Snow accumulation in North Greenland over the last millennium

Stefanie Weißbach, Anna Wegner and Sepp Kipfstuhl

Abstract: Knowledge of snow accumulation rates of the large polar ice sheets and their variability over time is crucial for mass budget studies and sea level predictions. Here we present mean long-term snow accumulation rates of 12 shallow ice cores drilled by the North Greenland traverse in the northern part of Greenland. The ice core records cover the last 500 to 1000 years. We find a trend of decreasing accumulation rate from the southwest (~180 mmWE/a) to northeast (~95 mmWE/a). Ice divide sites show higher accumulation rates but also higher variability (up to 20%) than sites off the ice divides (less than 10%). Unlike a recent modeling study our results indicate no change in the accumulation in the north of Greenland during the last 400 years.

Keywords: Greenland, accumulation rate, polar ice sheet, mass budget, North Greenland, ice divide

1. Introduction

Polar ice sheets are unique archives of present and past climatic and environmental conditions. Ice cores drilled on the polar ice sheets provide not only extended records of the Earth's climate in the far past but give also insight into the most recent development in remote parts of the globe where instrumental records are sparse or not available at all. The polar ice sheets are not only unique paleo-archives they are also an important active component of the climate system. Changes in the accumulation rate affect the mass balance of the ice sheets but also reflect changes in the hydrological cycle and atmospheric circulation.

Accumulation rates in Greenland were compiled first by Ohmura and Reeh (1991). Updated maps of the accumulation rate were then presented by Ohmura et al. (1999), Bales et al. (2001) and Bales et al. (2009). More recently, maps of the accumulation rate or estimates of the mass balance for varying periods are produced by modeling the precipitation over Greenland using regional atmospheric circulation models (e.g. Dethloff et al. 2002, Burgess et al. 2010, Hanna et al. 2011, Box et al. 2013). Box et al. (2013) reconstructed the accumulation history over the last 400 years and find for example that the Greenland ice sheet net snow accumulation rate increased by 12% from the end of the Little Ice Age (1840 AD).

Due to the huge dimensions of the polar ice sheets data coverage is not at all evenly distributed (e.g. Ohmura and Reeh 1991; Box et al. 2013). Until the beginning of the era of deep cores in Greenland (GRIP, GISP2, NGRIP and NEEM) at about 1990 most work focused on the central and southern parts of Greenland (e.g.

NEEM community members 2013). North Greenland was only covered sparsely, mainly by the PARCA activities (e.g. Mosley-Thompson 2001) and the North Greenland Traverse (NGT). The NGT started at the Summit of the Greenland ice sheet after the GRIP ice core was completed (in summer 1993) and ended at the NGRIP drill site about 350 km northwest of Summit in summer 1996. A total of 13 deep ice cores 70-175m long were drilled during the NGT (see Fig. 1).

In this contribution within the ESSReS-framework we present an overview of the evolution of the accumulation in North Greenland over the last 500-800 years, the first such overview for the data sparse North Greenland region. The accumulation histories are derived by carefully aligning the time scale for the 13 NGT cores by volcanic matching, and subsequently using measured density data to convert average annual layer thickness between volcanic horizons to accumulation rate estimations.

2. Methods

The lengths of the investigated ice cores and the coordinates of the drill sites are given in Table 1. An overview of their positions is given in Figure 1.

Table 1. Site information about the NGT drill locations.

Core	Dill site	Core lenght (m)	Altitude (m)	Latitude °N	Longitude °W
B16	NGT 03	102.4	3040	73.94	37.63
B17	NGT 06	100.8	2820	75.25	37.63
B18	NGT 14	150.2	2508	76.62	36.40
B19	NGT 19	150.4	2234	78.00	36.40
B20	NGT 23	150.4	2147	78.83	36.50
B21	NGT 27	100.6	2185	80.00	41.14
B22	NGT 30	120.6	2242	79.34	45.91
B23	NGT 33	150.8	2543	78.00	44.00
B26	NGT 37	119.7	2598	77.25	49.22
B27	NGT 39	175.0	2733	76.66	46.82
B28	NGT 39	70.7	2733	76.66	46.82
B29	NGT 42	110.5	2874	76.00	43.50
B30	NGT 45	160.8	2947	75.00	42.00

