SPATIAL AND TEMPORAL VARIABILITY OF NET ACCUMULATION FROM SHALLOW CORES FROM VESTFONNA ICE CAP (NORDAUSTLANDET, SVALBARD)

BY
EMILIE BEAUDON[1], LAURA ARPPE[2], ULF JONSELL[3,6], TÕNU MARTMA[4], MARCO MÖLLER[5], VEIJO A. POHJOLA[6], DIETER SCHERER[7] AND JOHN C. MOORE[1,8]

[1]Arctic Centre, University of Lapland, Rovaniemi, Finland
[2]Department of Geosciences and Geography, University of Helsinki, Finland
[3]ETSI de Telecomunicación, Universidad Politécnica de Madrid
[4]Institute of Geology, Tallinn University of Technology, Estonia
[5]Department of Geography, RWTH Aachen University, Germany
[6]Department of Earth Sciences, Uppsala University, Sweden
[7]Department of Ecology, Technische Universität Berlin, Germany
[8]Colleges of Global Change and Earth System Science, Beijing Normal University, China

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ABSTRACT. We analyse ice cores from Vestfonna ice cap (Nordaustlandet, Svalbard). Oxygen isotopic measurements were made on three firn cores (6.0, 11.0 and 15.5 m deep) from the two highest summits of the glacier located on the SW–NE and NW–SE central ridges. Sub-annual $\delta^{18}O$ cycles were preserved and could be counted visually in the uppermost parts of the cores, but deeper layers were affected by post-depositional smoothing. A pronounced $\delta^{18}O$ minimum was found near the bottom of the three cores. We consider candidates for this $\delta^{18}O$ signal to be a valuable reference horizon since it is also seen elsewhere in Nordaustlandet. We attribute it to isotopically depleted snow precipitation, which NCEP/NCAR reanalysis shows was unusual for Vestfonna, and came from northerly air during the cold winter of 1994/95. Finding the 1994/95 time marker allows establishment of a precise depth/age scale for the three cores. The derived annual accumulation rates indirectly fill a geographical gap in mass balance measurements and thus provide information on spatial and temporal variability of precipitation over the glacier for the period spanned by the cores (1992–2009). Comparing records at the two locations also reveals that the snow net accumulation at the easternmost part of Vestfonna was only half of that in the western part over the last 17 years.

Key words: accumulation rate, firn core, oxygen isotope ratio, sea ice, wind anomaly, Vestfonna

Introduction

Firn and ice core studies are key tools to reconstruct regional characteristics of glacier processes and climatic and environmental changes. The retrieval of three shallow firn cores from Vestfonna ice cap (Nordaustlandet, Svalbard) was carried out during the IPY-KINNVIKA project whose main objective was to enhance the understanding of the Arctic system, to monitor Arctic climate change and to study effects of human activity on Arctic islands (Pohjola *et al.* 2011).

Svalbard is in an interesting geographical position surrounded by the Arctic Ocean, the Barents Sea, and at the southerly edge of the permanent Arctic sea ice. In addition, it is near to the overturning point of the North Atlantic thermohaline circulation whose warm waters contribute to high average winter temperatures. Vestfonna ice cap is located in the western part of Svalbard's northernmost island (Nordaustlandet) whose atmospheric circulation is dominated by easterly winds bringing moisture from the Barents Sea (Førland *et al.* 1997). Due to its maritime climate and its low altitude (from sea level to 630 m a.s.l.), Vestfonna experiences seasonal melting during most summers and occasional melting during winter. However, glaciers that are subject to moderate melt can provide valuable ice core records (Pohjola *et al.* 2002; Moore *et al.* 2005).

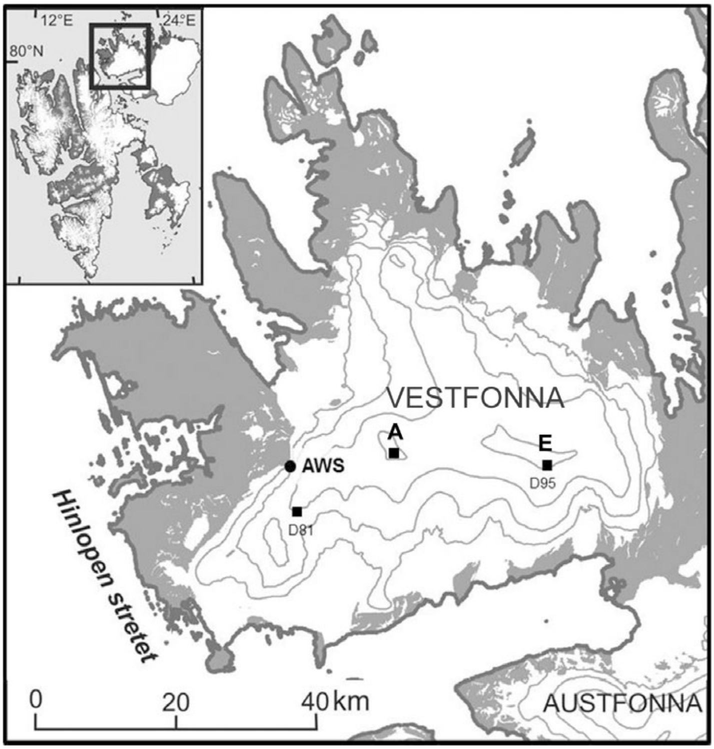

Fig. 1. Map of Western Nordaustlandet with locations of the drilling sites (Ahlmann summit as A and Eastern summit as E), Automatic Weather Station (AWS) and previous deep drilling sites in 1981 (D81) and in 1995 (D95).

