A long-term Arctic snow depth record from Abisko, northern Sweden, 1913–2004

This article was modified in February 2008: Fig. 8 has been corrected.

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A newly digitized record of snow depth from the Abisko Scientific Research Station in northern Sweden covers the period 1913–present. Mean snow depths were taken from paper records of measurements made on a profile comprising 10 permanent stakes. This long-term record yields snow depths consistent with two other shorter term Abisko records: measurements made at another 10-stake profile (1974–present) and at a single stake (1956–present). The measurement interval is variable, ranging from daily to monthly, and there are no data for about half of the winter months in the period 1930–1956. To fill the gaps, we use a simple snowpack model driven by concurrent temperature and precipitation measurements at Abisko. Model snow depths are similar to observed; differences between the two records are comparable to those between profile and single stake measurements. For both model and observed snow depth records, the most statistically significant trend is in winter mean snow depths, amounting to an increase of about 2 cm or 5 % of the mean per decade over the whole measurement period, and 10 % per decade since the 1930–40s, but all seasonal means of snow depth show positive trends on the longest timescales. However, the start, end, and length of the snow season do not show any statistically significant long-term trends. Finally, the relation between the Arctic Oscillation index and Abisko temperature, precipitation and snow depth is positive and highly significant, with the best correlations for winter.

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The importance of snow cover to hydrology, domestic water supply, hydropower, albedo and Arctic ecology is overarching (e.g. Jones et al. 2001). In an ecological context, snow provides insulation for plants and soils (Sokratov & Barry 2002), a source of soil moisture in the growing season, shelter for animals and protection from predators (Callaghan et al. 2004). A recent assessment (ACIA 2005) finds that pan-Arctic temperatures have been increasing both on the century timescale and, more rapidly, over the past few decades. The pattern for precipitation also shows an overall increase over the 20th century, but a more varied spatial response in recent decades. The ACIA report concludes that the climate of the Arctic is already changing, that the rate of change is faster than at other latitudes and that the changes are very likely to continue.

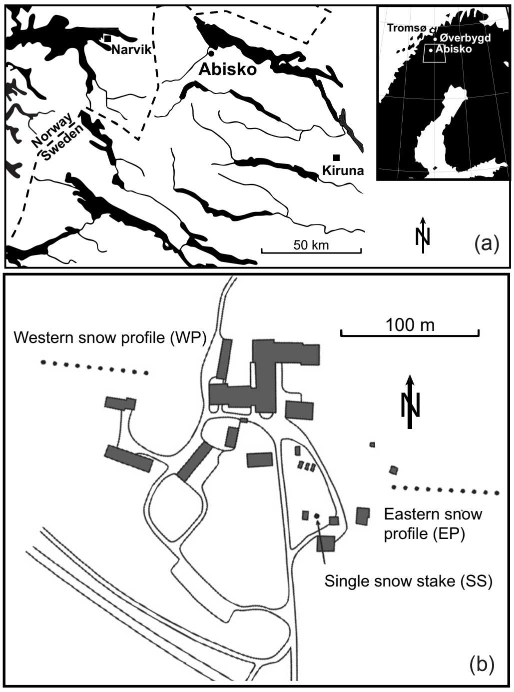


Fig. 1. (a) Location map of Abisko, Tromsø and Øverbygd. (b) Close-up view of station with buildings (black rectangles) and stakes used for snow measurements.

There is also increasing recognition that the most profound changes will be in winter. Although less is known about this period than summer, it is clear from satellite measurements that precipitation and snow cover in northern latitudes have decreased during recent decades (Brown 2000; Dye 2002; Bamzai 2003). However, long-term observational data records are rare and are furthermore prone to inhomogeneities since precipitation and snow measurements are easily influenced by local factors. Snow depth and snow properties such as density can vary over relatively short timescales, such that minor changes in the surrounding terrain, like the construction of buildings or the growth or removal of a stand of trees near the measurement site, can influence the deposition of snow.

Here we present a newly digitized long (1913–2004) record of snow depth measurements from the Abisko Scientific Research Station in northern Sweden. We describe and present the record, check it for consistency against other shorter term snow measurements at the Station, and compare it to a model snow record generated from concurrent temperature and precipitation measurements. We then present and discuss data and trends of such parameters as the length of snow season, dates of first and last snow, and various means of winter snow depths. We also compare our data to long-term snow records from Tromsø and Øverbygd, Norway, to see if trends observed at Abisko are part of a regional pattern.

Finally, we examine the connection between large-scale climate indices and the Abisko snow record. The Northern Hemisphere annular mode (NAM) is the most prominent pattern of atmospheric circulation variability in the Northern Hemisphere, influencing climate variability throughout the Arctic, particularly in winter (Thompson & Wallace 1998). The NAM is often referred to as the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO), but the basic phenomenon is essentially the same (e.g. Wallace 2000). Temporal variations in the NAM are embodied in this study by the AO index, the first principal component of the Northern Hemisphere sea level pressure field (e.g. Thompson & Wallace 1998).

Site description

Abisko is in northernmost Sweden (68° 21' N, 18° 49' E), near the Norwegian border (Fig. 1), and lies at an altitude of 385 m a.s.l. The Abisko Scientific Research Station was established as a year-round station in 1912. In 1913, climate monitoring began at the station. The mean annual temperature at Abisko is 0.7 °C for the period 1913–2000. Due to its location in a rain shadow, Abisko is relatively dry, with a mean annual precipitation of 310 mm for the period 1913–2000. July is both the warmest and rainiest month (Fig. 2); over 40 % of the annual precipitation occurs in summer (JJA), while only 15 % occurs in spring (MAM).

Data

Abisko snow measurements

Snow data for the period 1913–1929 are taken from meteorological yearbooks (Rolf 1930). Data from 1929 until 1988 were digitized directly from paper records held at the Abisko Station. Some snow data have been previously presented as graphs (Eriksson 1989). Since 1988, snow data have been entered digitally at the time the measurements were made. All snow measurements are

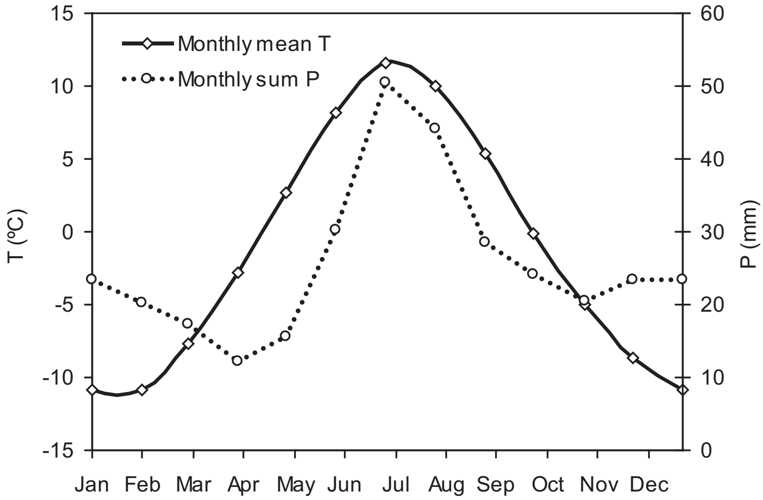


Fig. 2. Average climatology for Abisko: mean for the period 1913–2000 of the monthly mean temperatures and monthly summed precipitation.

made just after the daily morning meteorological observations at 07:00 local time.

Snow depth measurements were started on an eastern snow profile (EP) in 1913 (Fig. 1). From January until May 1913, snow depth was measured at five unmarked points equally divided between the main station building and the temperature screen at the meteorological station. In the autumn of 1913, a line of 10 stakes was established 50 m east of the original main building. These stakes were relocated in January 1914, since which time the stake locations have remained unchanged. Until 1929, measurements of the EP stakes were carried out daily, with only a few gaps (Fig. 3). From 1930 to 1956 the measurements were made at more variable intervals, typically 3 - 5 measurements per month, but occasionally there are significant gaps; several years are completely missing (Fig. 3). After 1956 the measurements become regularized and the EP series is then essentially uninterrupted from 1956 until the present, with measurements made usually every 5th day, year round, when appropriate.

A single stake (SS) snow measurement was started in 1956, at the meteorological station (Fig. 1), and has been carried out daily since then. This is a nearly complete series; there are no more than a few days without measurements. In 1974, an additional profile consisting of 10 stakes was established to the west of the main station (Fig. 1); snow depth has been monitored along this western profile (WP) at 5 day intervals since then. For the most part WP is measured on the same days as EP (Fig. 3).

The monthly mean EP snow depths are presented in Table 1. Months for which there were no measurements are indicated with a dash. Prior to 1929, monthly means are based on 20 - 31 measurements. For the period January 1930–September 1956, there are substantial gaps, and a lower measuring frequency, usually about 4 - 6 measurements per month. For several months there is just one measurement; means for these months are not included in Table 1. In other cases, 2 - 3 measurements are reported for only part of the month; these are not included either when it was not obvious that the unreported days in the month were days with zero snow depth. After 1956 the measurements are made regularly enough (4 - 7 times per month) to be considered complete and sufficiently representative for averaging.

Snow density

Between December 1914 and 1929, snowpack density was measured at Abisko Station throughout the winter at irregular intervals (Rolf 1930). No information is provided as to how or where exactly the density data were obtained. There are no density data after 1929.

Other snow records

The nearest long-term snow records available digitally are daily measurement series of snow depth made by the Norwegian Meteorological Institute at stations in Tromsø (100 m a.s.l.) and Øverbygd (230 m a.s.l.). Snow depth has been recorded at

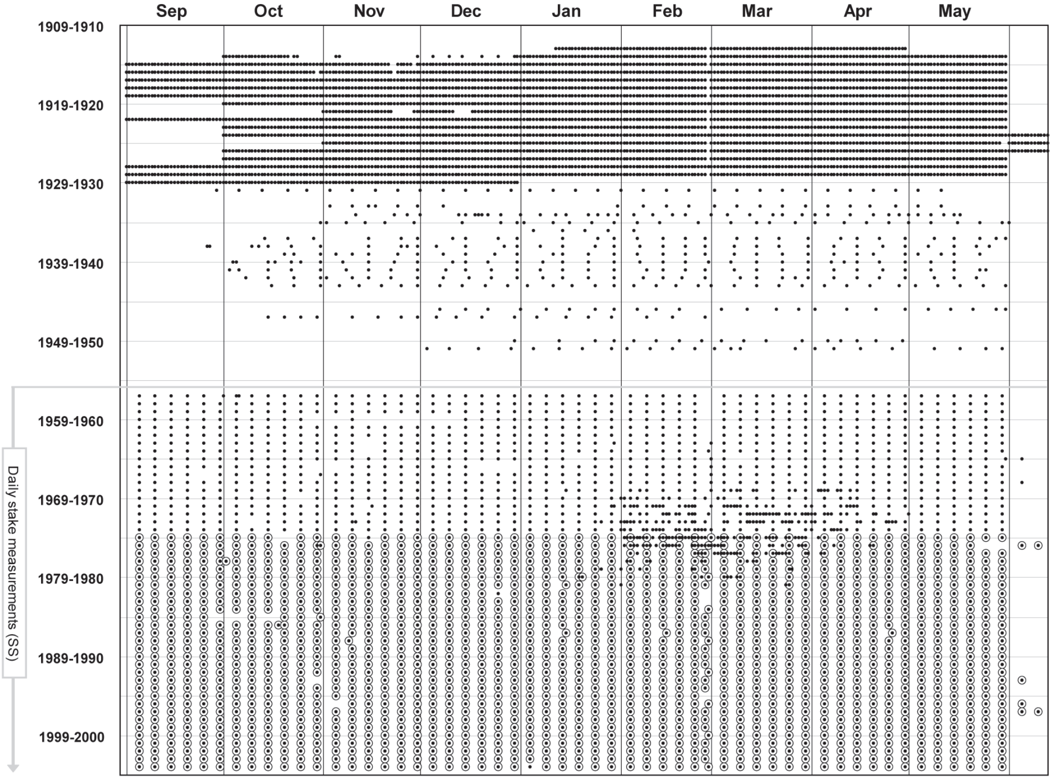


Fig. 3. Snow measurement dates. Black dots indicate snow depth recorded for eastern profile (EP), circles snow depth for western profile (WP) and the grey line daily measurements made at the single stake (SS) since October 1956.