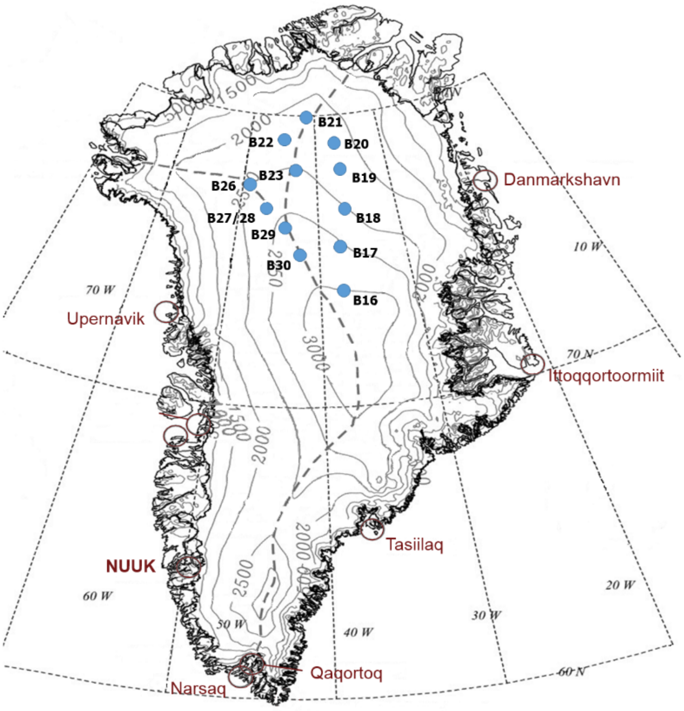


Figure 1. Map of drill sites of the NGT cores (blue dots). The dashed line represents present ice divides whereas solid lines mark the surface topography.

The drill sites of cores B21 to B30 (except B22) are lying on the main ice divide leading from the Summit to the Northwest and then splitting north of site B29 into a branch towards the Northeast (B23 and B21). Core B22 has been drilled in the windward side and all other cores (B16 to B20) in the lee-side of the ice divides.

The DiElectric Profiling (DEP)-records of the cores which reflect the impurity content in the ice are used to date the cores. The basis of the dating is the well know pattern of volcanic events present in DEP records (Fig. 2).

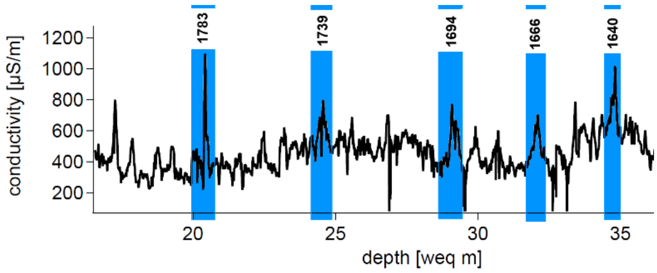


Figure 2. Dating example. Volcanic marker horizons (blue bars) in the DEP record (here core B20 on water equivalent depth scale) provide ice core ages.

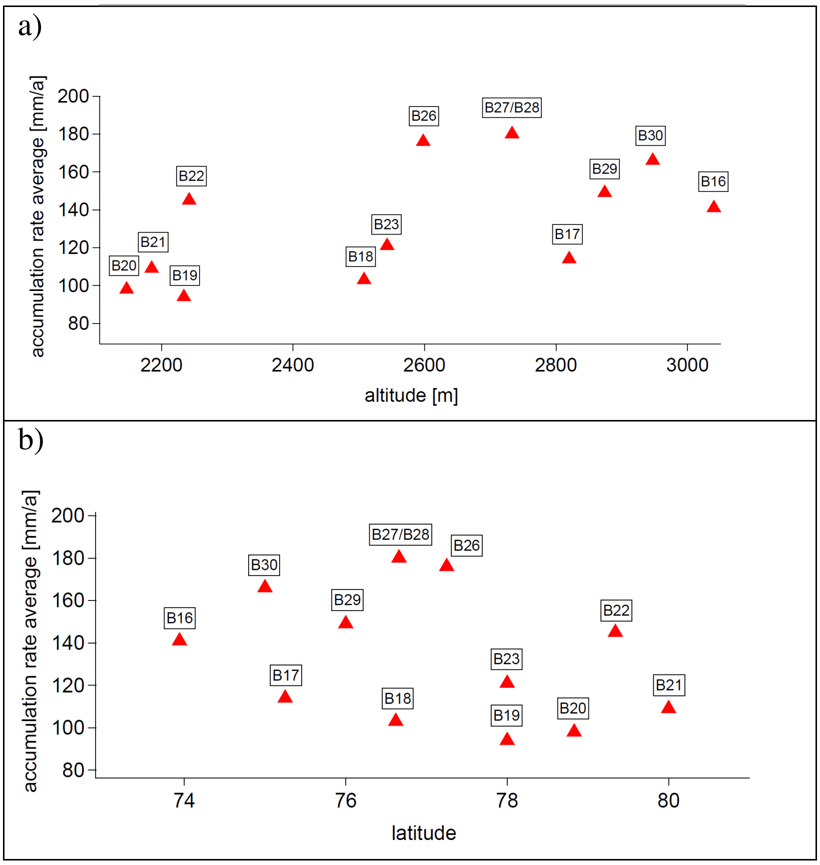
The accumulation rate, given here as equivalent height of a water column (mmWE/a), is derived from the deposited snow mass per time in a core. During the field campaign the length and weight of each single piece of core were measured. From these results and the known diameter of the cores an average density for each single piece was calculated. In the AWI cold room laboratories the density of the cores was additionally measured in millimeter resolution by γ absorption (Wilhelms 1996) or X-ray imaging (Freitag et al. 2013). To account for the increase of density in the top 100 m of the ice sheet from about 300 kg/m^3 for the uppermost firn layers to the density of ice (920 kg/m^3) an exponential function was fit to the obtained density profiles.

