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SNOWPACK OBSERVATIONS FROM A CIRCUMNAVIGATION OF THE GREENLAND ICE SHEET (SPRING 2014)

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ABSTRACT. *We report the characteristics of the Greenland ice sheet snowpack, based on data collected during the first wind-propelled circumnavigation of the ice sheet, undertaken in spring 2014. The dataset included snow depth measurements made in 100 m^2 plots, and data on the snow bulk density and snowpack temperature at 1 m depth at 25 sites distributed along the 4301 km route traveled during the 49 days of the circumnavigation. In addition, eight snow pits of 1 m depth were dug to measure the snow temperature and density at 10 cm intervals in the upper layer of the snowpack. All this information may help to better understand snow characteristics on this remote area, and provide data to validate and calibrate atmospheric and cryospheric models.*

Snow depths exceeding 4 m were measured in the snow accumulation area, but in many cases the presence of an ice layer prevented penetration of the snow probe below 70 cm depth. This ice layer may be associated with the melting event that occurred in July 2012, and affected 98% of the ice sheet. Beyond the main snow accumulation zone, very constant snow depth values of approximately 1.5 m were measured. The snow temperature at 1 m depth generally ranged from -20°C to -10°C, and was highly correlated with the average atmospheric temperature during the 15 days prior to the snow temperature measurements. The snow bulk density was relatively homogeneous at the majority of sampling sites, ranging from 320 to 390 kg m^{-3}. The snow temperature and density profiles measured in the snow pits indicated that the snowpack became progressively colder from the surface to 1 m depth. The temperature gradient measured in the snow pits was particularly steep (shallow) at the warmest (coldest) sampling sites. The snow density was characterized by denser snow at 60-80 cm depth, coinciding with the depth of the ice layer identified when depth was measured. A dense layer was also found close to the surface at the warmest snow pit sites, and it is likely that this corresponds to a more recent snow melt event.

Observaciones del manto de nieve durante una circunnavegación del casquete de hielo de Groenlandia (primavera de 2014)

RESUMEN: *Este trabajo describe las características del manto de nieve de Groenlandia a partir de datos recogidos durante la circunnavegación del casquete de hielo de Groenlandia durante la primavera de 2014. La base de datos incluye medidas de espesor de nieve en parcelas de 100 m^2, y datos de densidad y de temperatura del manto de nieve a un metro de profundidad medido en 25 puntos a lo largo del trayecto de 4301 kilómetros realizados durante 49 días. Además, se midió la temperatura y densidad de la nieve a intervalos de 10 centímetros en ocho perfiles de un metro de profundidad. Esta información puede resultar de interés para el estudio del manto de nieve en está remota región, así como proporcionar información de utilidad para modelizadores de la atmósfera y procesos criosféricos.*

El espesor de nieve excedió con frecuencia los 4 metros de profundidad, si bien no se pudo superar en ocasiones una capa de hielo localizada aproximadamente a 70 centímetros de profundidad. Esta capa de hielo está posiblemente asociada al evento de fusión de julio de 2012 que afectó a un 98% de la superficie del casquete de hielo. Fuera de la zona de acumulación, el espesor de nieve medido fue bastante constante en torno a 1.5 metros. La temperatura del manto de nieve osciló entre los -20º y -10ºC en la mayor parte de los casos, y ha mostrado una correlación muy alta con la temperatura del aire de los 15 días anteriores a la medida. La densidad del manto de nieve fue bastante homogénea en la mayoría de los puntos de medición, oscilando entre los 320 to 390 kg m^{-3}. Los perfiles de temperatura y densidad informan de un manto de nieve progresivamente más frío en las capas más profundas, observándose los mayores (menores) gradientes en las zonas más cálidas (frías). Se detecta un tramo de mayor densidad en torno a los 60-80 cm, coincidiendo con la capa de hielo previamente detectada. En las zonas menos frías del recorrido, se ha encontrado una capa más densa relativamente próxima a la superficie, posiblemente debida a un evento de fusión más reciente.

Key words: Greenland ice sheet, snow, snow density and temperature, snow pits.

Palabras clave: casquete de hielo de Groenlandia, nieve, temperatura y densidad de nieve, perfiles de nieve.