Tromsø since January 1931, with only one missing month (September 1943), and at Øverbygd between January 1941 and December 1996, with only a few missing days. Monthly means were computed from the daily data.

Meteorological measurements

Meteorological measurements at Abisko have been made at the same site since 1913 (Fig. 1). The data we use are the 2-m screen air temperature, with observations made manually at three hour intervals from 01:00 to 22:00 local time, and the daily accumulated precipitation, measured daily at 07:00.

The temperature and precipitation records have been determined to be homogeneous over the entire measurement period (Holmgren & Tjus 1996). While a change of the site only some few tens of metres could disturb the homogeneity of a temperature record because of the sensitivity of temperature to small-scale topography, measurements have been carried out at the same site (atop a locally high point in the terrain) since 1913, using the same thermometer screen and similar instruments and calibration methods. Environmental changes, mainly the addition of nearby buildings, should have a comparatively small effect on the temperature trends. While such changes might have more influence on gauged precipitation, we use the precipitation data as recorded since there are no detailed investigations that could provide the data necessary for corrections. Similarly, we do not apply corrections for wind speed, which can influence snow catch. However, we note that the Swedish Meteorological and Hydrological Institute standard gauges with wind shields have been used since the start of the measurements, and that the buildings are comparatively far away from the measurement site and low in the terrain. The efficiency of low precipitation catch may have improved after aluminum gauges replaced the older zinc gauges, since zinc absorbs slightly more water, and after a lid was placed

Table 1. Monthly mean eastern profile (EP) snow depth (1913–2004), and model (MS) snow depth (1913–1999), by month and year (all depths in cm). Gaps in the EP record are indicated with a dash. (Table continues next page.)

	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS
1913	32		38		39		22		0		0	0	0	0	0	0	0	0	3	3	12	13	13	22
1914	35	32	45	42	54	50	43	41	7	9	0	0	0	0	0	0	0	0	0	0	2	3	16	9
1915	16	11	19	17	27	24	26	27	17	39	0	2	0	0	0	0	0	0	0	1	4	5	3	8
1916	14	20	23	32	25	33	25	33	0	5	0	0	0	0	0	0	1	0	8	6	8	10	16	19
1917	20	24	40	40	47	47	50	51	36	49	0	1	0	0	0	0	0	0	2	3	9	8	29	30
1918	36	47	52	76	51	73	49	67	11	22	0	0	0	0	0	0	0	0	0	0	1	4	3	11
1919	8	15	15	22	23	29	23	34	3	5	0	0	0	0	0	0	0	0	6	11	13	21	18	27
1920	37	39	44	46	51	52	38	25	8	7	0	0	0	0	0	0	0	0	0	0	4	1	5	1
1921	16	11	34	28	43	37	26	18	5	2	0	0	0	0	0	0	0	0	5	3	14	17	18	21
1922	19	25	20	25	25	27	27	26	0	0	0	0	0	0	0	0	0	0	3	1	21	12	37	27
1923	45	36	54	41	49	37	37	28	15	12	0	0	0	0	0	0	0	0	1	1	5	4	11	11
1924	18	18	27	28	34	37	35	40	7	10	0	0	0	0	0	0	0	0	0	0	4	2	8	3
1925	25	26	36	36	44	42	37	34	13	11	0	0	0	0	0	0	0	0	16	6	19	10	24	18
1926	30	23	38	29	35	35	44	47	11	13	0	0	0	0	0	0	0	0	0	0	7	4	23	16
1927	41	34	50	49	54	60	55	61	31	42	0	0	0	0	0	0	0	0	0	1	6	4	15	7
1928	15	10	17	11	13	7	8	7	0	0	0	0	0	0	0	0	2	1	15	13	32	36	36	39
1929	28	37	39	45	45	55	45	52	19	20	0	0	0	0	0	0	0	0	1	2	9	6	9	8
1930	-	12	-	16	-	29	-	20	-	0	0	0	0	0	0	0	0	0	2	3	4	4	11	9
1931	18	16	23	20	32	26	43	33	3	0	0	0	0	0	0	0	-	0	-	2	-	9	-	7
1932	-	10	-	44	-	46	-	50	-	37	-	0	-	0	-	0	-	0	-	1	10	4	-	17
1933	-	7	52	16	59	20	69	32	-	16	-	0	-	0	-	0	-	0	-	1	28	8	56	19
1934	76	47	93	70	99	76	98	75	38	7	0	0	0	0	0	0	-	0	-	0	50	21	52	26
1935	69	43	77	72	73	65	75	66	53	52	0	5	0	0	0	0	-	0	-	0	-	1	-	16
1936	55	30	-	45	-	54	-	58	-	3	0	0	0	0	0	0	0	0	4	2	12	6	32	14
1937	41	29	54	32	61	49	46	45	0	2	0	0	0	0	0	0	1	0	2	0	4	2	9	4
1938	17	12	34	27	41	35	36	37	7	11	0	0	0	0	0	0	0	0	1	0	7	4	15	8
1939	19	13	40	32	38	40	42	42	29	36	0	0	0	0	0	0	0	0	1	0	3	3	15	10
1940	24	23	31	27	40	36	45	47	8	7	0	0	0	0	0	0	0	0	3	1	11	6	22	12
1941	34	23	42	31	42	35	40	35	14	22	0	0	0	0	0	0	0	0	4	0	2	1	10	3
1942	27	22	37	25	50	35	34	36	5	8	0	0	0	0	0	0	0	0	16	7	29	22	36	40
1943	33	40	51	50	72	74	66	79	25	24	0	0	0	0	0	0	-	0	-	3	-	3	-	6
1944	-	16	-	23	-	26	-	26	-	7	-	0	-	0	-	0	-	0	-	0	-	2	-	20
1945	-	41	-	53	-	61	-	63	-	13	-	0	-	0	-	0	-	0	-	2	-	13	21	25
1946	30	33	31	42	46	53	38	61	9	25	0	0	0	0	0	0	0	0	9	9	9	7	8	4
1947	17	7	21	11	-	17	-	15	-	0	-	0	-	0	-	0	-	0	-	0	-	10	-	25
1948	-	34	-	41	-	41	-	8	-	2	-	0	-	0	-	0	-	0	-	2	-	2	-	28
1949	-	37	-	54	-	62	-	39	-	0	-	0	-	0	-	0	-	0	-	4	-	0	-	7
1950	21	9	25	7	33	9	28	4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	20	12
1951	35	22	39	24	36	19	34	18	11	3	-	0	-	0	-	0	-	0	-	0	-	5	-	21
1952	-	30	-	36	-	43	-	32	-	1	-	0	-	0	-	0	-	0	-	0	-	8	-	38
1953	-	55	-	74	-	90	-	98	-	19	-	0	-	0	-	0	-	0	-	0	-	1	-	2
1954	-	16	-	27	-	36	-	35	-	7	-	0	-	0	-	0	-	0	-	0	-	3	-	9
1955	-	17	-	27	-	45	-	52	-	60	-	1	-	0	-	0	-	0	-	1	-	6	-	40
1956	-	55	-	70	-	72	-	69	-	24	0	0	0	0	0	0	0	0	1	1	16	15	18	18
1957	28	30	36	44	39	51	16	32	0	1	0	0	0	0	0	0	0	0	5	3	3	1	23	15
1958	44	34	49	47	66	61	65	62	27	44	0	0	0	0	0	0	0	0	4	2	12	10	15	26
1959	30	37	42	42	44	36	38	25	0	0	0	0	0	0	0	0	0	0	0	0	-	1	8	4

Table 1. Continued from previous page.