3. Results

The mean accumulation rates at the 12 drill sites are presented in Table 2. They do not exceed 200 mmWE/a and show a west-east as well as a south-north trend (Fig. 3). The accumulation rates decrease northward from between 150 and 200 mm/a just north of the summit to less than 100 mm/a between 78°N and 79°N, and they are strongly influenced by the ice sheet topography (Fig. 3). The highest accumulation rates (180 and 176 mmWE/a) are found at the B27 and B26 drill sites on the ice divide. The cores with the lowest accumulation rates are B19 and B20 (94 and 98 mmWE/a) with the largest distance to the ice divides in the far north-east. This pattern in the accumulation results probably from a combination of factors. Besides temperature and humidity of the air the shape of the coastline, the topography and the inclination of the slopes west of the inland ice plateau play some role for the clouds moving on to the inland ice (Benson, 1962).The moisture-bearing air masses come generally from the west or southwest originating in cyclones forming in the Hudson or Baffin Bay (Chen et al., 1997). They loose most moisture on the coast in front of and on the slopes to the inland ice plateau. East of the ice divide in its wind shadow and at similar or even slightly descending altitude the amount of precipitation is reduced.

Table 2. Mean accumulation rates for North Greenland at the NGT drill sites. Given are mean values over the period from present (1993-1995) back to the time of the deepest volcanic event identified in the core.

	B16	**B17**	**B18**	**B19**	**B20**	**B21**
mm/a	141	114	103	94	98	109
period	1993-1640	1993-1479	1993-934	1993-934	1994-1179	1994-1514
	B22	**B23**	**B26**	**B27**	**B29**	**B30**
mm/a	145	121	176	180	149	166
period	1994-1479	1994-1179	1995-1601	1995-1783	1995-1479	1995-1259



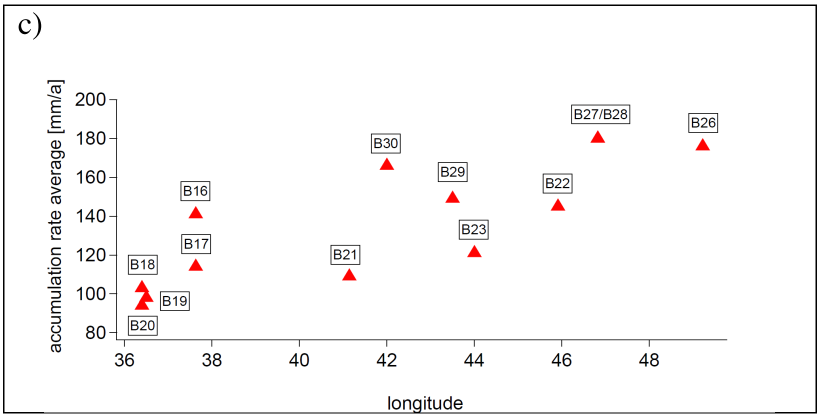


Figure 3. Accumulation rates at NGT sites vs. a) altitude, b) latitude and c) longitude

Table 3. Mean accumulation rates (mm/a) for periods between well dated volcanic eruptions eruptions of Tambora (1816) Laki (1783) Huyanaputina (1601) Mt. St. Helens (1479) and an unknown event at 1259. Fields are blank, when the respective time interval was not covered by the core.