Two deep ice cores have already been drilled on Vestfonna in the past (Kotlyakov *et al.* 2004): the first was extracted in July 1981 from the northwestern part of the ice dome (Vaykmyae *et al.* 1985), and the last one was drilled in May–June 1995 at the eastern peak (Watanabe *et al.* 2001) (Fig. 1, Table 1). Both ice cores provided regional low temporal resolution paleoclimate records spanning several centuries. This was achieved by measuring the isotopic composition of oxygen in ice which is controlled by the atmospheric deposition conditions, especially temperature, and the associated air mass trajectories from the source region (Matoba *et al.* 2002). The $\delta^{18}O$ records were found to correlate well with historical temperature records.

In this work, using high resolution $\delta^{18}O$ and density profiles, we use firn cores from two different locations on Vestfonna in order to extract recent climate information missing for the last 20 years and compare precipitation regimes and provenance at the two sites. The new data can be used to extend the data from the earlier deeper cores into the twenty-first century.

Materials and methods

Firn core retrieval

During the first IPY-KINNVIKA spring campaign on Vestfonna ice cap in April–May 2007, two shallow firn cores were retrieved from the two highest summits of the West–East ridge at 79° 59′ 22″ N and 79° 56′ 58″ N, respectively (Fig. 1). Percolation processes and ice flow are assumed to be less problematic for ice core studies at the ridges than at lower elevations and in local depressions where the role of melting and liquid precipitation is more important (Kotlyakov *et al.* 2004). At these sites, hereafter named Ahlmann and Eastern summits and respectively labelled ‘Ahl07’ and ‘E07’, cores were taken with a portable electromechanical corer. The coring was started from the summer 2006 surface layer, i.e., from the bottom of 1.9 m deep snow pits which have been previously described in terms of stratigraphy and chemistry by Beaudon and Moore (2009).

Table 1. Summary of firn and ice core information, average isotope values and annual accumulation rates calculated from the three shallow firn cores (this work) and compared with older Vestfonna 95 ice core.

Drilling site	Reference	Latitude (N)	Longitude (E)	Elevation (m a.s.l.)	Drill depth (m)	Time span (year)	Average[1] $\delta^{18}O$ (‰) ($\pm\sigma$)	Average[2] accumulation (m w.e. yr^{-1}) ($\pm\sigma$)
Ahl07	this study	79°59′22″	20°07′07″	622	11.81	12	−15.0 (1)	0.54 (0.16)
Ahl09	this study	79°58′53″	20°06′51″	619	15.42	17	−14.9 (1.1)	0.52 (0.15)
E07	this study	79°58′	21°01′	600	5.76	13	−15.5 (0.9)	0.25 (0.08)
Vestfonna 95	(Watanabe *et al.* 2001)	79°58′	21°01′	600	210	>210	−17.2	0.34
Austfonna 99	(Watanabe *et al.* 2001)	79°50′	24°01′	750	289	800	−16.7	0.45

[1] 1996-2006 for Ahl09, Ahl07 and E07, 1985-1995 for Vestfonna 95, 1989-1999 for Austfonna.
[2] over the entire time span for this study and 1963-1995 for Vestfonna 95 and Austfonna.

In April–May 2009, a new 15.4 m long core ‘Ahl09’ was drilled at Ahlmann summit using a lightweight Kovacs corer, which was also capable of drilling through the many thick ice layers encountered. The firn-glacier ice transition was not reached in either core. The stratigraphic melt index for the Ahl09 core is 46%, which is lower than in the 1990s in other Svalbard cores (Pohjola *et al*. 2002).

Laboratory analyses

The cores were processed in the cold room (−22°C) of the Finnish Forest Institute in Rovaniemi. The diameter, length and weight of each core section were first measured for density calculations. The entire density profiles of the cores are shown in Fig. 2. After removing the outer part of the core with a band saw, a 20 mm thick plate cut along the core length and placed on a light bench was photographed in order to accurately determine ice facies and calculate high resolution density profiles following the method proposed by Pohjola *et al*. (2002). For purposes of oxygen isotopic analysis, prisms were cut from the inner part and sub-sampled in 10 to 15 cm long increments for Ahl07 and E07, and in 2 to 5 cm long increments for Ahl09. The samples were then melted in closed vials and the water was analysed for the isotopic composition of oxygen.

Ahl07 and E07 isotope samples were processed at the Laboratory for Geochemistry of the Department of Geosciences and Geography, University of Helsinki, where the oxygen isotope ratios were measured on a ThermoFinnigan Gasbench II coupled to a ThermoFinnigan Delta^{Plus} Advantage continuous flow mass spectrometer. Replicate measurements of in-house water standards indicate a reproducibility of ±0.1‰. Analysis of Ahl09 samples were carried out at the University of Technology in Tallinn on a Gasbench II with Delta V Advantage mass spectrometer. The reproducibility of replicate analysis is ±0.1‰.

Mass balance survey and meteorological data

An array of 31 accumulation and ablation stakes was installed on the western slope of the ice cap during the 2007 spring campaign. The 2007 array was resurveyed during the two following fieldwork seasons, when new stake arrays were set up