	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS	EP	MS
1960	13	9	25	19	29	23	12	5	0	0	0	0	0	0	0	0	0	0	1	0	8	4	18	13
1961	25	20	35	35	54	51	55	54	15	33	0	0	0	0	0	0	0	0	0	0	16	10	33	24
1962	47	32	44	37	53	42	52	42	15	14	0	0	0	0	0	0	0	0	7	3	14	10	42	43
1963	57	57	69	64	72	66	66	61	7	6	0	0	0	0	0	0	0	0	0	1	18	10	26	16
1964	40	30	53	40	60	44	55	44	10	13	0	0	0	0	0	0	0	0	0	0	25	13	31	23
1965	45	38	61	50	74	65	80	100	39	86	0	13	0	0	0	0	0	0	4	4	2	0	10	14
1966	23	49	26	56	35	68	32	80	5	29	0	0	0	0	0	0	2	0	17	17	21	28	21	28
1967	29	34	35	42	42	44	34	38	5	9	0	0	0	0	0	0	0	0	3	2	17	17	32	25
1968	36	34	54	53	76	69	71	73	42	67	0	1	0	0	0	0	0	0	12	7	17	19	16	15
1969	28	23	30	25	39	30	37	32	3	14	0	0	0	0	0	0	0	0	7	5	7	7	9	17
1970	21	23	30	28	31	32	30	31	5	7	0	0	0	0	0	0	0	0	0	0	7	4	25	17
1971	28	33	44	47	47	50	46	50	12	22	0	0	0	0	0	0	0	0	4	3	11	5	25	19
1972	21	21	26	23	41	29	35	26	10	12	0	0	0	0	0	0	0	0	6	0	36	23	42	43
1973	57	58	66	68	73	75	71	72	32	39	0	0	0	0	0	0	0	0	5	1	15	10	26	24
1974	36	42	50	54	39	50	22	33	0	8	0	0	0	0	0	0	0	0	1	0	4	1	10	6
1975	27	26	32	30	36	28	36	26	3	2	0	0	0	0	0	0	0	0	4	1	7	2	35	28
1976	67	67	68	76	70	82	66	76	27	29	4	0	0	0	0	0	0	0	12	1	18	13	27	26
1977	32	30	42	37	57	55	59	63	19	33	0	0	0	0	0	0	0	0	9	11	11	14	24	25
1978	58	53	63	67	67	74	67	76	34	43	0	0	0	0	0	0	0	0	9	5	13	8	19	11
1979	33	20	36	26	44	37	37	37	0	14	0	0	0	0	0	0	0	0	4	2	6	3	15	12
1980	24	22	31	31	35	33	20	27	4	0	0	0	0	0	0	0	0	0	5	2	12	3	29	23
1981	42	37	46	54	55	60	42	58	12	24	0	0	0	0	0	0	0	0	2	0	6	1	25	18
1982	35	33	46	46	48	47	59	54	6	16	0	0	0	0	0	0	0	0	0	0	16	8	24	17
1983	37	26	47	30	59	35	51	32	5	2	0	0	0	0	0	0	0	0	8	1	38	41	64	69
1984	73	93	68	91	70	79	66	77	9	9	0	0	0	0	0	0	0	0	5	1	6	5	9	7
1985	23	15	36	26	40	32	44	39	10	12	0	0	0	0	0	0	0	0	6	1	21	12	26	17
1986	33	23	44	32	53	44	49	42	6	8	0	0	0	0	0	0	0	1	2	1	13	5	23	14
1987	28	16	51	37	55	47	54	50	14	24	0	0	0	0	0	0	0	0	0	0	24	11	48	34
1988	56	51	60	57	64	60	63	61	15	22	0	0	0	0	0	0	0	0	3	1	21	16	42	40
1989	58	58	89	89	85	92	67	69	10	11	0	0	0	0	0	0	3	0	6	1	9	2	27	20
1990	35	28	38	32	48	41	27	17	0	0	0	0	0	0	0	0	0	0	0	0	20	9	28	25
1991	30	23	38	24	48	31	26	10	1	0	0	0	0	0	0	0	0	0	3	4	24	19	43	50
1992	63	73	72	84	82	98	81	98	25	38	0	0	0	0	0	0	0	0	0	4	18	12	41	46
1993	56	85	78	103	97	128	97	136	37	54	0	0	0	0	0	0	0	0	7	2	10	4	25	13
1994	42	32	50	41	53	47	45	43	5	3	0	0	0	0	0	0	0	0	7	4	13	11	24	18
1995	33	31	37	37	36	39	32	37	12	22	0	0	0	0	0	0	0	0	9	6	41	47	44	59
1996	58	68	72	81	71	80	76	89	55	73	0	0	0	0	0	0	0	0	1	0	16	9	25	20
1997	63	50	82	93	87	102	92	109	45	59	0	0	0	0	0	0	0	0	4	0	14	5	26	21
1998	21	25	50	46	63	77	49	65	6	10	0	0	0	0	0	0	0	0	3	0	10	4	7	10
1999	20	21	28	28	27	26	22	20	1	1	0	0	0	0	0	0	0	0	0	0	13	2	16	6
2000	28		59		63		55		14		0		0		0		0		0		9		14	
2001	16		22		30		30		0		0		0		0		0		3		29		24	
2002	21		34		41		27		0		0		0		0		0		5		6		13	
2003	35		36		41		39		3		0		0		0		1		7		3		35	
2004	43		42		33		27		0		0		0		0		0		3		16		19	

inside the gauge to suppress evaporation. However, these factors are most important during spring and summer, when the incoming solar radiation is high, and we are mainly concerned with the winter precipitation.

Northern Hemisphere annular mode

The snow record was correlated with the most prominent pattern of atmospheric circulation variability in the Northern Hemisphere that influences climate variability throughout the Arctic, particularly in winter (Thompson & Wallace 1998). Monthly AO data means were obtained from the website of the Department of Atmospheric Science at Colorado State University (www.atmos.colostate.edu/ao/index.html). A comprehensive bibliography of the NAM and its climatic impacts can be found at the same site.

Methods

Correlation of snow measurements

To test the homogeneity of EP, correlations were made between EP and WP, EP and SS, and EP and the model snow record MS (see below). All days for which there are measurements in both EP and the other record are used for the respective correlations. However, the trivial agreement incurred by multiple occurrences of zero snow depth in summer is eliminated by restricting the comparison to the period between the first and last snowfall.

Determination of trends

Trends are calculated for the conventional three-month averages of the snow records, for the onset, conclusion and length of the snow cover season, as well as for temperature and precipitation. Trends are computed using a robust linear fit to the data (Press et al. 1993), as implemented in the software package MATLAB, and are assumed significant for p levels of 0.05 or better.

Model snow depth (MS)

To fill in the large gaps between 1930 and 1956 for which data do not exist at EP, we use a simple snow model driven with available meteorological data. We use a degree-day model (e.g. Rango & Martinec 1995) whose primary output is a daily synthetic snowpack record. Each model day, when the daily mean temperature is below a certain threshold, the snowpack amount is increased by an amount scaled to daily precipitation or is reduced by an amount scaled to the temperature over a second threshold.

Input data are the temperature measurements and precipitation measurements described in the data section. The 3-hr temperatures are averaged to form an effective temperature $T(t)$ record appropriate for the preceding period t_i during which the precipitation $P(t)$ collected in the gauge. Output data are daily snowpack water equivalent depth $A(t)$ and daily snowpack depth $S(t)$.

Three parameters control the behaviour of the model: T_{SR}, T_{DD0}, and DD_S. At each time-step t_i, when the air temperature $T(t_i)$ is less than a threshold temperature T_{SR}, precipitation occurs as snow, and $A(t_i)$ increases by the precipitation amount $P(t_i)$. When $T(t_i)$ is greater than or equal to T_{SR}, precipitation occurs as rain. We ignore the complication of modelling the water and heat budget of the snowpack or of the ground, and allow rain to pass through the snowpack box and out of the model. When $T(t_i)$ is greater than a second threshold temperature T_{DD0}, the snowpack water equivalent depth $A(t_i)$ is reduced at a rate:

$$DD_S\,[T(t_i) - T_{DD0}]\,.$$

Melted snow is treated like rain, as described above, moving out of the model.

The degree-day factor DD_S and the degree-day zero point T_{DD0} determine the amount of snowmelt. Degree-day factors are affected by the air, snowpack and ground temperatures, and snow albedo, and typically are found to vary during the season (e.g. Rango & Martinec 1995). We implement another parameterization, namely we multiply DD_S with a sawtooth function that varies linearly throughout the season, from 0 in October to a maximum of 1 in June. This simple parameterization is suggested both from the literature (Rango & Martinec 1995) and from our own analysis of the Abisko data, in which we compare daily temperatures to observed decreases in snow depth, for days with no precipitation.

The parameter T_{SR} can often be taken directly from meteorological records, but in the case of Abisko, there do not appear to be any data available that distinguish the precipitation type. We must thus treat TSR as an adjustable parameter.

Finally, $A(t)$ is converted to snow depth using

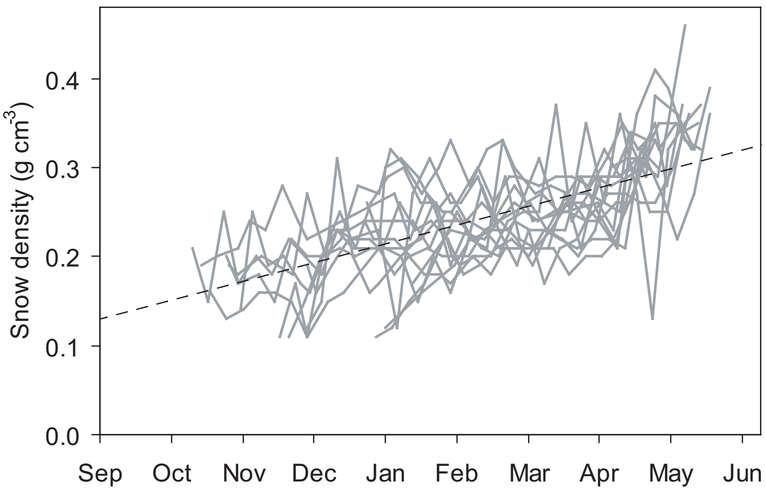


Fig. 4. Snow density for 15 winters (1914–1929, individual years not distinguished), and a linear fit (slope = 0.00068 g cm^{-3} d^{-1}) for all years (dashed line).

the formula:

$$S(t) = A(t)\,)\,/\,\rho_s(t)\,,$$

where $\rho_s(t)$ is a time-dependent density function. Strictly speaking, this represents another free parameter, but we use the limited density measurements to specify $\rho_s(t)$. Many physical processes influence the density of a snowpack, but most of these correlate with the relative age of the snowpack, that is, the number of days into the winter season (e.g. Pomeroy & Gray 1995). This can be seen in the Abisko data, which show a consistently linear trend from year to year (Fig. 4). Although these data are restricted to the early period (1913–1929), it seems unlikely that there should be a significant change in the average seasonal linear trend implied by these measurements, given the high year-to-year variability, so we simply use the mean linear trend of 0.00068 g cm^{-3} d^{-1} to parameterize $\rho_s(t)$ (Fig. 4).

Estimating model parameters

Degree-day models (e.g. Rango & Martinec 1995; Lindström et al. 1997) must be calibrated since parameter values, particularly degree-day coefficients, vary widely according to the location (e.g. Hock 2003). Thus we seek to optimize the model parameters to get the best fit of observed to modelled data. Many optimization schemes (e.g. Menke 1989) search parameter space for minima in a merit function that evaluates the fit between model and data, but such schemes can easily become stuck in local minima of the merit function. We take the simpler approach of exhaustively exploring the merit function on a regular grid in parameter space.

We assume an expected range of values for the parameters and, moving systematically at reasonable step-sizes between these minimum and maximum values, obtain a trial modelled daily snowpack thickness S^* time-series for each combination of parameters. We assess model goodness-of-fit by performing a linear regression of S^* to the observed EP values, on the appropriate days with data, in this case from 1 January 1914 to 31 December 1999. This results in a goodness-of-fit coefficient (r^2) computed for each combination of the model parameters T_{SR}, T_{DD0}, and DD_{S}.

In performing a linear regression between S^* and EP we are applying implicitly a constant adjustment factor relating modelled to observed snow. The factor is about 2.7, that is, the actual observed snowpack is only one-third the thickness implied by the amount of reported precipitation and the average bulk snow density. This factor might be explained by undercatch in the precipitation gauge, post-depositional wind erosion of the snowpack or sublimation.

We explore the region in parameter space delimited by

$$T_{\mathrm{DD0}} = -0.5 - +2.5\,^{\circ}\mathrm{C}\,,$$

$$T_{\mathrm{SR}} = -1.5 - +1.0\,^{\circ}\mathrm{C}\,,$$

and

$$DD_{\mathrm{S}} = 2 - 12 \text{ mm } ^{\circ}\mathrm{C}^{-1}\ \mathrm{d}^{-1},$$

and evaluate the goodness-of-fit coefficient (r^2) at intervals of 0.25 in each parameter. The resultant best-fit modelled snowpack, selected on the basis of the best r^2 value within this defined parameter space, comprises daily snow depths and is hereafter referred to as MS.