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1. Introduction

The evolution of the Greenland ice sheet (GIS) is of major importance to the regional and global climate, and for the future evolution of sea level rise (Wang *et* *al.*, 2007). The GIS is the second largest ice body on Earth (the largest being the Antarctic ice sheet); it is almost 2400 km long in a north-south direction, and reaches 1100 km at its greatest width, near its northern margin (latitude 77°N). The total volume of frozen freshwater in the Greenland ice sheet is estimated to be almost $3x10^6$ km^3 (Church *et al.*, 2001).

The deposition and accumulation of snow on the ice sheet is a key element in explaining the mass balance of the Greenland ice sheet. There has been little change in overall mass, but significant thinning has occurred near coastal regions (Nghiem *et al.*, 2005; Højlund Pedersen *et al.*, 2015 associated with the observed increase in global temperature in recent decades (Hansen *et al.*, 2006; Birger *et al.*, 2006). This warming has led to an unprecedented acceleration in melting, particularly during the years 1998, 2003, 2005, 2007, and 2012 (Fetweiss *et al.*, 2011; ARC, 2014). Despite the global impacts of the recent and future evolution of the ice sheet, there remain many uncertainties in estimates of its mass balance (Zwally *et al.*, 2005). This is particularly the case in respect of the snowpack evolution and its characteristics, as most of the information has been derived from remote sensing sources, a limited number of research stations, and automatic weather stations (i.e. the Greenland Climate Network: GC-Net; http://cires1.colorado.edu/science/groups/steffen/gcnet/). In situ measurements of the snowpack in the region have been largely limited to the permanent Summit research station on the ice sheet (Dibb and Fahnestock, 2004; Castellani *et al*., 2015), and isolated field studies that have typically involved only small parts of the ice sheet. The data obtained on snow depth, and from density and temperature profiles has been used to calibrate remote sensing products, and to create various models of snow densification and ice layer formation (Nghiem *et al.*, 2005; Tedesco *et al.*, 2008; Morris and Wingham, 2014).

During May-June 2014, a five member team (from Spain, Denmark and Greenland) completed the first ever wind-propelled circumnavigation of the Greenland ice sheet, as part of the project "Inuit Windsled: A Project for the Scientific Research of the Poles" (http://greenland.net/windsled/project/). Using kites that harness Aeolian energy, the team travelled 4301kilometers in 49 days, and demonstrated the usefulness of this device for scientific purposes. During the expedition the sled carried a micrometeorological station to collect data on temperature and atmospheric humidity. In addition, the team systematically collected information on snow depth, and measured density and temperature profiles in the upper part of the snowpack along the route. Here we summarize the data collected from 26 locations spanning the majority of the latitudinal gradient (63.9-79.4°N) at both the east and west margins of the ice sheet.

2. Expedition details, data collected and analysis

The first wind-propelled circumnavigation of Greenland was conducted from 5 May to 23 June 2014, and involved a distance of 4301 km covered in 49 days. The maximum distance traveled in a single day was 427 km. The wind sled used was composed of three modules, and was powered only by wind using a set of interchangeable kites that were selected depending on the wind conditions (Fig. 1). The route started and finished at Kangerlussuaq (southeast Greenland; 63°5´), proceeded in a clockwise direction to almost 80°N (Fig. 2), and ranged in elevation from 1540 to 3025 m a.s.l. Throughout the circumnavigation, regular snowpack measurements (approximately every 100 km) were made including: snow depth (ten random measurements in 100 m^2 plots); snow density (using a Snow-Hydro snow water equivalent sampler); and temperature, up to 1 m depth). At approximately every 500 km, snow pits of 1 m depth were dug for measurement of the snow density and temperature at 10-cm intervals. Interpretation of snow depth measurements in this environment is complex. In the ablation area, the depth may represent the snowpack accumulated in previous months, while in the accumulation area it is only the depth to which the snow probe is able to penetrate until snow becomes firm, or a consistent ice layer is found (Wang *et al.*, 2007). Previous reports suggested that in most cases the upper 1 m of the snowpack represents the snow accumulated in the previous 1-2 years, as the reported mean annual rate of accumulation of snow is 60-70 cm yr^{-1} (Bales *et al.*, 2001; Dibb and Fahnestock, 2004), most of which accumulates during summer months.