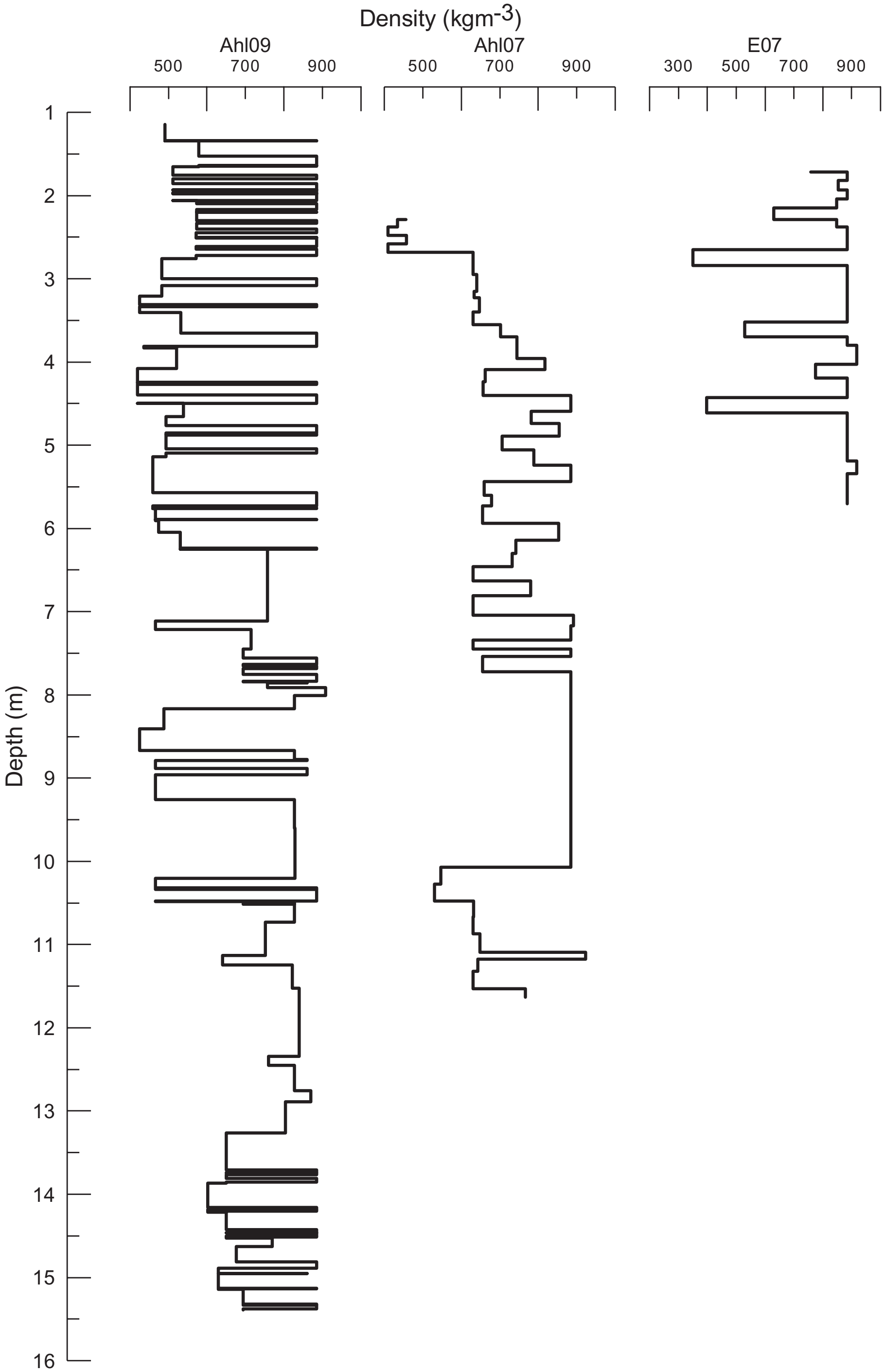

Fig. 2. Density depth profiles of the three shallow firn cores.

in the Ahlmann and Eastern summit areas. Repeat readings were carried out during spring and summer campaigns from 2007 to 2010. Stake surveys are described in detail by Pohjola *et al*. (2011).

The surface air temperature data used to identify the sub-annual $\delta^{18}O$ cycles and to establish a precise chronology for the uppermost firn and ice layers of the Ahl09 core were measured from April 2007 to May 2009 by an *automatic weather station* (AWS) set up on the western slope of Vestfonna at 335 m a.s.l. (Fig. 1).

The ERA interim temperatures we use are 2 m air temperatures from a grid point located at 79° 5′ N; 19° 5′ E. These temperatures were statistically downscaled to match local conditions at summit Ahlmann on Vestfonna (Möller *et al*. 2011a). The wind data that are taken from the NCEP/NCAR reanalysis dataset (monthly mean values; Kistler *et al*. 2001) for the grid point 80° N; 20° E (close to summit Ahlmann) are representative of the synoptic-scale wind conditions near summit Ahlmann and are very similar to those of the entire Svalbard region.

Dating procedure

The preliminary dating of the three shallow cores we propose is based on visual counting of $\delta^{18}O$ (winter) minima with the addition of information from ERA-interim air temperatures and NCEP/NCAR reanalysis wind data. The three ice core timescales, adjusted to a common stratigraphic horizon, are used to calculate the net annual accumulation (or amount of water per reconstructed annual layer) at each site that are then compared with results of a climatic mass balance model for the period 2000–2009 (Möller *et al*. 2011b).

Results and discussion

Preliminary dating of the cores

Sub-annual $\delta^{18}O$ cycles In the first 6.3 m of the Ahl09 core, the $\delta^{18}O$ profile presents pronounced oscillations of high amplitude which, $\delta^{18}O$ being commonly used as a (condensation) temperature proxy in ice core studies, clearly correspond to seasonal variations. By matching the $\delta^{18}O$ minima measured in Ahl09 with the winter temperature minima recorded on the western slope of Vestfonna (AWS; Fig. 1) since 2007, it is possible to precisely date the uppermost part of the core.

