014 within 5–10 m distance of the three meteorological stations: C1 on the Valley floor, M2 in a snowdrift, and M3 on a southwest-facing mountain slope. The total number of observations was 260, and most densities (91) were collected in May. No density observations were collected in November–February because the Zackenberg Research Station is unmanned during these months. The whiskers mark the data ranging between 1st quartile – 1.5 × IQR (the interquartile range) and 3rd quartile + 1.5 × IQR.

1997–2014 with the highest frequency (36) in January (Fig. 5, total given without parentheses). The highest number of annual snowfall events (16) occurred during the winter 2005/2006, whereas the winters 2001/2002 and 2007/2008 both included 15 snowfall events. Included in the 150 snowfall events were 17 large snowfall events (Fig. 5, totals given in parentheses). The highest frequency of large snowfall events (4) was found in winter 1998/1999, and over the years the month of February had the highest frequency of large snowfall events. There were no significant temporal trends in the number of all snowfall events or large snowfall events through the study period (Table 4).

Spring Snow Cover

The 10 June snow cover showed a pronounced interannual variation through the 18-year period ranging between 3% (7 June 2013) and 92% (10 June 1999) (Fig. 3). Furthermore, the 10 June snow-cover fraction showed a statistically significant decreasing trend and decreased on average 50% from

TABLE 4

Statistical details for temporal trends (significant trend at the 95% confidence level in bold) for snow variables observed in Zackenberg, Northeast Greenland.

						Linear Regression Statistics			
Snow variable	Station/ region	Period	Unit	Mean	SD	R^2	F	p	Slope ($year^{-1}$)
10 June snow cover	**SCR**	**1997–2014**	**%**	**61**	**24**	**0.27**	**5.803**	**0.03**	**–2.3**
Mean annual snow depth	C1	1998–2014	m	0.28	0.16	0.05	0.734	0.41	<0.1
Maximum snow depth	C1	1998–2014	m	0.79	0.38	0.06	0.984	0.34	<0.1
Max. snow-depth timing	C1	1998–2014	date/days	20 Apr	16	0.13	2.272	0.15	–1.1
Snow-cover onset	C1	1998–2014	date/days	8 Dec	45	0.08	1.217	0.29	2.3
Snow-cover end	C1	1998–2014	date/days	16 Jun	14	0.14	2.427	0.14	–1.0
Snow-cover duration	C1	1998–2014	days	189	54	0.11	1.769	0.20	–3.6
Mean annual snow depth	M2	2003–2014	m	0.49	0.25	0.23	2.654	0.14	<0.1
Mean annual snow depth	M3	2003–2014	m	0.13	0.13	0.28	3.181	0.11	<0.1
Snowfall events, all	C1	1998–2014	#	9	4	0.04	0.676	0.42	–0.2
Snowfall events, large	C1	1998–2014	#	1	1	0.10	1.724	0.21	–0.1
Snowmelt duration	VF	1998–2014	days	9	3	0.19	3.328	0.09	0.3
Snowmelt duration	HS	1998–2014	days	24	10	0.10	1.622	0.22	–0.6
Timing of :									
80% snow-cover fraction	VF	1998–2014	date/days	10 Jun	11	0.16	2.623	0.13	–0.9
50% snow-cover fraction	VF	1998–2014	date/days	15 Jun	10	0.14	2.427	0.14	–1.0
20% snow-cover fraction	VF	1998–2014	date/days	19 Jun	11	0.07	1.208	0.29	–0.7
80% snow-cover fraction	HS	1998–2014	date/days	10 Jun	11	0.17	2.971	0.11	–0.9
50% snow-cover fraction	HS	1998–2014	date/days	21 Jun	13	0.13	2.152	0.16	–0.9
20% snow-cover fraction	HS	1998–2014	date/days	5 Jul	20	0.16	2.847	0.11	–1.6

SCR = 10 June snow-cover region; C1, M2, and M3 = climate stations; VF = Valley floor region; HS = Hill slope region (all seen in Fig. 1). SD = Standard deviation, R^2 = coefficient of determination, p = P-value, F = F-statistics.

1997 to 2014 (R^2 = 0.27, F = 5.803, p = 0.028, Table 4, Fig. 3). There was no significant difference in the variance between the periods prior to and after 2006. However, the 10 June snow-cover time series varied up to 24 percentage points in standard deviation throughout the period.