Figure 1. Researchers with the Windsled during a stop to survey the snowpack.

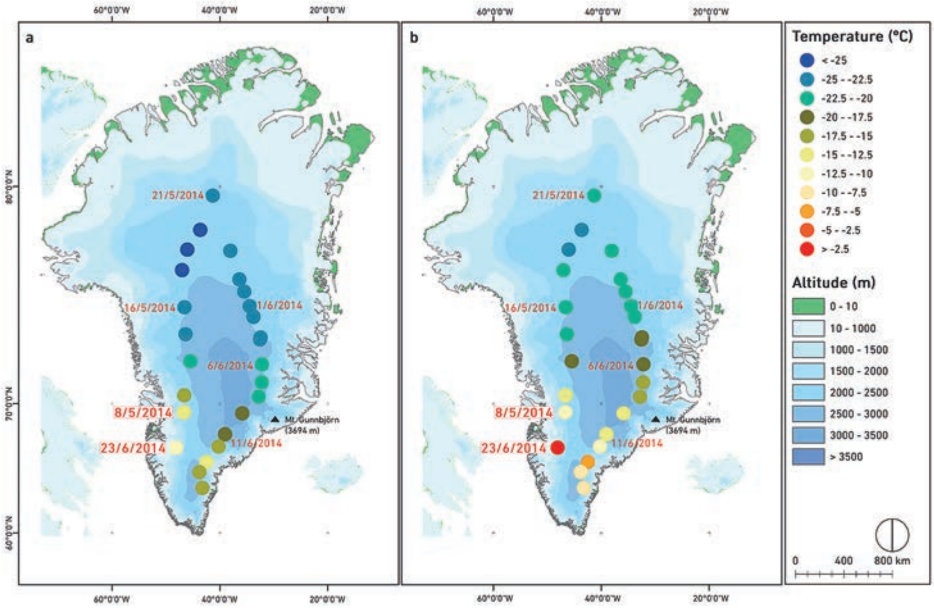

Figure 2. Route followed during the circumnavigation. 2a: Average air temperature from March to June at the sites where snow measurements were conducted. 2b: Average air temperature during the 15 days prior to the snow measurements.

To illustrate temperature differences along the route we determined the average air temperature for the period March–June, obtained from the ERA-Interim reanalysis product (http://apps.ecmwf.int/) for the locations were snow measurements were made (Fig. 2a). This shows that the northwest part of the route was the coldest, with average temperatures < -25°C. At the northernmost and most northeastern points reached the temperature ranged from -20 to -25°C; warmer temperatures (-20 to -10°C) dominated below 70°N, especially in the western part, where the elevation is lower. To record the advance of spring on the characteristics of the snowpack along the route we also determined the average atmospheric temperature for the 15 days prior to each individual snow survey (Fig. 2b). Logically, the temperatures were warmer than presented in Figure 2a, especially those recorded during the final days of the circumnavigation, which occurred in the southernmost part of the ice sheet during the second half of June. Reanalysis data was compared with the temperature measured using a Tinytag TGP4104 sensor installed in an open module on the sled (protected by a DataMate™ radiation shield). As shown in Figure 3, the reanalysis data were consistent with observed temperatures along most of the route; the mean bias error was -0.7°C and the mean absolute error was 1.5°C. A larger error was detected for the middle section of the route, which was furthest from the coast, and probably from the observatories on which the reanalysis was based.