Snow phenology

We define the start of the snow season WS as the first of any successive five days in autumn with snow depths 1 cm or more. In some years the snowpack may melt away again later in the autumn, but as long as there are five consecutive days with non-zero snow depths, this constitutes the start.

Both MS and SS are daily records, making identification of their respective start of snow season dates WS_{MS} and WS_{SS} straightforward. It is also easy enough to determine WS_{EP} for the early part of the EP record (1914–1929) since these years comprise daily measurements, and in most years there are a sufficient number of zero snow depths to permit ready identification of the start. For the period 1929–1956, EP measurements are more difficult to interpret. In some years, snow depth measurements start at amounts that suggest there may have been snow prior to the first recorded day. In such cases we assume that the snow season starts on the first day with measurements, although there could have been snow as many as five to seven days earlier, the exact number depending on the typical measurement frequency for a given year. For this period, the measurement frequency is erratic, resulting in the most unreliable estimate of WS_{EP}. After 1956, the measurements are made at a more consistent five-day interval. Here we use the criterion that WS_{EP} occurs on the first of two consecutive non-zero autumn measurements, assuming implicitly that the intervening days are not precisely zero. Owing to these inherent difficulties, we identified WS_{EP} manually.

We then define the end of the snow season WE as the first of three consecutive days with zero snow depth. As with WS_{EP}, the sparse EP data hinder identification of WE_{EP}. In spring, however, it is easy in most years to estimate the last day with snow by extrapolating snow depths, which often decrease linearly over a 1 - 2 week period. Similar to WE_{EP}, we indicate uncertainty by determining the most extreme values that WS_{EP} could take.

Finally we calculate the length of snow season WL_{EP} as simply the difference in number of days between WS_{EP} and WE_{EP}, and similarly for MS and SS.

Leap years overcorrect for annual differences that arise between the absolute timescale imposed by the equinoxes and the 365 day calendar (e.g. Sagarin 2001), such that long-term trends in phenology that are not corrected to the absolute time of each year's equinox include a slight drift, amounting to nearly a day over the years 1900–1999. The length of season is also affected, although this is less significant, with less than an hour's difference between the vernal and autumnal equinoxes for the same period. We adjust the phonological data by subtracting from the WE and WP records the difference in days between the 20th century mean date of the vernal equinox, and the actual date for each year, available from a variety of sources (in this case, http://aom.giss.nasa.gov/srvernal.html).

Results

EP means and extremes

The maximum EP monthly snow depth usually occurs in March, the mean of which is 51.5 cm for the 79 complete winter records (Fig. 5). The lowest annual maximum monthly observed values occurred in 1928 (17 cm), 1919 (23 cm) and 1916 (25 cm), whereas the highest annual maximum monthly values occurred in 1934 (99 cm) and 1993 (97 cm). Snow usually persists from October through May. In two years, 1924 and 1976, snow persisted until June and in 1976, only July and August were snow-free (Table 1).

Intercorrelations between Abisko snow measurements

The concurrent measurements made at EP and WP since 1974 show that snow depths on the two profiles agree well with each other (Fig. 6a, b). There is a slight tendency for more snow to accumulate at WP when snow depths are large (Fig. 6b), and there is also an intraseasonal temporal trend to the EP–WP differences (Fig. 6c), indicating that EP snow depths increase relative to WP as each winter season progresses. However, the latter trend is not consistent; in a few years WP increases more than EP throughout the winter. There is also a slight but statistically significant temporal trend to EP–WP differences for most

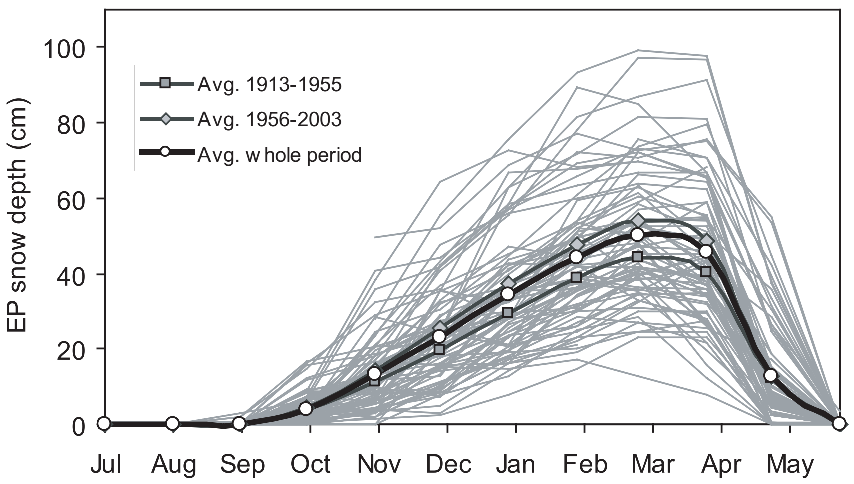


Fig. 5. Monthly EP snow climatology for Abisko, 1913–2003 (individual years, represented by grey lines, are not distinguished) and means for the entire measurement period, 1913–2003 (black line with open circles), the first part of the record, 1913–1955 (black line with grey squares) and the second part of the record, 1956–2003 (black line with grey diamonds).

months, with a maximum for March and April of about 2.5 mm a^{-1} over the entire joint 30 year measurement period. Neglecting these temporal trends, the mean of the EP–WP differences is 1.4 cm, and the standard deviation 4.4 cm.

The correlation between SS and EP (Fig. 7a, b) is poorer than for EP–WP, with more than twice the variability (the standard deviation of the differences is over 10 cm). This is to be expected since we are comparing a single stake measurement to an average based on 10 stakes. The variability is comparable to the variability between individual stake measurements in EP, as determined from data in the first year of the EP measurements, the only year for which we have complete data for each stake in the network.

There is no strong intraseasonal temporal trend to the EP–SS differences (Fig. 7c); however, there appears to be a sudden decrease in the differences after 1974 for the months February–May, giving a slight negative temporal trend over the joint measurements period. Again neglecting this small temporal trend, the mean of the differences EP–SS is 1.6 cm, and the standard deviation 10.4 cm.

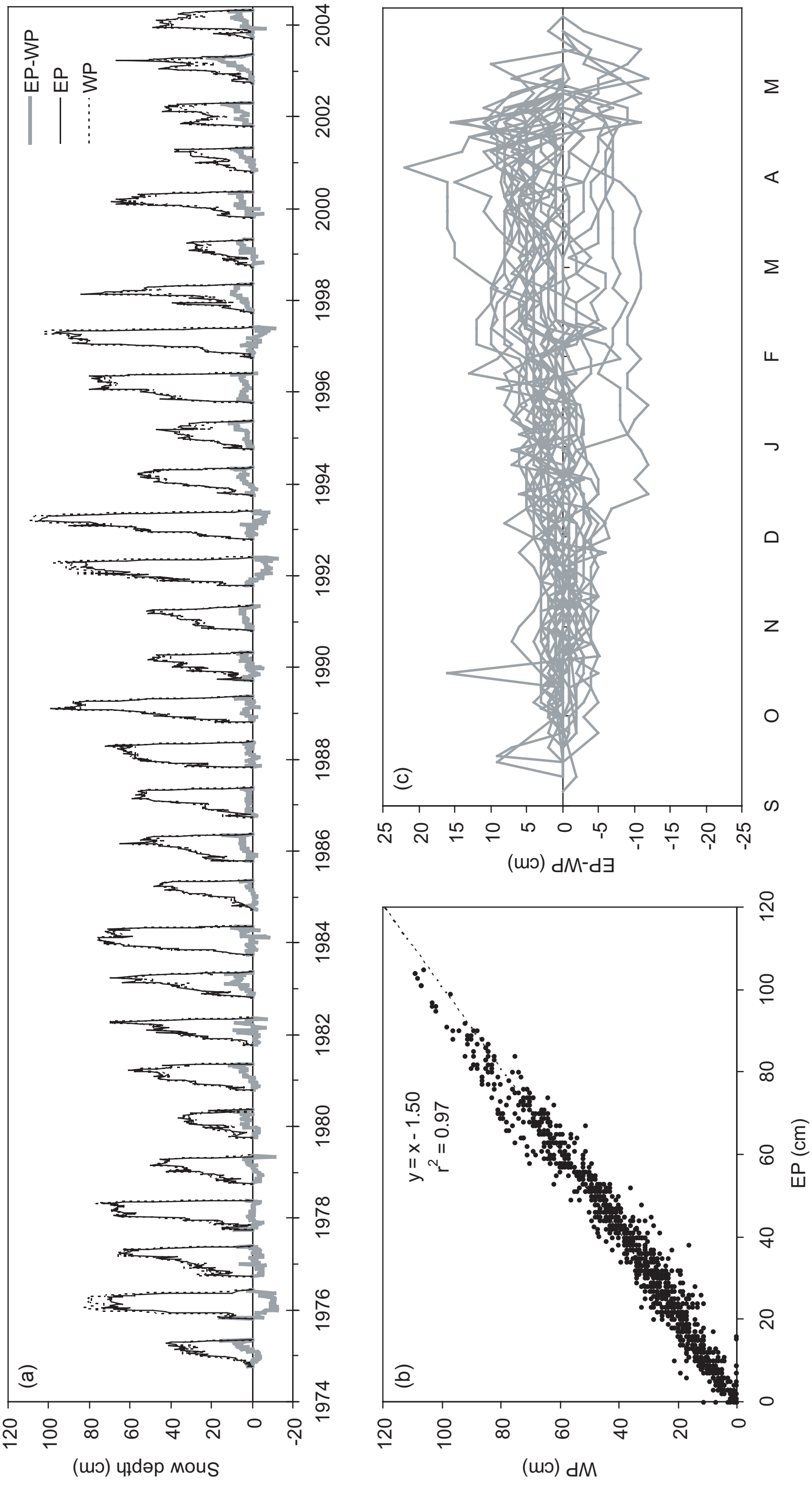
Model results

The resultant daily best-fit modelled snowpack compares well to the observed snow depths EP (Fig. 8a). The mean of the differences EP–MS is 0 cm (a result of the fitting procedure), and the standard deviation 8.8 cm. The spread in EP–MS differences is therefore less than, but essentially comparable to, that for the EP–SS differences. Outliers are more extreme in the EP–MS comparison, however, and there is a consistent tendency to underpredict snow depth during the winter and to overpredict the spring melting (Fig. 8c). Nevertheless, seasonal averaging yields good agreement between the two series (Fig. 9), suggesting that on a monthly or longer averaging timescale, MS is a reasonable proxy for EP, within the bounds of the uncertainties in the measurements and in the variability of snow accumulation in general. Monthly means of the MS record are readily formed from daily data, and are given in Table 1.