Figure 3 shows this fitted dating, which is also partly constrained by stratigraphic features such as clear ice or depth hoar layers shown in pictures inserts in Fig. 3. The uppermost $\delta^{18}O$ minimum (−18.3‰) at 1.6 m depth, marked as (1), is associated with the winter temperature minimum that occurred in January 2009 (−28°C). The second $\delta^{18}O$ minimum (2) at 2.7 m is matched to the March 2008 winter temperature minimum (−26°C). We note that the small peaks, marked with yellow arrows, succeeding (in depth) the minimum in the temperature profile are also visible in the $\delta^{18}O$ profile. The same late autumn shoulder pattern is systematically observed in other Svalbard air temperature records for the past 10 years (Fig. 4b).The small local $\delta^{18}O$ peak corresponds to late autumn/early winter precipitation on Vestfonna. The relatively high $\delta^{18}O$ value of −13.9‰ at 2.3 m (3) is measured in the uppermost clear ice layer (5 cm thick at 0.91 m w.e.) of the core probably resulting from summer melting and refreezing of surficial snow layers. We suggest this layer was formed by percolation of part of the surface snow in June 2008 when the first positive temperatures of the year are measured. At 3.3 m depth, we find a depth hoar layer (4) filled with refrozen water ice, characteristic of an autumnal layer (Pohjola *et al*. 2002) and followed by clear ice at 3.7 m depth (5). The $\delta^{18}O$ values of samples taken in these layers are respectively attributed to August and June 2007. We suggest that the high positive correlation ($r^2 = 0.53$) between $\delta^{18}O$ and T (for the period 2007–2009) found with this method shows that depth-age is fairly well established for the two last years. Furthermore, it supports using the oxygen isotope ratios from Ahl09 firn core as a reliable indicator of air temperature variability for Vestfonna, which makes dating the firn cores possible as long as isotopic cycles are discernable. This is the case for the five first cycles in Ahl09 that are clearly visible, however the signal becomes more difficult to read with increasing depth as the amplitudes of the $\delta^{18}O$ fluctuations are smoothed by post-depositional processes. Simple visual counting in Ahl09 and Ahl07 gives 15–20 and 12–16 $\delta^{18}O$ cycles, respectively.

Finding a time marker to refine the dating A substantial averaging of the original isotopic signals, perhaps due to vapour diffusion and/or mixing of percolating melt water, is observed along all cores.

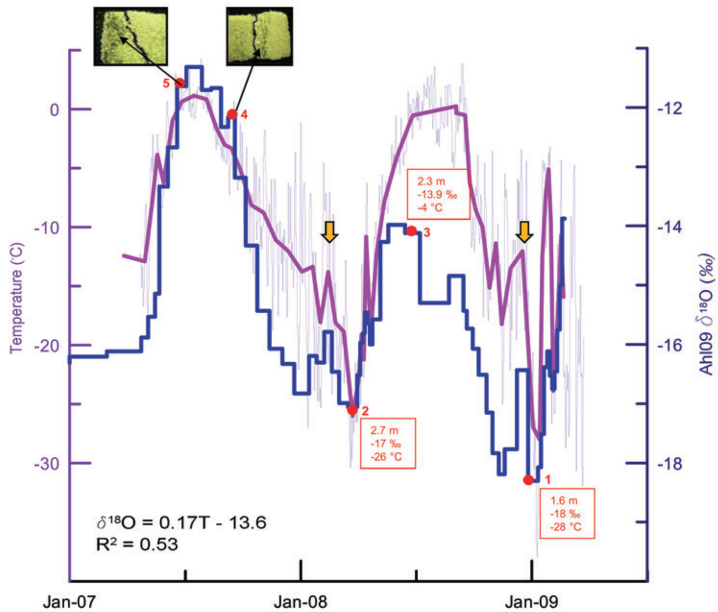

Fig. 3. Oxygen isotopic ($\delta^{18}O$) measurements (blue) on the upper 3 m (1.4 m w.e.) of the Ahl09 firn core matched with stratigraphy features (photographs of melt layers with corresponding depth (m) of the layer) and daily air temperature (°C; violet) recorded from April 2007 to May 2009 at the AWS. The dating of the isotopic profile is interpolated between stratigraphical tie points numbered in red. The pink curve is the averaged air temperature over each $\delta^{18}O$ sample increment. The yellow arrows point the small autumnal temperature peaks.

According to Johnsen (1977), vapour diffusion causes the annual cycle's amplitude to decay rapidly in the firn and much slower at deeper depths as vapour diffusion is slower in solid ice than in firn. The isotopic signal amplitude of the top firn layers of Ahl07 and E07 is lower than in the top firn layers of Ahl09 where the diffusion was probably limited by the formation of thin ice layers. For the 2007 cores we suspect that in addition to firn diffusion, the isotopes could have been redistributed within the top layers by melt water percolation or/and by mechanical mixing of snow and wind scouring (Fisher *et al*. 1988). However in our case it is impossible to evaluate the respective impact of these post-depositional processes in the alteration of the $\delta^{18}O$ seasonal records. All cores show a high degree of smoothing (Fig. 4 d–f, grey section) in a thick ice layer (between 5 m w.e. down to 7.5 m w.e. for Ahl09; Fig 4a), probably driven by warm summers (June to September) and winters (December to March). In this part of the $\delta^{18}O$ profiles, the identification of annual layers is almost impracticable or at least very subjective, while below 7.5 m w.e. (Ahl09 depth) the $\delta^{18}O$ signal is better preserved. In this part of the ice layer, the Ahl09, Ahl07, and E07 $\delta^{18}O$ records all show an absolute minimum of −17.6‰, −19.3‰ and −18.4‰ , respectively, above a $\delta^{18}O$ maximum measured in fine-grained firn lying below the ice.