Spatial Distribution of Snow

Snow-Depth Variability with Elevation and Vegetation Type

The mean snow depth in the 250-m distance intervals along the ZERO-line ranged between 0.3 m and 0.9 m for the years 2005–2014 (black points in Fig. 6, part a), and the maximum snow-depth point measurement was 3.5 m in 2012 at the lowest elevations (0–50 m a.s.l.) in a snowdrift near the M2 climate station (Fig. 1). The maximum snow depths of the ZERO-line time series were observed in the end of the snow-rich winter 2011/2012—that is, in spring 2012 (red points in Fig. 6, part a)—while the minimum snow depths were observed in spring 2009 along the transect (blue points in Fig. 6, part a). The snow-depth observations along ZERO-line (Fig. 1) showed the highest snow depth in the lowland (0–150 m a.s.l., 0–4 km in distance from the transect starting point) with varying slopes of smaller hills and depressions, where snow accumulated (Fig. 6, parts a and c). The lower snow depths were found at higher elevation (150–300 m a.s.l. and 4–5 km distance), where steeper slopes (~15%) and outcrops are blown free of snow. At elevation 300–350 m a.s.l., we found locally higher snow depths potentially due to snowdrifts building up on the lee-side of the edge

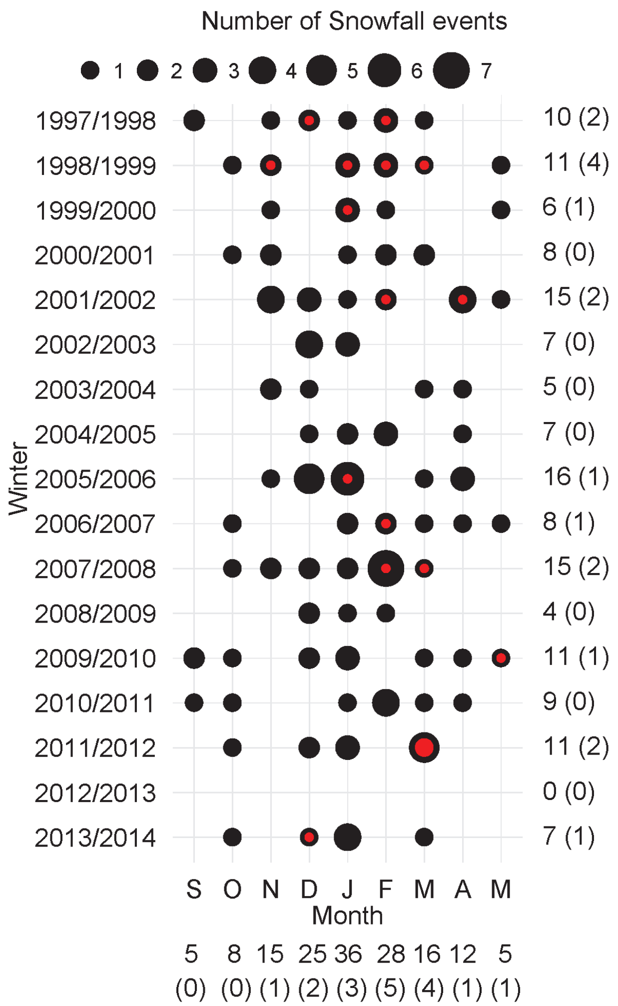

FIGURE 5. The monthly and annual sums of identified snowfall events (>0.05 m snow-depth increase per day, black points) and their distribution across the period September 1997 through August 2014. Large snowfall events (>0.20 m snow-depth increase per day) are marked with red points (large red point = 2 and small red point = 1 large snowfall event). In the margin, annual and monthly sums of snowfall events are given with the number of large snowfall events in parentheses.

of a relatively flat, wind-blown plateau at approximately 350 m a.s.l., where the slope decreased. There was no significant temporal trend in the annual variance in snow depth observations through the period 2005–2014 ($p > 0.05$).

Across the years, snow depth exhibited a consistent pattern of statistically significant different snow depths among vegetation types ($p < 0.01$) (Fig. 6, part b) and altitude ($p < 0.01$). The effect of "year" was also significant ($p < 0.01$), reflecting the interannual variation in the amounts of snow precipitation. We identified the vegetation types that had significantly different mean snow depth from other vegetation types ($p < 0.01$) (Fig. 6, part d).