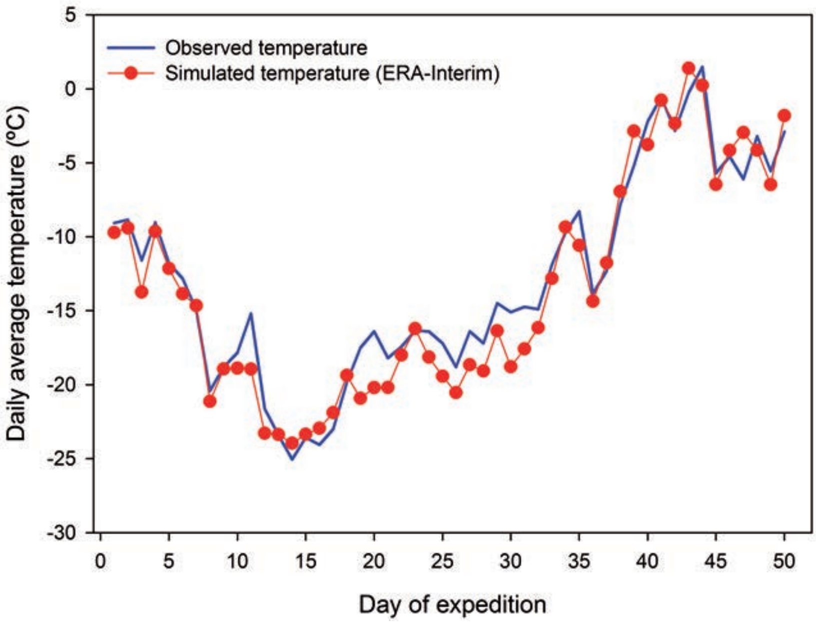

Figure 3. Observed and simulated (ERA-Interim) daily average temperature.

3. Results and Discussion

Figure 4 shows the measured average snow depth (A), and the coefficient of variation (B) for measurements made at the 25 measurement sites along the route. At each site 10 random measurements within a plot of 100 m^2 were made. Those sites where the presence of ice layers was confirmed are also marked. The measured average depth ranged from 0.4 m (on the last day of survey) to 3.5 m, whereas the coefficient of variation ranged from 0.01 to 1. For more than 50% of the sites the coefficient of variation was < 0.3, what is consistent with snow deposition on smooth surfaces (López-Moreno *et al.*, 2011), which typically characterizes the ice sheet. The greatest small-scale variability values corresponded to sites where ice layers were detected, mostly in the accumulation zone. In these plots the snow probes sometimes penetrated the layer, while at others it did not; this explains the high degree of local variability. In all these cases the ice layer was located at approximately 0.7–0.8 m. The depth measurements when the probe was able to penetrate the ice layer often exceeded 3 m, and sometimes exceeded the length of the snow probe (5 m). Based on reported accumulation rates for the snow accumulation areas (Bales *et al.*, 2001; Dibb and Fahnestock, 2004; Shen *et al.*, 2012; Shupe *et al.*, 2015), the ice layer located at 70 cm depth could be associated with a generalized melting event that occurred in July 2012, and affected 98% of the surface area of the ice sheet (Shuman *et al.*, 2012). In addition, the presence of the ice layer at depths up to or exceeding 5 m indicates the relatively slow densification of polar snow

(Morris *et al.*, 2014). In general, the colder sites and those where the temperature during the previous 15 days had been < -15°C had the greatest snow depths, whereas sites where the average temperature during the 15 previous days was > -15°C (below 70°N), the snow depth was relatively constant at approximately 1.5 m, as a result of more frequent melting events and more rapid snow densification.

Figure 5 shows the snowpack temperature at 1 meter depth. It was evident that the measured temperature was not determined solely by the geographic position of the measurement site, but also at what time during the circumnavigation the measurements were carried out. Thus, at the edges of the ice sheet the measured temperatures were < –10°C at the beginning of the study (early May), but well above -10°C during the last days of the study (late June). In the accumulation zone (mainly in the northwest of the ice sheet) the snow temperature was < -20°C during the first days of the study, but because the route was further to the north there was no recorded decrease in temperature because the measurements were being taken progressively later in the season. The temperature had increased above -20°C by late May-early June, despite the high latitude and elevation of the route. In the southernmost part of the ice sheet the snowpack was very close to isothermal conditions during the second half of June. The snow temperature responded linearly ($r^2 = 0.97$) to the average temperature over the 15 days prior to the measurement (Fig. 6), suggesting that this is a useful way to easily obtain an approximation for the near surface snow temperature.