The model parameters found in the fitting procedure also appear to be reasonable. The 60 best model results (those with 99th percentile or better in r^2) show uniform values in T_{SR}, although a wider range in the other two parameters. The mean values are T_{SR} = 0.2 °C, T_{DD0} = 1.4 °C and DD_S = 5.6 mm °C^{-1} d^{-1}. Much of the variability in DD_S is explained by covariance in T_{DD0}, however. In other words, lower values of DD_S lead to increased amounts of snow, such that higher values of T_{DD0} are needed to melt the model snow to obtain a better match to the observed. This shows that the model is relatively insensitive to the choice of one or the other of these values.

The best-fit mean value of T_{SR} around 0 °C seems reasonable. In the literature (e.g. Rango & Martinec 1995), T_{DD0} is usually assumed to be 0 °C, such that starting melt only at temperatures above 1.4 °C might seem unduly high. On the other hand, snowmelt on days with mean temperatures around 0 °C could be refreezing in the

Fig. 6. (a) EP, WP and EP–WP differences for 1974–2004. (b) EP vs. WP, with best fit line. (c) All EP–WP differences plotted on the same seasonal axis.



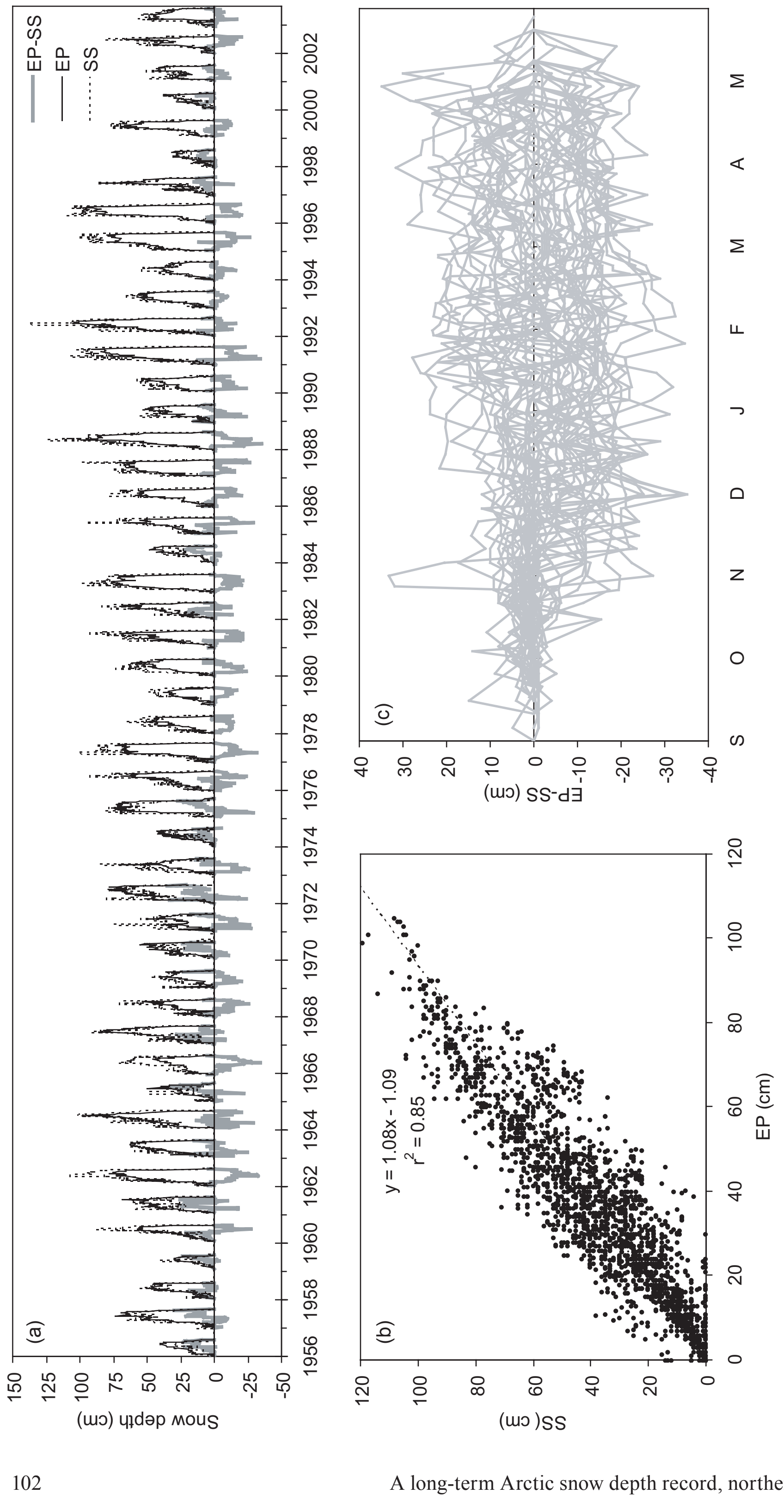


Fig. 7. (a) EP, SS and EP–SS differences for 1956–2004. (b) EP vs. SS, with best fit line. (c) All EP–SS differences plotted on the same seasonal axis.

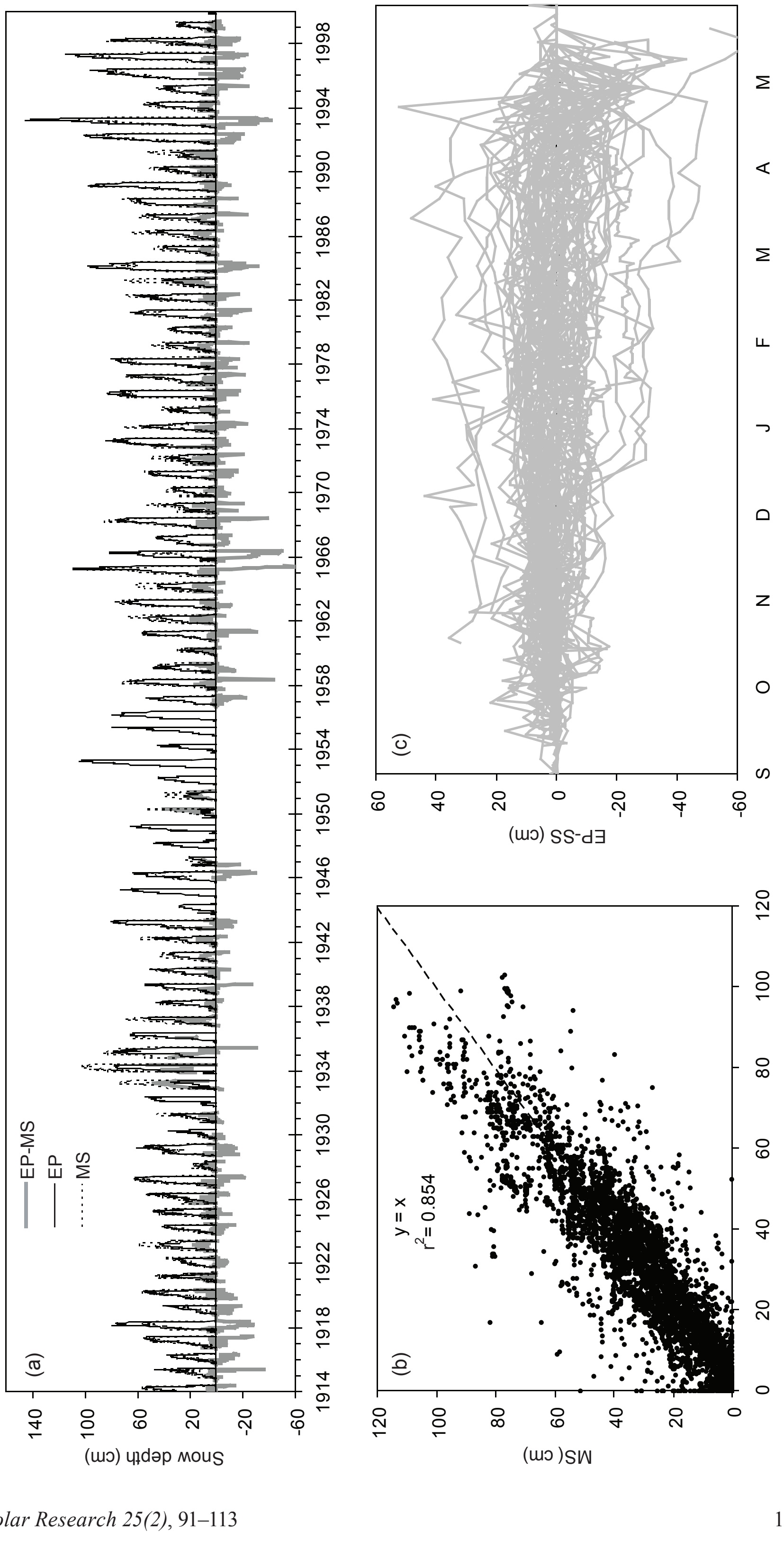


Fig. 8. (a) EP, model snowpack (MS) and EP–MS differences for 1914–1999. (b) EP vs. MS, with best fit line. (c) All EP–MS differences plotted on the same seasonal axis.

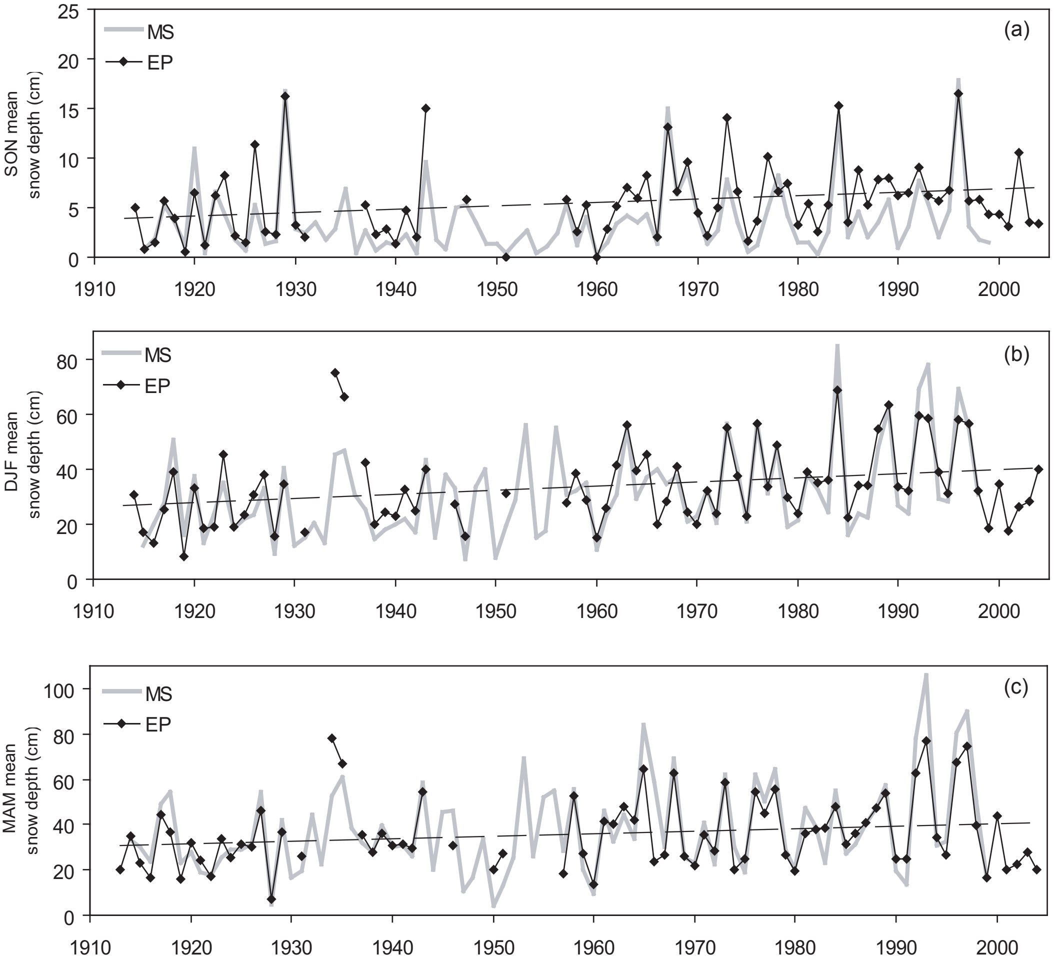


Fig. 9. Averages of all snow depth measurements in three-month blocks: (a) SON, (b) DJF, (c) MAM. Long-term trends (see Table 3) shown for EP (dashed lines).