Period	B16	B17	B18	B19	B20	B21	B22	B23	B26	B27	B29	B30
1993-1816	138	115	107	95	97	110	144	121	176	174	146	168
1816-1783	148	119	107	96	93	110	154	132	190	184	161	178
1783-1601	143	114	105	95	101	109	144	121	173	171	148	166
1601-1479	142	114	105	90	103	107	144	120		172	152	169
1479-1259			101	90	98					167		161

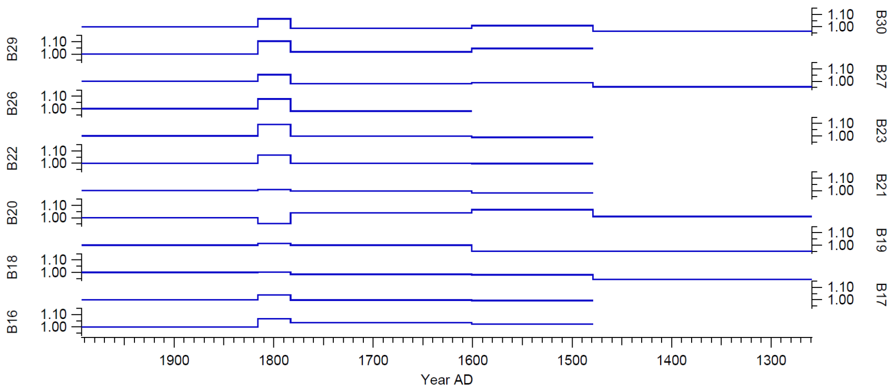


Figure 4. Relative changes in the accumulation rates for periods between well dated volcanic eruptions (Tambora 1816; Laki 1783; Huyanaputina 1601; Mt. St. Helens 1479; unknown 1259). Reference for each core is the mean accumulation rates over the period between 1816 and present (1993-1995).

Changes in the accumulation rates over the last 400-800 years are given in Table 3 and displayed in Figure 4. Except for the 33 years lasting period between the Laki and Tambora eruptions (1783-1816) the accumulation rates do not show any significant changes during the entire period of the last millennium. The changes are mostly around 1% but never exceed 5% relative to the mean since the Tambora eruption (1816-1993).

4. Discussion and conclusion

The accumulation rates derived from 12 shallow ice cores in northern central Greenland indicate only little variability over the past millennium. The changes are generally less than 10 % for all sites. Except for the short period between the Laki and Tambora eruptions (1783 and 1816, respectively) the accumulation rates do not show clear trends, however, these changes may be caused by the shortness of this time period.

Our mean accumulation rates agree well with the results of Benson (1962) and Bales et al. (2009). Compared to our accumulation rates the values presented in the map of Ohmura and Reeh (1991) seem to overestimate the accumulation in central parts of North Greenland between 10 and up to more than 30% (Fig. 5).

In future work the causes of these differences have to be investigated in more detail. They may be explained by the different interpolation techniques or differences in accumulation rates on shorter distances.

A direct comparison to the accumulation rates obtained by Box et al. 2013 is not possible as no details about regional distribution is given.

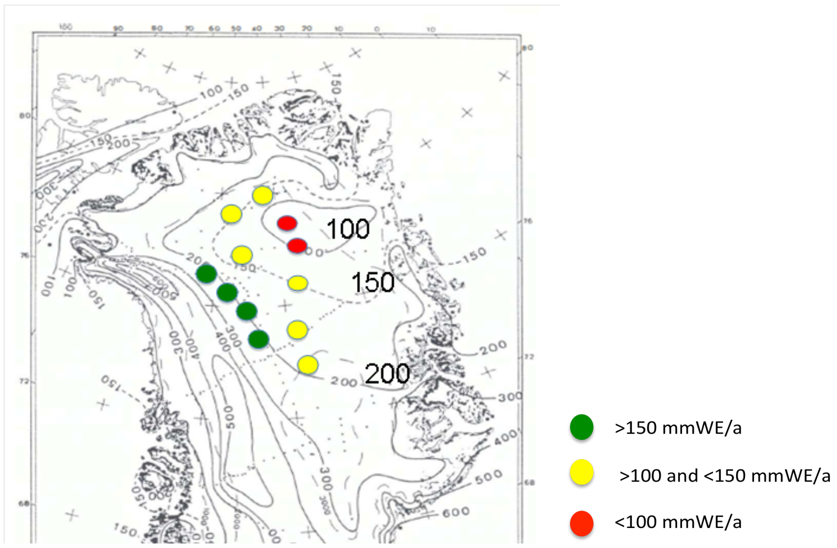


Figure 5. Accumulation rates from NGT-cores compared to values by Ohmura and Reeh (1991). The color-coded dots represent the accumulation rates from this study, covering up to 1000 years (red: <100 mmWE/a, yellow: >100 and <150 mmWE/a, green: >150 mmWE/a). The contour line give accumulation rates as given in Ohmura and Reeh (1991).