Unlike the altered isotopic signal within melt layers, the minimum $\delta^{18}O$ value common to the three shallow cores cannot result from melt water infiltration. In fact, $\delta^{18}O$ values measured in layers affected by refrozen percolation tend to be higher than the original signal. Downward percolating fluid would more likely be enriched in ^{18}O since it results mostly from summer rain or melting of spring/summer snow, isotopically heavier than average pack (Pohjola *et al*. 2002). Therefore, we consider that the $\delta^{18}O$ minimum can be regarded as a climatological signal and its corresponding ice layer can be used as a dating reference horizon. More precisely, and based on the earlier assumption that precipitation $\delta^{18}O$ values on Vestfonna are a good proxy for air temperatures, with the lowest $\delta^{18}O$ values in winter, we suggest this ^{18}O-depleted snow layer at the two summits most likely results from the precipitation from a notably cold air mass, which additionally may have been affected by an

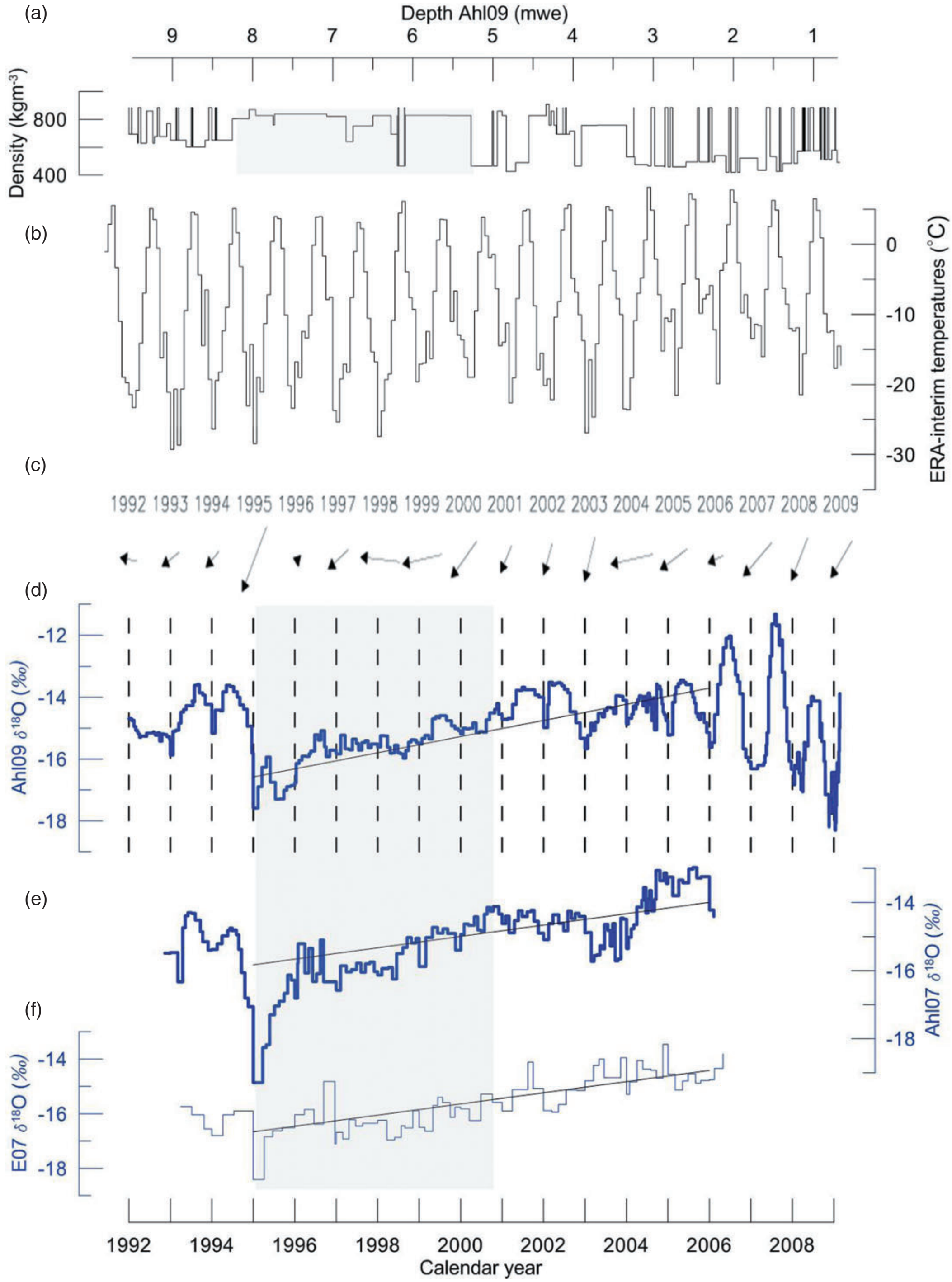

Fig. 4. Ahl09 densities plotted with depth (a), ERA-interim air temperatures downscaled to 600 m a.s.l. on Vestfonna (b), NCEP/NCAR reanalysis surface wind direction annual anomaly. The maximum wind is displayed as a fixed arrow length and used to scale the arrows (c), δ18O profiles of Ahl09 (d), Ahl07 (e) and E07 (f).The grey section marks the thick ice layer mentioned in the text.