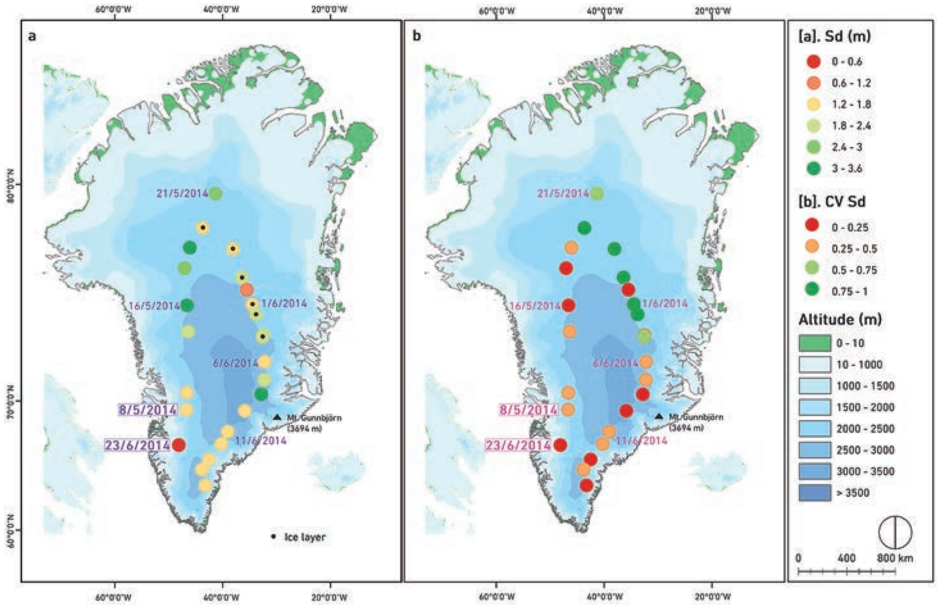

Figure 4. Average snow depth and the coefficient of variation for 10 random measurements within plots of 100 m².

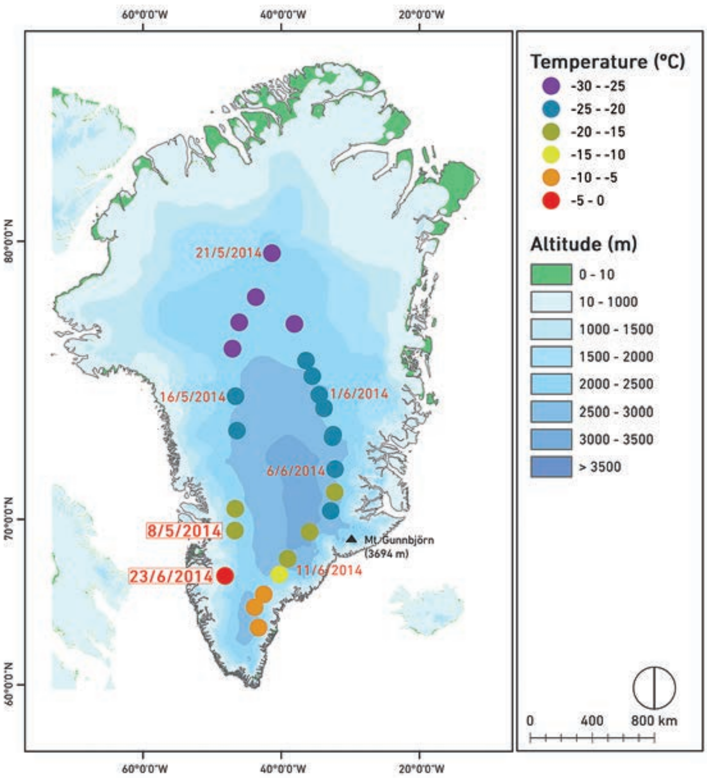

Figure 5. Average snow temperature of snowpack at 1 meter depth.