Snowmelt and Snow-cover Depletion

The Valley floor and Hill slope, located in elevation levels at 0–50 m and 150–300 m a.s.l., respectively, were characterized by different topographic relief with a mean terrain ruggedness of 8 ± 5 m and 42 ± 8 m, and a mean terrain slope of 3.3% ± 3.7% and 14.3% ± 1.6%, respectively. Snow-cover depletion curves derived from the automatic cameras showed a difference in snowmelt timing and depletion rate between the two regions (Figs. 7 and 8). The timing of 80% and 20% snow cover was derived for each year-specific depletion curve for each region (Fig. 8, Table 3). The duration of the snowmelt period (80%–20% snow cover) lasted 3–13 days in the Valley floor and 11–47 days in the Hill slope. In all years, the Valley floor had the shortest snowmelt period of the two regions (Fig. 8). The snowmelt start (80% snow cover) occurred between 19 May and 30 June in the two regions (Figs. 7 and 8). The timing of snowmelt end (20% snow cover) occurred between 30 May and 6 July in the Valley floor and 30 May and 16 August in the Hill slope—that is, the snowmelt end occurred later in the Hill slope than in the Valley floor. Hence, the timing of snowmelt end varied less between years in the Valley floor than in the Hill slope region. We found no significant trends in the duration of snowmelt period for the two regions from 1998 through 2014 (Table 4). Episodic snowmelt events, when rapid snowmelt occurs during foehn wind events, are identified in other regions of ice-free Greenland (Pedersen et al., 2015). However, no such events have been identified in Zackenberg using either local meteorological station data or reanalysis data (Pedersen et al., 2015).

Modeled SWE 1979–2014

The modeled and observed end-of-winter SWE during the period 2004–2014 showed strong correspondence (Fig. 9, $R^2 = 0.82$, $F = 37.51$, $p < 0.001$, intercept = –0.02, slope = 1.03), and the interannual variances for the two data sets were not significantly different in either 5-year or 11-year intervals (F = 0.85–1.80, $p > 0.05$). Hence, the SnowModel repro-