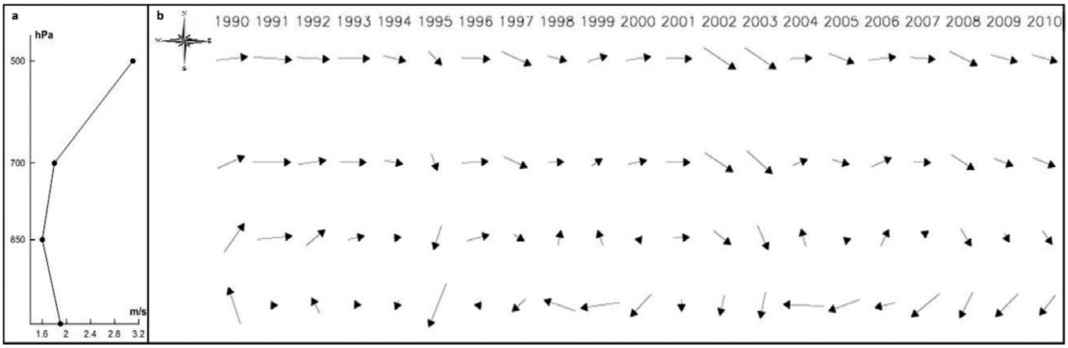

Fig. 5. (a) Wind speed in 1995 calculated from the NCEP/NCAR reanalysis dataset (data source: NCEP reanalysis produced at NOAA/ESRL PSD at http://www.esrl.noaa.gov/psd/data/timeseries/) at the grid point 80 N; 20 E, (b) 1990–2010 annual wind direction anomaly at 4 pressure levels (surface, 850 hPa, 700 hPa and 500 hPa). Time series of wind speed in each pressure level. The maximum wind is displayed as a fixed arrow length and used to scale the arrows.

advanced 'amount effect' (Rozanski *et al*. 1993), that is condensation-driven isotopic depletion and limited recycling of moisture. Owing to the lack of direct meteorological observations (temperature, precipitation) in Nordaustlandet area over the last 20 years, we compare the isotopic and stratigraphic data with ERA-Interim air temperatures downscaled to represent conditions at 600 m a.s.l. and NCEP/NCAR reanalysis time series of wind direction and speed in order to assign a date to the cold winter precipitation event and thus refine the shallow core time scale.

Figure 4 shows the Ahl09 density profile (a), the downscaled Vestfonna monthly temperatures since 1992 (b), the annual mean wind direction and speed at the surface (c) and the three complete $\delta^{18}O$ profiles (d–f). The pronounced negative $\delta^{18}O$ value could possibly correspond to one of the three coldest winters of the last two decades: 1992/93, 1994/95 and 1997/98 with respective average downscaled January temperatures of −29.2°C, −28.4°C and −27.4°C. The Vestfonna 95 isotope record contains the deepest winter minimum of the twentieth century at 1.2 m depth (Motoyama *et al*. 2008) that certainly corresponds to the previous winter (1994/95) since the summer 1994 surface was found below 1.5 m depth (Matoba *et al*. 2002). The NCEP/NCAR reanalysis for the grid point 80° N; 20° E (Fig. 4c) shows that 1995 (winter 1994/95) had an unusually strong Northern component. In the surface and the 850 hPa pressure levels (Fig. 5b), this is the most pronounced anomaly in the mean annual wind conditions since at least 1992 suggesting the source area of water vapour was shifted more to the North in 1995 compared to other years. The increase of the mean wind speed at the surface shown in Fig. 5a for 1995 also indicates a strong inversion keeping most of the water vapour in the *planetary boundary layer* (PBL) where most of its transport and condensation takes place. Similar pronounced wind-dynamic features associated with low surface temperatures are also observed in winter 2002/03, which is also characterized in the ice cores isotope profiles by notably lower $\delta^{18}O$ ratio (−15.7‰ for Ahl09). Furthermore, there is a clear relationship between the amplitude of the isotopic signal and the wind field, with low amplitude periods characterized by easterly air flow. No exceptional wind conditions favouring exceptionally depleted precipitation over Vestfonna ice cap are found for the winters 1992/93 and 1997/98, hence we choose to rule out these dates for the 'cold' isotopic signal.

Besides its thermodynamic impact on the lower troposphere, wind, depending on strength and direction, also affects the sea ice cover in various ways. Wind can cause ice floes to break into smaller pieces making them more vulnerable to melt. Wind induces sea ice drift to other regions, including warmer waters where the ice melts, and compaction of the ice cover through rafting and ridging (Comiso 2006). Because thermodynamic mechanisms are likely to be involved in the forcing of the sea ice anomalies, strong northern surface wind component calculated for 1995 could have forced the negative Barents sea ice extent observed in spring 1995 (Fig. 6). By blowing the sea ice out of the Barents Sea, and also presumably out of Hinlopen Strait between Nordaustlandet and Spitsbergen, we argue that the strong cold northerly wind may have caused

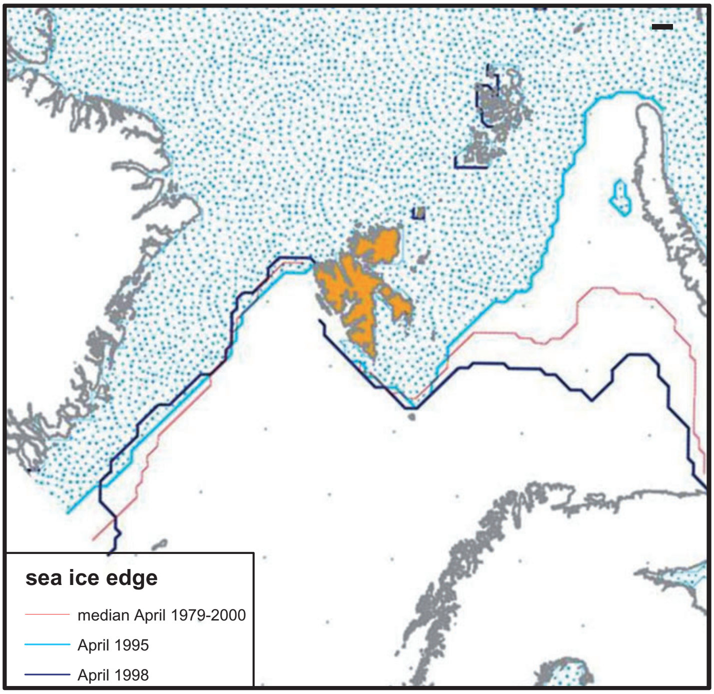

Fig. 6. Map of the Barents Sea area with indication of the April sea ice edge in 1993, 1995, 1998 and the median spring extent over the period 1979–2000.

the opening of sea ice leads (Bengtsson *et al*. 2004; Petoukhov and Semenov 2010) and the formation of frost flowers on young sea ice leading to the high marine salt concentrations (not shown) measured in the same ice layer as the $\delta^{18}O$ minimum (Beaudon and Moore 2009).