Table 2. Trends and statistical significance for temperature and precipitation. Bold indicates significance at the $p \leq 0.05$ level.

	Period		SON	DJF	MAM	JJA	Annual
Temperature	1914–2000	trend (°C a^{-1})	0.004	0.003	**0.014**	–0.001	0.005
		p value	0.42	0.72	**0.01**	0.84	0.17
	1956–2000	trend (°C a^{-1})	0.004	**0.055**	**0.029**	0.012	**0.02**
		p value	0.71	**0.03**	**0.04**	0.28	**0.01**
Precipitation	1914–2000	trend (cm a^{-1})	0.033	**0.107**	–0.003	0.004	0.034
		trend (% a^{-1})	0.13	**0.46**	–0.02	0.01	0.17
		p value	0.38	**0.02**	0.92	0.94	0.10
	1956–2000	trend (cm a^{-1})	0.019	0.214	0.116	0.173	**0.129**
		trend (% a^{-1})	0.08	0.91	0.84	0.42	**0.50**
		p value	0.87	0.08	0.17	0.27	**0.03**

snowpack at nights; only at higher temperatures does melting actually lead to a reduction in the amount of water contained within the snowpack. Finally, the range of values for DD_S is entirely consistent with the wide range of values reported elsewhere (Hock 2003).

Snow phenology

Since MS and SS are daily records, identification of their respective start and end of snow season dates (Fig. 10a) is much more straightforward than in the case of WS. While EP and SS do not yield the identical days, the correlation between the two is reasonable (Fig. 10b). The agreement between WS_{MS} and WS_{EP} is not quite as good (Fig. 10d). For example, MS fails to predict the late start of winter in autumn 1959 (Fig. 10c), although the model does predict small amounts of snow for that period (Table 2). The correlation between WS_{EP} and WE_{SS} is much better than for WS, as is the agreement between WS_{EP} and WE (Fig. 10d).

Trends: temperature and precipitation

We consider 3-month and annual means, and calculate trends over the longer term period 1913–2000 as well as the late period 1956–2000 (Table 2), recognizing that varying the period by even a year on either end can lead to different values for trends (e.g. Polyakov & Johnson 2000).

For temperature, there is a statistically significant trend of 0.14 °C per decade in the March–May (MAM) mean temperature over the longest period. For the recent period, there are two other statistically significant trends: a strong warming in December–February (DJF) temperatures (over 0.5 °C per decade) and a smaller trend in the annual mean (Table 2). As for precipitation, the trend for the DJF mean of the monthly summed precipitation is the strongest over both the long and short periods, about 1 and 2 cm per decade, respectively, or 4.6 and 9.1 % of the long-term mean per decade; however, the statistical significance of the short period trend is above the cutoff level of $p = 0.05$. Finally, the trend for annual mean precipitation is significant for the recent period.

Trends: snow amount

We calculate trends for 3-month block means of EP and MS for September–November (SON), DJF and MAM, as well as for the winter months October–May (Fig. 9). Table 3 presents the trends for the entire measurement period (since 1914) and for the shorter modern period (since 1956) and for the two different records EP and MS. Bearing in mind that the two records are slightly different in length and completeness (MS is uninterrupted from 1914–1999, EP is incomplete but covers five more years), the results for both records are essentially similar. First, there are no statistically significant trends for the modern period. Second, the most positive trend over the entire measurement period is in the DJF mean snow depths; this amounts to nearly 2 cm per decade for both EP and MS, and is a highly significant trend in both records (Table 3). Finally, the long-term trends

Table 3. Trends, standard error and statistical significance in snow depths for both EP and MS. Bold indicates significance at the $p \leq 0.05$ level.

	EP mean snow				MS mean snow			
Period	1914–2004				1914–1999			
Number years	73	77	77	73	85	85	86	86
Months	SON	DJF	MAM	Oct–May	SON	DJF	MAM	Oct–May
Trend (cm a^{-1})	**0.038**	**0.170**	0.098	**0.116**	0.012	**0.198**	**0.175**	**0.137**
Trend (% a^{-1})	**0.7 %**	**0.5 %**	0.3 %	**0.4 %**	0.3 %	**0.6 %**	**0.5 %**	**0.5 %**
p value	**0.004**	**0.003**	0.133	**0.015**	0.258	**0.004**	**0.041**	**0.018**
Period	1956–2004				1956–1999			
Number years	47	49	49	53	43	44	44	46
Months	SON	DJF	MAM	Oct–May	SON	DJF	MAM	Oct–May
Trend (cm a^{-1})	0.021	0.112	−0.008	0.046	0.010	0.167	0.194	0.148
Trend (% a^{-1})	0.3 %	0.3%	0.0 %	0.2 %	0.2 %	0.5 %	0.5 %	0.5 %
p value	0.531	0.467	0.967	0.722	0.764	0.432	0.482	0.421

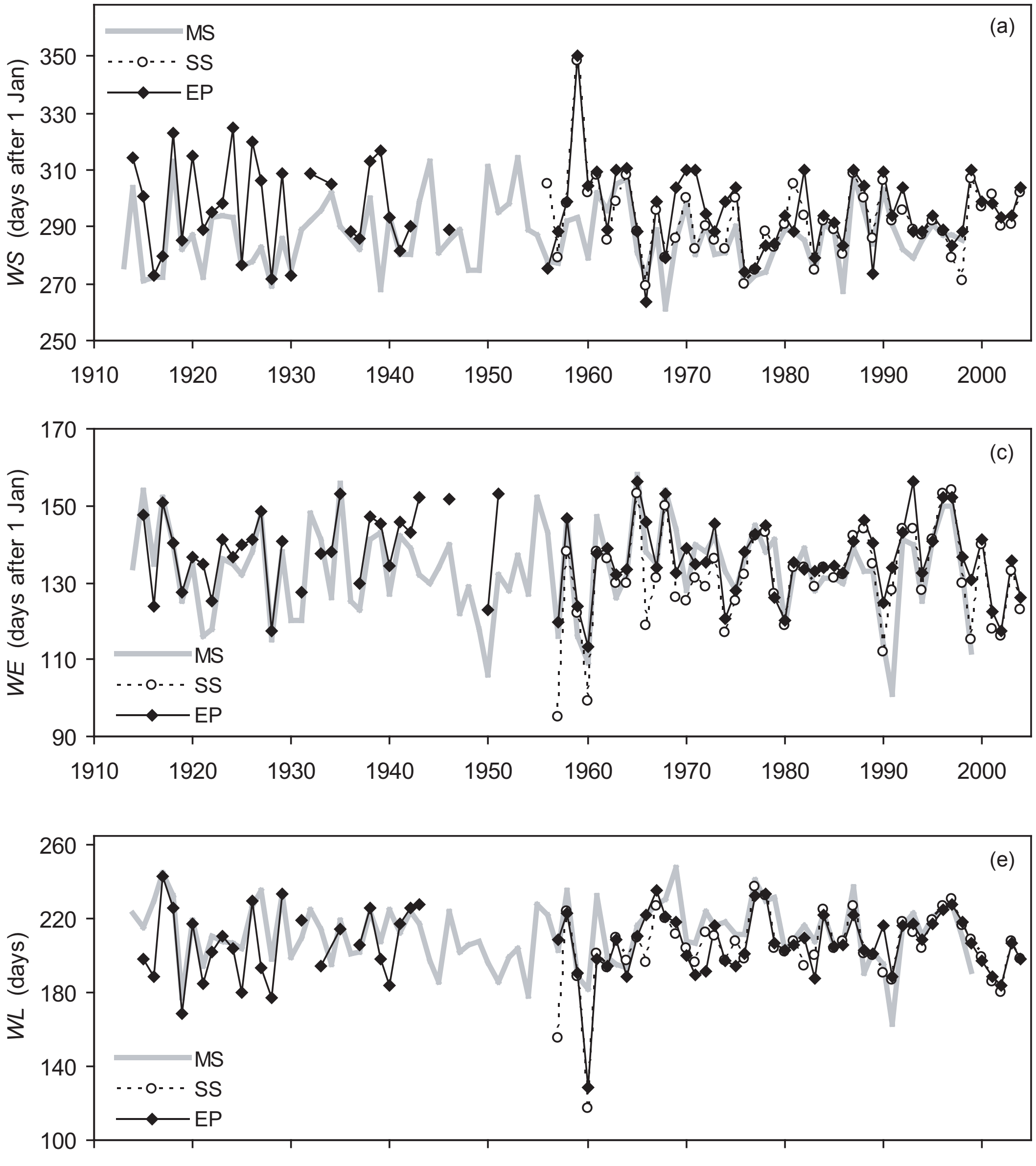


Fig. 10. Snow phenology. (a) *WS*, the first of five consecutive snow-free days, in days since 1 January for each year, for EP, SS and MS. (b; opposite page) Comparison of WS_{EP} to WS_{MS} and WS_{SS} with regression to WS_{MS} (black line) and to WS_{SS} (dotted line). (c) Similar to (a), but for *WE*, the first of three consecutive days without snow. (d; opposite page) Similar to (b), for *WE*. (e) Total length of snow season *WL*, number of days between *WS* and *WE*. (f; opposite page) Similar to (b), for *WL*.

in the winter means (October–May) are significant (Table 3) and highly positive, with 1.2 and 1.4 cm per decade for EP and MS, respectively. This long-term trend represents 4 - 5 % per decade of the 1914–1999 October–May mean snow depth (28 and 27 cm for EP and MS, respectively). Calculating trends using only years with a common time-base in both EP and MS leads to fundamentally the same result, only increasing the EP DJF trend and the significance levels of the EP fits.