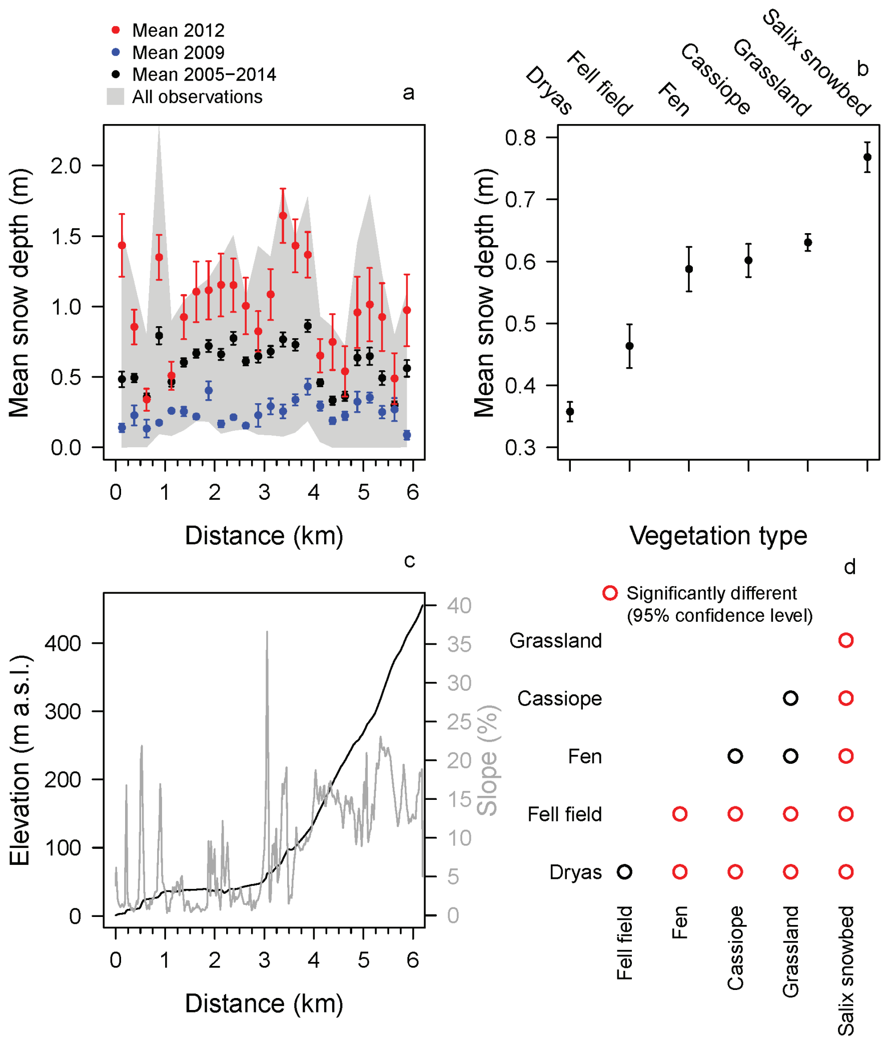

FIGURE 6. (a) Mean snow depth (m) (error bars are error on the mean) aggregated per 250 m along the ZERO-line transect in distance (km) from the starting point for all observations in the years 2005–2014 (black points), a snow-rich year 2011/2012 (red points), and a snow-poor year 2008/2009 (blue points). Gray shading: all snow-depth observations for all years excluding the 10% lowest and 10% highest values. (b) Mean snow depth (m) (error bars are error on the mean) for the period 2005–2014 for the six vegetation types observed along ZERO-line. (c) ZERO-line elevation (m above sea level) and slope (%) with distance (m) from the starting point of the transect (Fig. 1). (d) Matrix presenting results from Tukey's Honest Significant Differences for multiple comparisons of mean snow depths in six vegetation types. Red circles mark significantly different (*p* < 0.01) vegetation types in the pairwise comparison of mean snow depths.

duced the temporal variability in the snow conditions in Zackenberg and was a valid tool to model snow variables back in time. The variances in modeled end-of-winter SWE in 5-year periods (1980–1984, 1985–1989, 1990–1994, 1995–1999, 2000–2004, 2005–2009, and 2010–2014) and 11-year periods (1980–1990, 1991–2001, and 2002–2014) did not differ significantly ($F = 0.10–5.69$, $p > 0.05$). The modeled end-of-winter SWE showed no linear trend through the 35-year time series ($R^2 < 0.01$, $p > 0.05$, slope = 0.001), but the interannual variability was as variable as in the recent 11 years (2004–2014).

Discussion

In the present study, we found few temporal trends but high interannual variability in a suite of snow variables in the High Arctic ecosystem in Zackenberg. The spring snow cover decreased significantly through the period 1997–2014, indicating an increasingly patchy snow cover in the beginning of June. In addition, the spring snow cover on 10 June showed large interannual variation from 3% to 92% in the Valley floor region. The amount of snow—that is, the annual maximum snow depth—showed no significant temporal trend but a pronounced interannual variation up to an order of magnitude between years in Zackenberg. This interannual variation was particularly related to the variable number of snowfall events per winter, ranging between 0 and 16 events through the period 1997–2014, and occurring throughout the winter season from September through May. Moreover, the highly variable number of snowfall events and variable timing of snow-cover onset, which ranged over a period of approximately 162 days (~5 months) caused the durations of the snow-covered period to range from 74 to 265 days. Such variable duration of the snow-covered period effectively led to a relatively prolonged and shortened snow-free