References:

Bales, R.C., McConnell, J.R., Mosley-Thompson, E., Csatho, B.: Accumulation over the Greenland ice sheet from historical and recent records. J. Geophys. Res. **106**, 33,813-33,826 (2001)

Bales, R.C., Guo, Q., Shen, D., McConnell, J.R., Du, G., Burkhart, J.F., Spikes, V.B., Hanna, E., Cappelen, J.: Annual accumulation for Greenland updated using ice core data developed during 2000–2006 and analysis of daily coastal meteorological data. J. Geophys. Res. **114**, 1-14 (2009)

Benson, C.S.: Greenland snow pit and core stratigraphic data 1952, 1953, 1954, 1955. U.S. Army Corps of Engineers Snow Ice and Permafrost Res **70**, 1-182 (1962)

Box, J.E., Cressie, N., Bromwich, D.H., Jung, J.-H., van den Broeke, M., van Angelen, J.H., Forster, R.R., Miège, C., Mosley-Thompson, E., Vinther, B., McConnell, J.R.: Greenland Ice Sheet Mass Balance Reconstruction. Part I: Net Snow Accumulation (1600–2009). J. Clim. **26**, 3919-3934 (2013)

Burgess, E.W., Forster, R.R., Box, J.E., Mosley-Thompson, E., Bromwich, D.H., Bales, R.C.,Smith, L.C.: A spatially calibrated model of annual accumulation rate on the Greenland Ice Sheet (1958–2007). J. Geophys. Res. : Earth Surface **115**, F02004 (2010)

Chen, Q.S., Bromwich, D.H., Bai, L.:Precipitation over Greenland REtrieved by a dynamic Method and its Relation to Cyclonic Activity. J. Clim. **10**, 839-870 (1997)

Dethloff, K., Schwager, M., Christensen, J.H., Kiilsholm, S., Rinke, A., Dorn, W., Jung-Rothenhäusler, F., Fischer, H., Kipfstuhl, S.,Miller, H.: Recent Greenland Accumulation Estimated from Regional Climate Model Simulations and Ice Core Analysis*. J. Clim. **15**, 2821-2832 (2002)

Freitag, J., Kipfstuhl, S., Laepple, T.: Core-scale radioscopic imaging: a new method reveals density-calcium link in Antarctic firn. J. Glaciol. **59**, 1009-1014 (2013)

Hanna, E., Huybrechts, P., Cappelen, J., Steffen, K., Bales, R.C., Burgess, E., McConnell, J.R., Peder Steffensen, J., Van den Broeke, M., Wake, L., Bigg, G., Griffiths, M.,Savas, D.: Greenland Ice Sheet surface mass balance 1870 to 2010 based on Twentieth Century Reanalysis, and links with global climate forcing. J. Geophys. Res. **116**, D24121(2011)

Mosley-Thompson, E., McConnell, J.R., Bales, R.C., Li, Z., Lin, P-N., Steffen, K., Thompson, L.G., Edwards, R., Bathke, D.: Local to regional-scale variability of Greenland accumulation from PARCA cores. J. Geophys. Res. (Atmospheres) **106** (D24), 33,839-33,852 (2001).

NEEM community membery: Eemian interglacial reconstructed from a Greenland folded ice core. Nature **493**, 489-494 (2013)

Ohmura, A., Reeh, N.: New pewcipitation and accumulation maps for Greenland. J. Glaciol. **37**, 140-148 (1991)

Ohmura, A., Calanca, P., Wild, M., Anklin, M.: Precipitation , accumulation and mass balance of the Greenland ice sheet. Zeitschrift für Gletscherkunde und Glaziologie **35** (1), 1-20 (1999)

Wilhelms, F.: Leitfähigkeits- und Dichtemessung an Eisbohrkernen. Berichte zur Polarforschung, Bremerhaven (1996)