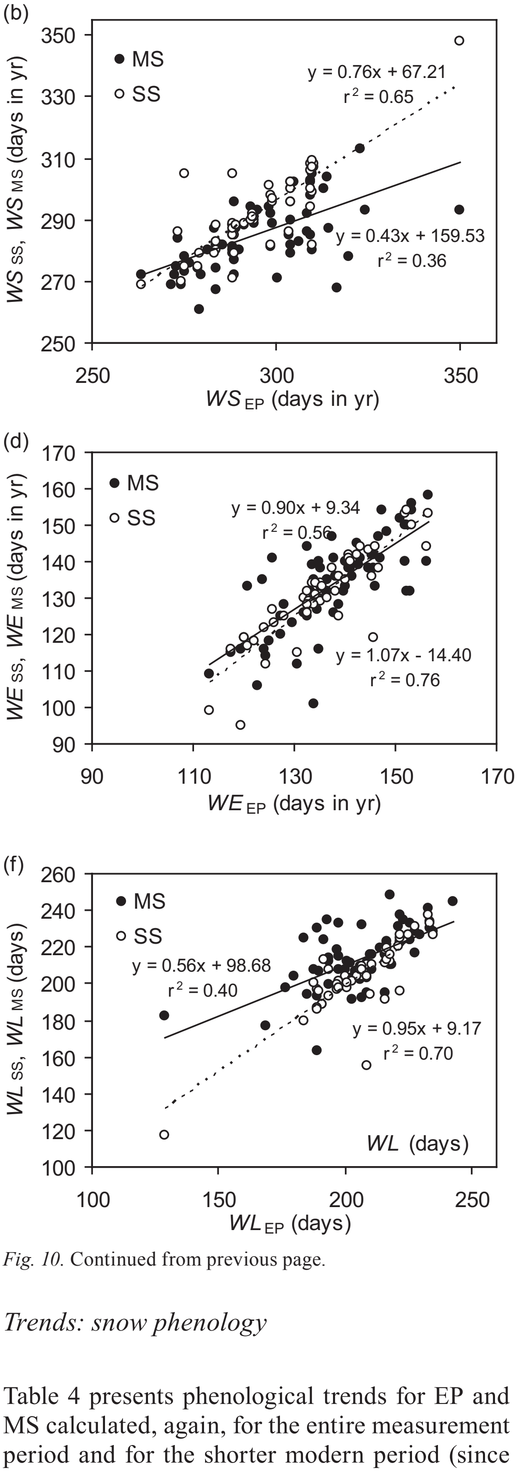


Fig. 10. Continued from previous page.

Trends: snow phenology

Table 4 presents phenological trends for EP and MS calculated, again, for the entire measurement period and for the shorter modern period (since 1956). The long-term trends for WE_{EP} and WS_{EP} are negative, but positive for WL_{EP}, while for MS these trends are opposite in sign to EP (Table 4).

None of the phenological trends is statistically significant, however. The lack of agreement in sign between MS and EP might in part arise from the slightly different amounts of data comprising the MS and EP records, but calculating trends with a common time-base gives fundamentally the same result, leading us to conclude that there are no trends long-term or short-term at acceptable levels of significance. In fact, the only phenological trend that is significant is a very short-term trend (at about a 5 year timescale) in WL_{EP} for the 6-year period 1997–2002, which features a marked decrease in snow season length (Fig. 10).

Comparison to other snow records

To demonstrate that the trends observed in the Abisko snow record are part of a regional pattern, we compare October–May mean snow depths from Abisko to those from the two closest long-term records, at Tromsø and Øverbygd (Fig. 11). The records vary inconsistently for individual years (for example, 1973 was a relatively snow-free year at the Norwegian sites while Abisko experienced its fifth largest snow). This is not completely surprising since the heaviest snowfalls at the Norwegian coast arrive from the northwest, while winter low-pressure systems from the south typically bring mild weather and rain, but snow to Abisko. Abisko is also influenced by low-pressures systems coming from the east, which deliver little snow to Tromsø.

Nevertheless, correlations (Table 5) between the Norwegian sites and Abisko are relatively high, given the distances separating the sites and the somewhat different local climatic settings, and all have very high levels of statistical significance. The correlation between Øverbygd and Abisko is better than for Tromsø, which is reasonable given that Øverbygd has a more inland climate, more similar to Abisko.

Both Norwegian records show a statistically significant positive trend (Table 6), as is the case for Abisko (Table 3). When we calculate trends for the Abisko record over the same periods covered by the two Norwegian records, we obtain similar statistically significant positive trends (Table 3), amounting to about 10 % decade^{-1} since about the 1930s. These trends are larger than those for the entire measurement period, but we conclude in any case that snowfall at all three sites is increasing and that the trends observed at Abisko are part of a regional pattern.

AO

The best correlation of AO is to temperature (Fig. 12a). The relation between 3-monthly means of AO and temperature varies by season. The best and most statistically significant correlation is for winter months (DJF or JFM); otherwise only the summer months (JJA) are not significant. The relations between AO and Abisko precipitation and snow depth are weaker, and are only significant for winter (DJF) periods (Fig. 12b, c). However, for all periods, the relation between the AO index and precipitation or snow depth is positive.

Discussion and conclusion

This newly digitized long-term snow depth record from Abisko in northern Sweden starts in 1913 and, apart from significant gaps in the 1940s and 1950s, is complete to the present. While there is some variability in the relation between the snow

Table 4. Trends, standard error and statistical significance in phenology, for both EP and MS.

	EP phenology			MS phenology		
Period	1914–2004			1914–1999		
Number years	73	73	73	86	86	86
Parameter	WS_{EP}	WS_{EP}	WL_{EP}	WS_{MS}	WS_{MS}	WL_{MS}
Trend (d a^{-1})	–0.054	–0.038	0.025	0.007	0.004	–0.014
p value	0.402	0.395	0.736	0.888	0.941	0.849
Period:	1956–2004			1956–1999		
Number years	30	30	30	43	43	43
Parameter	WS_{EP}	WS_{EP}	WL_{EP}	WS_{MS}	WS_{MS}	WL_{MS}
Trend (d a^{-1})	–0.034	0.015	–0.006	–0.010	–0.080	–0.043
p value	0.804	0.894	0.971	0.941	0.577	0.836

Table 5. Correlation of October–May mean snow amount between Norwegian sites and Abisko for both EP and MS. Bold indicates significance at the $p \leq 0.05$ level.

	Correlation Oct–May mean snow			
Norwegian record	Øverbygd		Tromsø	
Period	1942–1996		1932–2003	1932–1999
Number years	42	55	53	68
Abisko record	EP	MS	EP	MS
r^2	**0.47**	**0.48**	**0.31**	**0.31**
p value	**<0.001**	**<0.001**	**<0.001**	**<0.001**

Table 6. Trends calculated for October–May mean snow amount at Øverbygd and Tromsø, over the indicated period, as well as for both EP and MS during the same period. Number of years is less at EP due to gaps. Trend in terms of percentage is relative to the mean at each site. Bold indicates significance at the $p \leq 0.05$ level.

	Temporal trends					
Record	Øverbygd	EP	MS	Tromsø	EP	MS
Period	1942–1996			1932–1999		
Number years	55	42	55	68	50	68
Trend (cm a^{-1})	**0.22**	0.22	**0.26**	**0.40**	**0.20**	**0.22**
Trend (% a^{-1})	**0.9%**	0.8%	**0.9%**	**0.9%**	**0.6%**	**0.8%**
p value	**0.040**	0.081	**0.014**	**0.001**	**0.027**	**0.010**

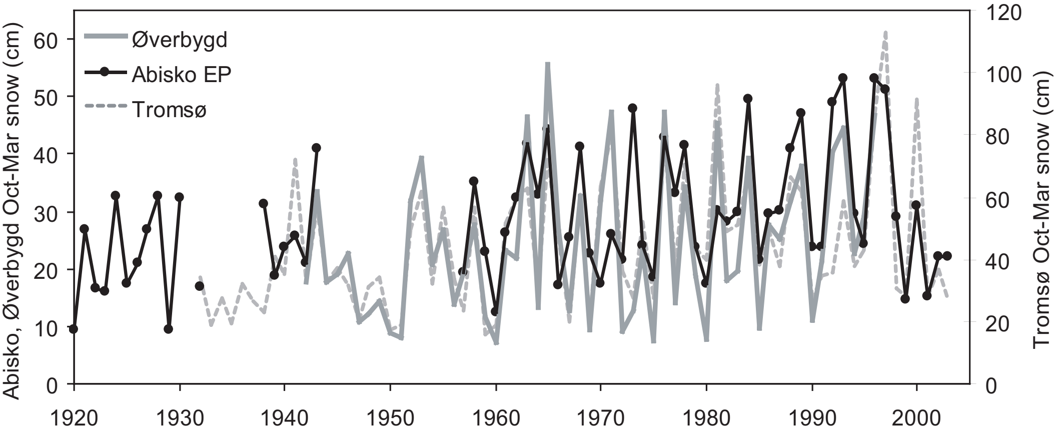


Fig. 11. Mean October–May snow depth at Abisko (EP, MS) compared to Tromsø and Øverbygd. Note different scale for the Tromsø record.

depths recorded at the long-term profile and the two other shorter term Abisko records, there do not appear to be any gross inhomogeneities in the long-term record, to the degree that it is possible to identify these from other local measurements.

To fill the gaps in observations, a synthetic snow depth record was derived using a simple snowpack model driven by concurrent temperature and precipitation measurements at Abisko. In contrast to the snow profiles, the daily model snow record is unbroken. Model snow depths are similar to the long-term measured snow depths and differences between modelled and observed records are comparable to those between single and averages of several snow measurements. This implies that at least part of the model error could be ascribed to variability in the precipitation record.

Both measured and modelled snow depth records show similar trends to the closest long-term snow records available, in Norway. Coupling this observation with the detailed intercomparison of the various Abisko snow measurements suggests that the measured and modelled Abisko records are essentially homogeneous.

We find a positive correlation between the winter AO index and temperature, precipitation and snow depth. This is expected since in the Scandinavian region the relation between the NAM indices and both temperature and precipitation anomalies is positive and highly significant (Thompson & Wallace 1998); high values of the AO (or NAO) index are coupled with more storm activity focused along and inland of the Norwegian coast, with resultant warmer and wetter weather (e.g. Hurrell et al. 2003). This contrasts with the situation in the Alps, where positive NAO (AO) winters are associated with low moisture conditions and less snowfall (e.g. Beniston & Jungo 2002). However, it is important to note that the sign of the relation for Scandinavia can vary by elevation: Pettorelli et al. (2005) find that positive NAO winters feature less snow at low altitude (since it is warmer, more precipitation occurs as rain), but more snow at high altitude (where it is colder, and more precipitation leads to more snow), and conversely for negative NAO winters.

The trend in the measured and modelled Abisko snow depths is positive over the whole measurement period, with the strongest and most statistically significant trend in the DJF mean snow amounts. The trend for winter (October–May) mean snow depth is positive over the whole measurement period, increasing by 1.2 and 1.4 cm per decade for EP and MS, respectively. This amounts to about 4 - 5 % of the winter mean per decade, or 2 % of the maximum snow depths per decade.