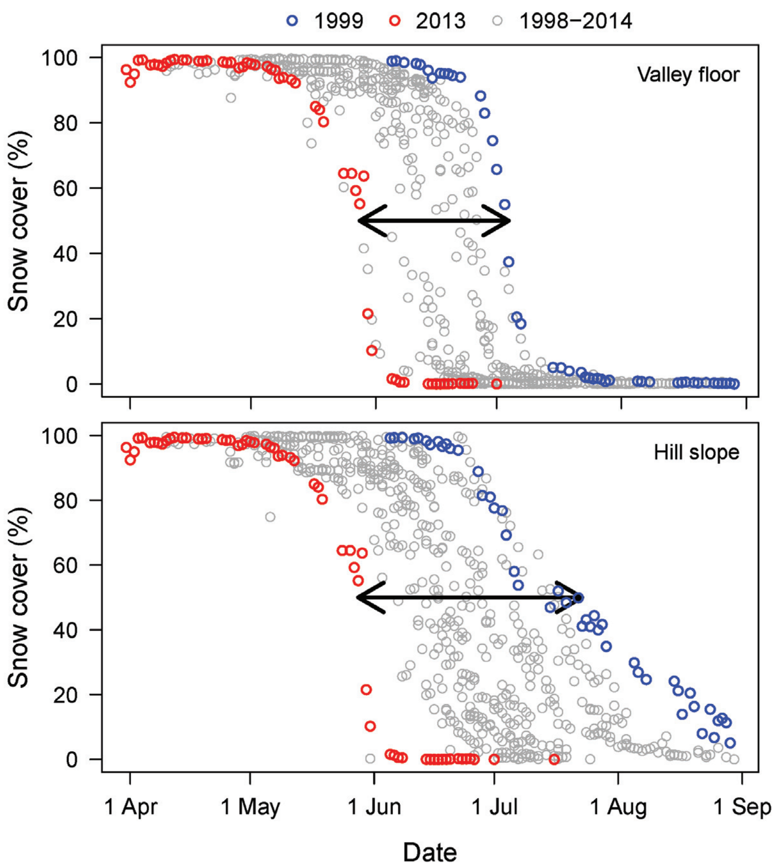

FIGURE 7. Snow-cover fraction per day during the snowmelt season (gray circles) for the two regions, Valley floor (top) and Hill slope (bottom) in the years 1998–2014. Snow-cover fractions in the snow-poor spring 2013 (red circles) and the snow-rich spring 1999 (blue circles). Arrows indicate the range in timing of 50% snow cover.

period from 1997 through 2014. In Svalbard, the onset of snowmelt shows large interannual variation (Rotschky et al., 2011), which can cause similar fluctuations in the length of snow-free period. In Zackenberg, where the lemming, a key species in the Arctic food web, has been monitored since 1996 (Meltofte and Berg, 2006), the predation pressure (by Arctic fox, stoat, snowy owl, and long-tailed skua) is high (Schmidt et al., 2008; Barraquand et al., 2014). Since the snow cover acts as protection and limits the foraging on lemmings for the local predators during winter, the lemming population size is sensitive to the length of the snow-free period and the variation between prolonged and shortened snow-free periods. Furthermore, the increased variability in the snow-cover onset in the recent years, may have caused the disappearance of the lemming population cycles in Zackenberg (Gilg et al., 2009; Schmidt et al., 2012) and hence affected the food web as a whole in this Arctic ecosystem.

However, despite years with contrasting snow conditions within the 11-year ZERO-line time series, with 2011/2012 being a snow-rich winter and 2008/2009 being a snow-poor winter, the relative spatial distribution of snow depth was similar from year to year (Fig. 6, part a), and we found no temporal trend in the variability of the transect snow depths through the observational period. The spatial pattern of relatively deeper snow and shallow snow packs along ZERO-line persisted from year to year given that the snow (re-)distribution during accumulation and erosion by wind is mainly controlled by the topography (Schirmer et al., 2011) and the spatial variability in slope. More specifically, there is a clear correspondence between areas with slope increase or decrease (i.e., a change in elevation; Fig. 6, part c) and mean snow depth (Fig. 6, part a). Hence in these areas, where wind-transported snow will accumulate on the lee-side slope of hills, the snow depth is found to be controlled by topography. The predominant wind direction during winter was from north in Zackenberg (observed at M3 and C1) and showed no interannual variation during the observation period. A similar persistent pattern in snow-depth distributions is found in annually repeated snow-depth transects in, for ex-