Consequently, winter 1994/95 is adopted as the most reasonable estimation of the cold event date. This time marker horizon allows for a more reliable layer counting to establish the chronology of the three shallow cores discussed in this paper (Fig. 4) and yields Ahl09, Ahl07 and E07 spanning respectively 17, 12 and 13 years (Table 1).

Spatial and temporal variability of snow accumulation rates and air mass influence

The mean oxygen isotope compositions over the 13 years are similar at the western and eastern part of the ice cap and are respectively −15.0‰ (±1) and −15.5‰ (±0.9). These values are higher than any 13 years block throughout the twentieth century reported by Watanabe *et al*. (2001) for the Eastern summit, suggesting the climate was cooler during the twentieth century over Nordaustlandet. In addition, the rapid increase of the $\delta^{18}O$ values in the profiles (Fig. 4 d–f) also characterizes a general warming trend at both sites from 1995 to 2007. The rise is so strong that it probably reflects an increase in percolating melt water that formed the thick ice layer between 5 and 8 m w.e. (Palosuo 1987).

For the period 1992-2009 covered by Ahl09, the mean annual accumulation is 0.52 m w.e. yr^{-1} (±0.15) (Table 1), close to the 0.53 m w.e. yr^{-1} found by Schytt (1964) at summit Ahlmann for the period 1957 to 1959. At the Eastern summit of the ice cap, the mean accumulation derived from E07 is 0.25 m w.e. yr^{-1} (±0.08) which is half that at Ahlmann summit. This result is somewhat lower than the 0.34 m w.e. yr^{-1} reported by Watanabe *et al*. (2001) for the eastern site for the period 1963 to 1999, and certainly lower than the 0.54 reported by Schytt (1964) for 1957–58. The location of western and eastern peaks of the ice cap at essentially the same elevation and latitude implies that the present day pronounced difference of accumulation rates is due to a longitudinal gradient in the precipitation regime over Vestfonna with a drier eastern side. At elevations above the PBL

(850–500 hPa and beyond) the circulation becomes increasingly westerly (Fig. 5b) such that precipitation is higher on the windward side, even when synoptic scale surface winds are different. However it would be surprising if this spatial precipitation gradient alone explains the net accumulation difference between the two summits that are only 20 km apart, and we speculate that wind scour and foehn effects caused by the Austfonna ice cap also contribute. With greater net accumulation in the West than in the East, the ice thickness at the western summit would be expected to grow faster unless mass loss compensates. The elevation across the summit ridge appears not to be significantly changing (Pohjola *et al.* 2011); hence the spatial and temporal accumulation trend may also result from outflow glacier dynamics, such as observed for Franklinbreen (Pohjola *et al.* 2011). This finding is seemingly not supported by the spatio-temporal snow-pit analysis of Möller *et al.* (2011b) that did not reveal statistically significant zonal variability of snow accumulation across the ice cap. However, to explain that discrepancy between our ice core study and their snow pits analysis Möller *et al.* (2011b) also invoked a spatial difference in the magnitude of the small-scale accumulation variability due to patchy deposition of wind-drift snow. Möller *et al.* (2011b) present a more detailed discussion of this topic.

Owing to the relatively high uncertainty associated with the dating of the cores, a calculation of snow accumulation at seasonal resolution is not possible. Hence, the discussion on the variability of the net accumulation rates is limited to a year-to-year (calendar years) comparison with the modelled *climatic mass balance* (CMB) data from Möller *et al.* (2011a). The complete time series of accumulation rates from Ahl09 and E07 with Vestfonna modeled CMB and measurements of stake arrays near the drilling sites in 2009 are shown in Fig. 7. Both Ahl09 and E07 cores display a high inter-annual variability in terms of net accumulation which ranges from respectively 0.36 and 0.77 m w.e., to 0.13 and 0.38 m w.e. Ahl09 values are in the same range as the modelled CMB and all time series covary well except for the year 2006. By definition, a climatic mass balance is a surface mass balance that includes internal accumulation, i.e. refreezing (Cogley *et al.* 2011). 2006 was one of the years with highest refreezing amounts within the last decades according to the CMB model (Möller *et al.* 2011a); hence the discrepancy with ice core data may reflect deep percolation processes or runoff. The net accumulation of 0.61 m w.e. at Ahlmann for the 2009 layer is in agreement with the 0.56 m w.e. measured from a nearby stake, although the latter only provides information about the winter and spring accumulation and not the whole calendar year. Therefore, considering dating uncertainties, the net accumulation data extracted from shallow core studies can be considered as useful climatological information. Furthermore, they constitute a valuable dataset for mass balance modelling of Vestfonna ice cap at Ahlmann summit where direct mass balance time series are still rare and Eastern summit where such records are completely lacking.