In contrast to the trend towards increasing snow depth, there is no statistically significant trend to the start and end of the snow season and hence the length of the snow season. It may seem surprising that snow amounts are increasing while the season length is unchanged, but this has also been seen in a recent analysis of other long-term snow measurements in Sweden (Larsson 2004). In contrast to our study, which uses daily to weekly data, Larsson based his analysis primarily on a data set (1905–2003) comprising only the annual

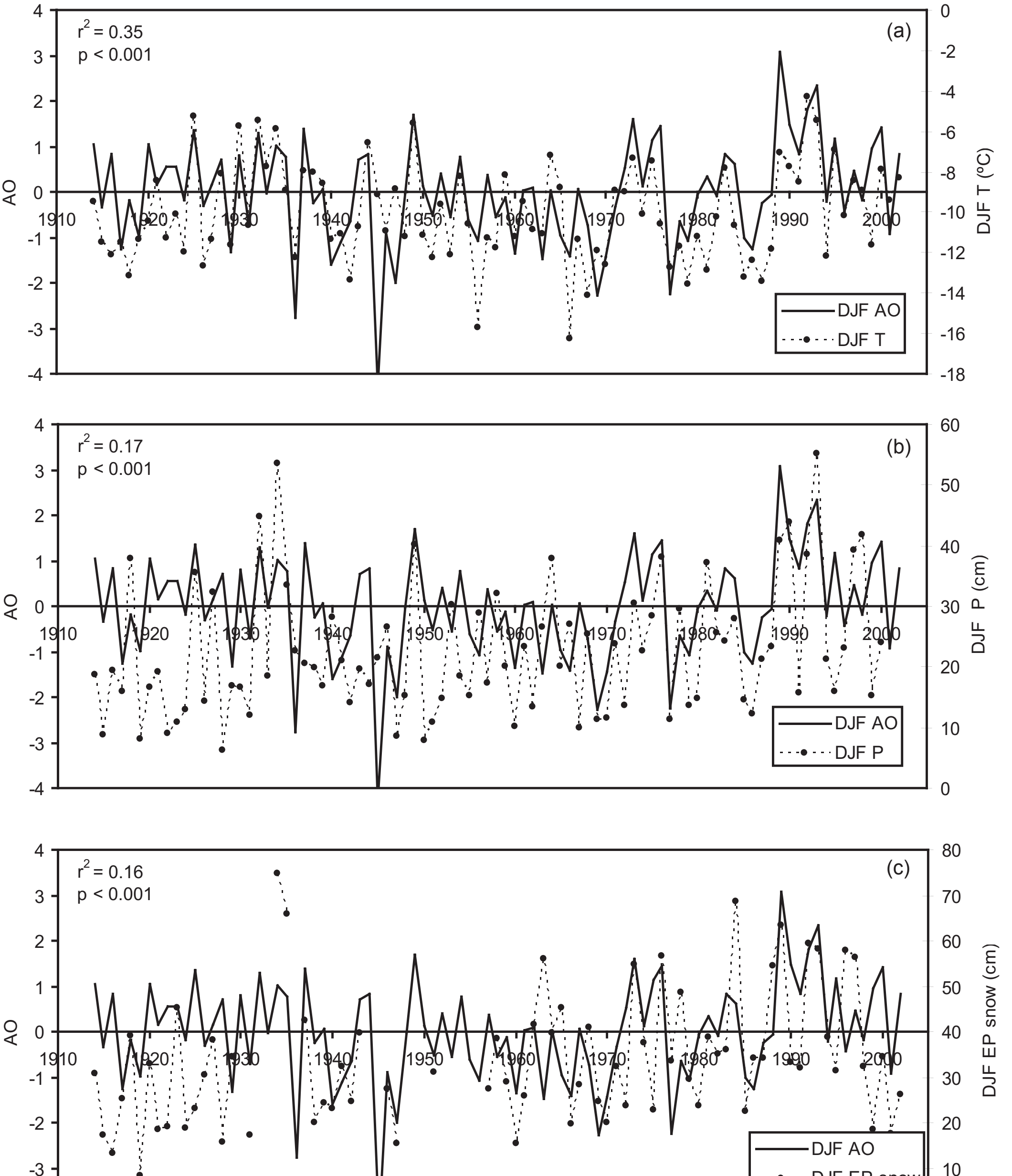


Fig 12. Comparison of DJF mean AO to (a) DJF mean temperature, (b) DJF mean sum precipitation and (c) EP snow depth.

number of days with snow cover and the annual maximum snow depth, at 48 stations from around Sweden. No check was made for individual station homogeneity, and results are reported for records grouped by region. Larsson finds no significant trend to the average number of days with snow cover, for the whole of Sweden, but a significant positive trend in maximum snow depth for northern Sweden. Trends in maximum snow depths for the remainder of the country are not

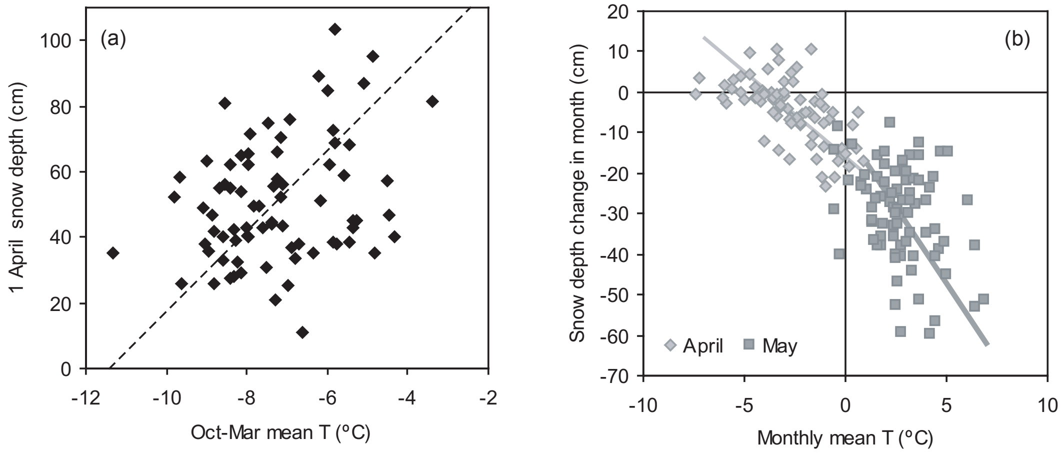


Fig. 13. (a) Mean winter (ONDJFM) temperature vs. end of winter (1 April) snow depth. (b) Change in snow depth over course of one month vs. the monthly mean *T*, for April and May. Lines in figures shows reduced major axis regression, which assumes equal error in both axes.

significant, although there is a slight tendency toward more negative trends in central to southern Sweden.

These findings for Sweden contrast to Dye's (2002) study using satellite imagery to determine interannual variability and trends in the annual snow cover cycle for the Northern Hemisphere land mass (1972–2000). Dye shows a significant trend toward earlier snowmelt and also a shortening of the snow season by 3 - 6 days per decade. Bamzai (2003) reported similar trends from his study in the Northern Hemisphere (1967–2000), namely that the number of snow-free days in a year has increased, due chiefly to a trend toward early snowmelt. Note that these are results averaged over very large areas while the results reported herein are specific for a particular region.

Increasing snow amounts with unchanged season length can be explained by an overall climate warming of a relatively cold winter climatic state. Initially, warming would be accompanied by increased winter snow amounts; with a commensurately warmer spring, however, there would be more rapid removal of snow, such that the overall season length can potentially remain relatively unchanged.

Extremely cold winters at Abisko are associated on the whole with less accumulation, as can be seen in a plot of mean winter (October–March) temperatures against the 1 April measured EP snow depth (Fig. 13a). Using reduced major axis regression (Davis 2002), which assumes equal error in both axes, we estimate an increase in snow depth with winter temperature of about 12 cm °C^{-1}. The temporal trend (0.006 °C a^{-1}) for mean winter (October–March) temperatures amounts to a change of 0.5 °C over the period 1914–2004. Accepting at face value the causality of the regression in Fig. 13a implies a total increase over the 90 year period of 6.4 cm in 1 April snow, associated to the warming trend. This can be compared to the observed increase of about 16 cm for 1 April EP snow depths

At the same time, spring temperatures at Abisko have been increasing. Snowmelt is of course more rapid in warmer spring months, as can be seen in Fig. 13b, which shows the change in snow depth over the course of the months April and May, as a function of the mean monthly temperatures. Again, using reduced major axis regression, we obtain a change of snow depth equivalent to about –4.1 and –7.5 cm °C^{-1} for April and May, respectively. Applying the observed trends for monthly mean temperature (0.011 and 0.013 °C a^{-1}), one gets a reduction of snow depth for April and May together amounting to 12.4 cm for the period 1914–2004, which is essentially comparable to the observed increase.

This illustrates how warming from very cold winters can lead to increased winter snow amounts without impacting the phenology. Further climatic warming will, of course, eventually result in decreased snow amounts and shorter winters. Temperatures in the Arctic, including the Abisko region, have been predicted by climate models to increase significantly relative to the overall global warming trend, with exact figures varying by model and scenario (e.g. Houghton et al. 2001). For example, a warming scenario from the coupled atmosphere–ocean climate model ECHAM4/OPYC3 was downscaled by both empirical and dynamical methods to determine changes in temperature and precipitation in Norway (Hanssen-Bauer et al. 2003; Førland et al. 2004). Model results predict a 0.4 (0.6) °C decade^{-1} increase in mean annual (DJF) temperatures, based on the differences between modelled temperatures in the two 30-year periods 1961–1990 and 2021–2050.

It seems safe to say, therefore, that while snow amounts at Abisko might continue to increase in the short-term, in the long-term, over the course of decades, snow amounts will eventually decrease, as will the length of snow season. This has also been suggested by precipitation and snowpack scenarios based on dynamic downscaling of a regional model covering the Abisko area (Sælthun & Barkved 2003).

Over the short-term, the weak but nonetheless positive and statistically significant correlation between AO and snow accumulation at Abisko might potentially hint at the expected sign of snow depth trends in the near future, as some modelling studies have suggested that the positive trend in NAO or AO will continue (e.g. Shindell et al. 1999). On the other hand, there does not appear to be a clear agreement on what changes are likely in NAO or AO, since the magnitude and character of trends across models vary greatly (ACIA 2005).

Increasing snow depth could have many consequences. Use of hydropower should benefit as water equivalents increase and the tourism—particularly the skiing—industry might benefit. However, an increase in avalanches and floods downstream and greater expenditure of clearing roads and railway can be expected.

Increasing snow depth should also have measurable effects on the ecology. It would lead to restricted access to winter pastures by, for example, reindeers. Their energy expenditure is also likely to increase while travelling across the snow. On the other hand, an increase in snow depth can provide a better shelter for warm-blooded small vertebrates (for example, voles) who may find thermal refuges when resting in snow dens. An increase in snow depth can lead to degradation of permafrost since the snow will act as an isolating layer preventing the cold winter air from penetrating and preserving the permafrost. Other consequences of increased snow cover remain to be determined.

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