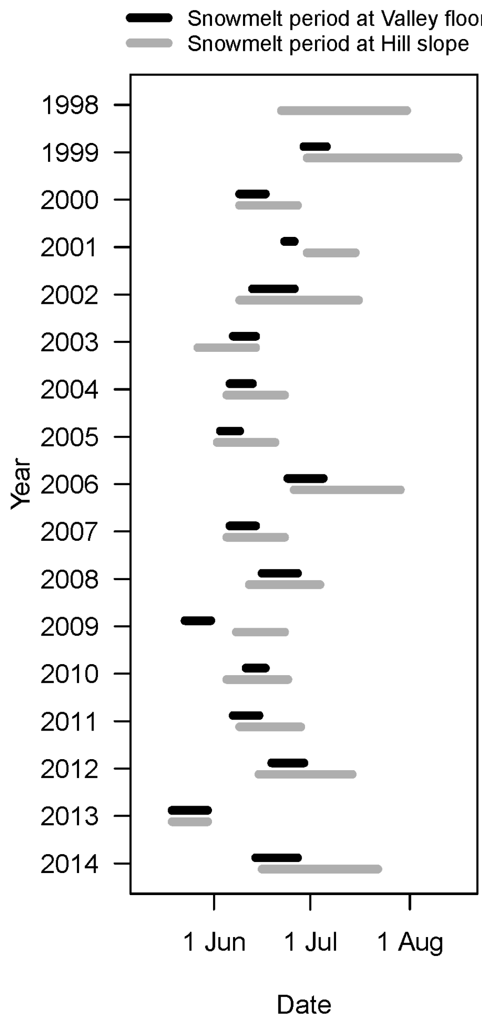

FIGURE 8. Timing and duration of the snowmelt period between 80% (left end of lines) and 20% (right end of lines) snow cover for two regions, Valley floor (black) and Hill slope (gray) in Zackenberg in 1998–2014. No data was available for Valley floor in 1998.

ample, Alaska, where it is primarily driven by the topographic relief but also the vegetation height (0–100 cm) and stand structure (Sturm and Wagner, 2010). However, for Zackenberg, located in the High Arctic climate zone where the vegetation cover is sparse and the vegetation height does not exceed 20 cm (Bay, 1998), it is most likely that the persistent pattern of the snow-depth distribution along the ZERO-line mainly controls the vegetation growth conditions and thus the spatial distribution of the vegetation types and not vice versa. This linkage was supported by the fact that the observed snow depths in the six vegetation types along the ZERO-line were significantly different and that vegetation types characteristic of wet and dry (i.e., snow-rich and snow-poor) environments could be distinguished from the snow depth data. The deepest snowpack was found in snowbeds dominated by *Salix arctica* (Fig. 6, part b), and the mean snow depth herein was consistently different from the mean snow depth in all other vegetation types across the 10 years (Fig. 6, part d). This may be expected since snowbed vegetation develop in moist environments, preferably down-slope from perennial snowdrifts (Björk and Molau, 2007). However, the mean snow depths in *Cassiope* heath, Fen, and Grassland did not differ significantly from each other, whereas both *Dryas* heath and Fell-field vegetation, which occur in more snow-poor areas (Fig. 6, part b), had a significantly different snow depth than observed for the remaining four vegetation types (Fig. 6, part d).

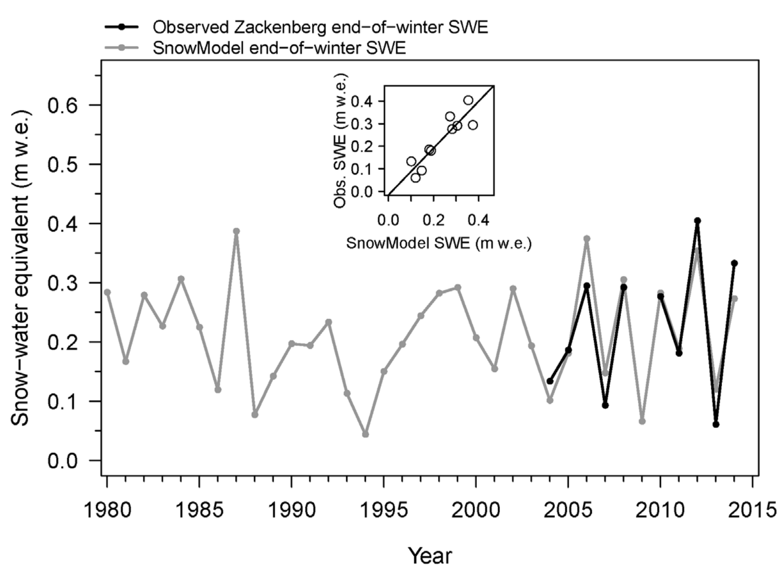

FIGURE 9. Modeled end-of-winter snow-water equivalent (SWE, m water equivalent [m w.e.]) from SnowModel in the period 1979 through 2014 compared with observed end-of-winter SWE (m w.e.) from snow pits dug in the period 26 March–6 June in 2004–2014 in Valley floor region, Zackenberg. Subplot: linear regression between observed and modeled end-of-winter SWE in 2004–2014 (no available SWE observation in 2009). Linear fit statistics: R^2 = 0.82, F = 37.51, p < 0.001, intercept = –0.02, slope = 1.03, n = 10.