Conclusion

Densities and stable oxygen isotopes ratios measured in three shallow firn cores from Vestfonna ice cap have been jointly analysed in the light of measured and modelled surface air temperature data. The Vestfonna $\delta^{18}O$ record captures the recently discovered autumnal warming local maximum and is confirmed as a good proxy for local air temperatures for the uppermost well preserved layers. There is a strong correlation between amplitude of isotopic cycles and downscaled wind field over Vestfonna with northerly winds leading to high amplitude signals and easterlies to smoothed signals. The Vestfonna isotopic records show a warming trend as seen in instrumental records from Svalbard (Isaksson *et al.* 2001) and thus could be used to reconstruct long-term trends of past atmospheric parameters driving the isotopic composition of local precipitation. A pronounced low $\delta^{18}O$ value has been found in the three cores within the same facies arrangement. This signal was interpreted as an imprint of a winter 1994/95 cold air mass that brought ^{18}O-depleted precipitation following a N–S trajectory. The counting of isotope cycles and the dating of the common 'cold winter horizon' led to an acceptable dating of the cores.

By assigning a time scale to the cores, annual net accumulation time series could be calculated for the western and eastern summits of the ice cap over 17 and 13 years. Spatial and temporal variability of snow accumulation was found to be very high with the eastern side accumulating half the snow than the western part perhaps because of snow drift, or the impact of Austfonna on wind dynamics. The verification of these hypotheses,

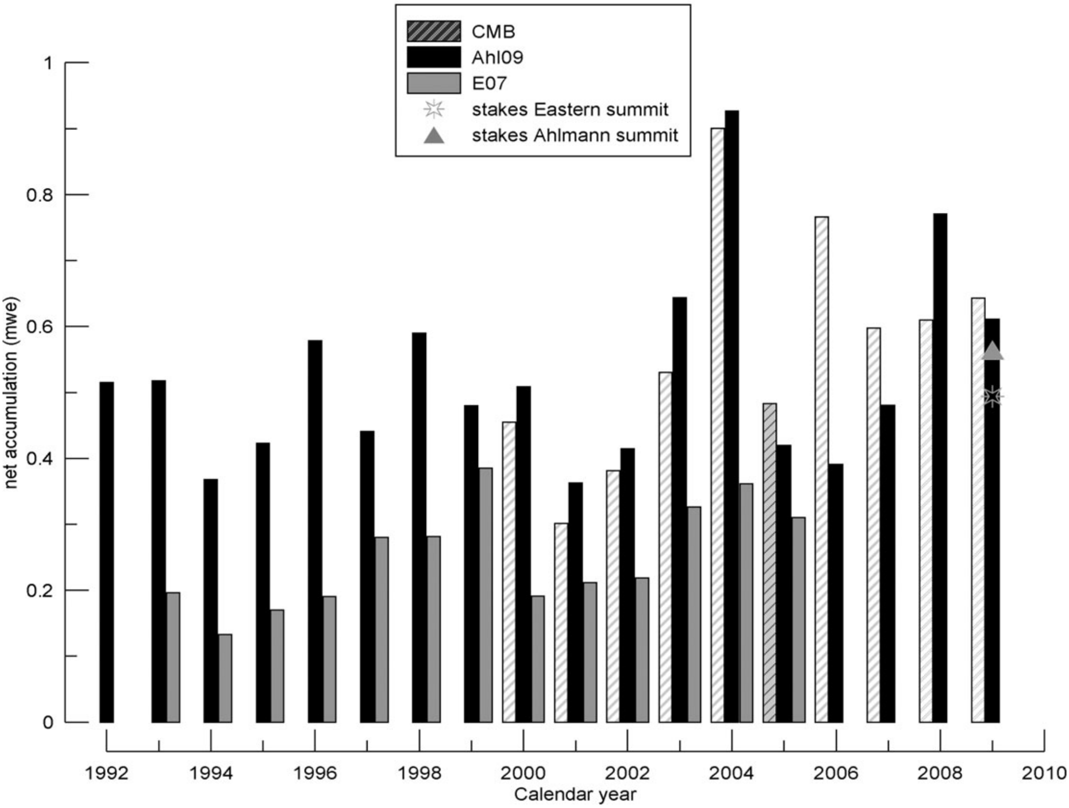

Fig. 7. Net annual accumulation calculated from the Ahl09 (black bars) and E07 (grey bars) cores dating proposed in this work and compared to modelled climatic mass balance (CMB) at Ahlmann summit (Möller *et al*. 2011a) and accumulation measurements at stakes near the drilling sites (2007–2010 averaged values).

however, requires further detailed investigations on wind fields, snow drift and resulting snow accumulation as well as a better characterization of spatial distribution of precipitation and moisture sources via the study of falling snow, snowpack and ice chemical compositions that is currently underway.

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Emilie Beaudon, Arctic Centre, University of Lapland, P.O. Box 122, 96101 Rovaniemi, Finland
Email: ebeaudon@ulapland.fi

Laura Arppe, Department of Geosciences and Geography, P.O. Box 64, 00014 University of Helsinki,Finland.
Email: laura.arppe@helsinki.fi

Ulf Jonsell, Department of Earth Sciences, Uppsala University, Sweden; ETSI de Telecomunicación, Universidad Politécnica de Madrid, Avenida Complutense 30, City University, 28040 Madrid Spain.
Email: ulfygge@gmail.com

Tõnu Martma, Institute of Geology, Tallinn University of Technology, Ehitajate tee 5 19086 Tallinn, Estonia.
Email: martma@gi.ee

Marco Möller, Department of Geography, RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany.
Email: marco.moeller@geo.rwth-aachen.de

Veijo A. Pohjola, Department of Earth Sciences, Uppsala University, Villavägen 16, S-752 36 Sweden.
Email: veijo.pohjola@natgeog.uu.se

Dieter Scherer, Department of Ecology, Technische Universität Berlin, Rothenburgstrasse 12, 12165 Germany.
Email: dieter.scherer@tu-berlin.de

John C. Moore, Colleges of Global Change and Earth System Science, Beijing Normal University, 19 Xinjiekou Wai street, Beijing, China,100875.
Email: john.moore.bnu@gmail.com

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