Despite the larger snow depth in the lowland than at higher altitude on the slope, seen on the ZERO-line (Fig. 6, part a), the duration of the snowmelt period was more than 1.5 times longer on the Hill slope than in the Valley floor. The snowmelt started on average at the same time in the two regions (Figs. 7 and 8), which is controlled by the time when ambient temperature rises above freezing (Liston, 1995; Liston and Hall, 1995; Clow, 2009). However, the Hill slope snowmelt almost consistently ended later than in the Valley floor (Figs. 7 and 8). This extended snowmelt season on the Hill slope may be explained by the snowdrifts that built up in the more rough terrain on the slope, which eventually created a larger spatial variability in snow depth, resulting in a less steep snow-cover depletion curve than for the Valley floor (Clark et al., 2011). These snowdrifts take a longer time to melt away, hence postponing the snowmelt end until July/August. In Zackenberg snowdrifts persisted throughout the summer in some snow-rich years—for example, 1999 and 2014 (unpublished observations from automatic digital camera photos in summer 1999 and 2014). This may explain the higher interannual standard deviation in the length of the snowmelt period at the Hill slope than at the Valley floor (Table 4), since it is dependent on the presence and absence of snowdrifts and their extent and thickness from year to year; that is, the timing of snowmelt (20% snow cover) is primarily dependent on the maximum snow depth ($R^2 = 0.76$, $F = 42.62$, $p < 0.001$). Furthermore, we identified that the 80% snow cover occurred on average on 10 June in both regions. This may highlight that currently 10 June is a relevant indicator for spring snow cover since it marks the beginning of the snowmelt season. However, in a warming Arctic, when snow is predicted to melt earlier in the spring than currently observed, we could expect a change in this date (e.g., Barnett et al., 2005).

Modeled end-of-winter SWE lacked significant temporal trends, and the pronounced interannual variation in end-of-winter SWE in the recent years (2004–2014) did not differ from the interannual variation in end-of-winter SWE in the periods 1980–1990 and 1991–2001. SWE was directly linked to winter precipitation amounts, and therefore a main driver for the interannual variation in the snow variables presented in this study (snow depth, spring snow cover, and indirectly timing of snowmelt). Hence, the magnitude of interannual variation in these snow variables has likely remained unchanged at least since 1979. Additionally, the interannual variation seen the last decade, including the particularly dry winter 2012/2013, did not appear unusual in the 35-year time series. The finding of no change in temporal variability through the 35-year period was supported by the fact that we found no significant difference between snow variables in recent years (2006/2007–2013/2014) and the early years (1997/1998–2005/2006), except for the timing of snow-cover onset, which in the recent period was 7.3 times more variable. This increased temporal variability may point to a change in the autumn weather conditions, when the snow cover is established.

Conclusions

This study presented and discussed interannual variability and trends in a suite of snow variables in the High Arctic environment of Zackenberg in Northeast Greenland between 1979 and 2014. In the observation period (1997–2014), apart from 10 June snow-cover fraction, no presented snow variables showed significant temporal trends across the 18-year time series. The observed pronounced interannual variability mainly masked any potential trends. The distribution of end-of-winter snow depth observed in the ZERO-line transect was significantly affected by elevation and showed a significant difference in snow depth between the present vegetation types. SnowModel reproduced the temporal variability in the snow conditions in Zackenberg. Extending the time series of end-of-winter SWE to 1979 using SnowModel showed that the pronounced interannual variability in snow amounts observed in the recent decade, also was present over the last several decades back to 1979.

We have left the detailed explanation of the interactions between the abiotic and biotic components of this ecosystem to future studies. Likewise, we acknowledge that the temporal variability in the time series of snow observations presented herein possibly originate from changes in large-scale patterns and trends in, for example, Arctic synoptic-scale circulation patterns, the Greenland Ice Sheet–related weather patterns, and/or the near-shore sea-ice extent and concentration in the Greenland Sea. However, it is beyond the scope of this paper to explain the effect of these large-scale patterns and trends on our results. Hence, further research into large-scale circulation patterns' effect on local-scale snowfall events and timing of snowmelt is required in order to explain the interannual variation observed in Zackenberg.

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