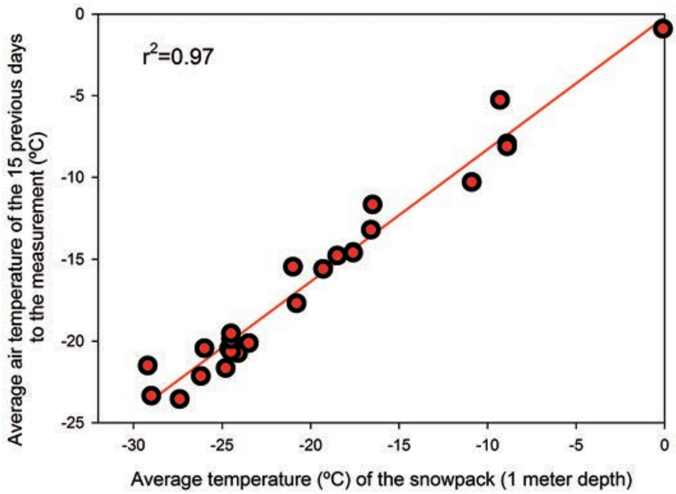

Figure 6. Average temperature for the upper 1 m of the snowpack as a function of the average temperature for the 15 days prior to the measurement.

Figure 7 shows the bulk snow density for the upper 1 m of the snowpack for the 25 measurement points. The range of values for snow density was very narrow (307-393 kg m^{-3}), except for the last measurement made during the study (when the snowpack was shallow, almost isothermal, and the density was 423 kg m^{-3}), and at one site where the ice layer impeded to recover more than 50 cm of snow, and the density was 282 kg m^{-3}. This relative homogeneity in snow density over a very large area is in stark contrast with the findings of other studies carried out in alpine environments (Fassnacht *et al.*, 2010; López-Moreno *et al.*, 2013). However, the values in the present study are very similar to those reported by Dibb *et al.* (2004; see Fig. 4 in that publication) for weekly measurements made over two years at the Summit research station. This suggests that the snow rapidly increased in density following snowfall (wind compaction being the main driver), and afterwards the densification process was relatively slow and homogeneous in space. Despite the spatial homogeneity of the bulk density, measurements taken during June (to the southeast and south of the ice sheet) tended to record a denser snowpack, with values generally exceeding 350 kg m^{-3}.

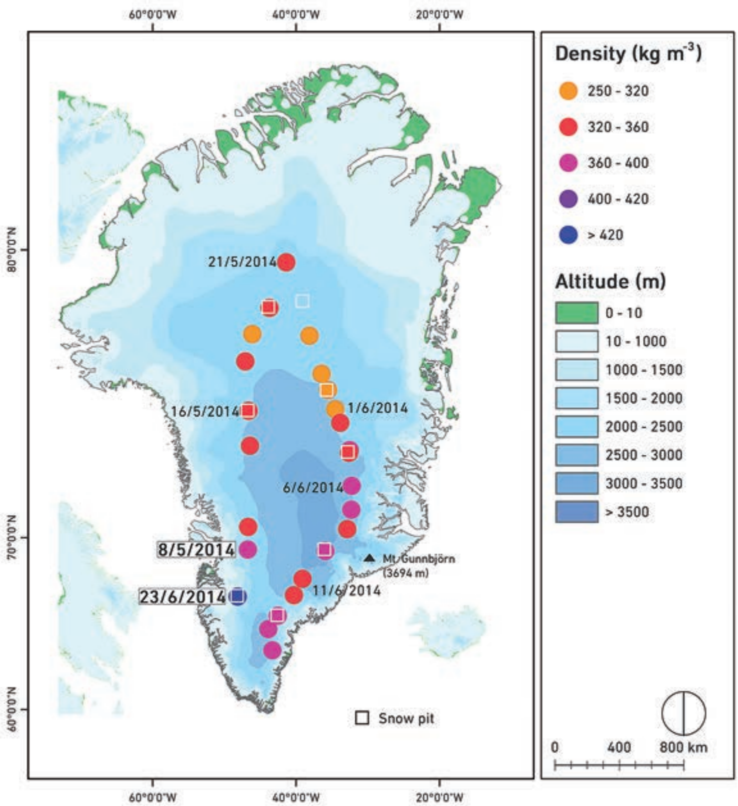

Figure 7. Bulk density of the upper 1 m of the snowpack, measured using a snow water equivalent sampler. The squares indicate the locations of the snow pits.

Figure 8 shows the vertical gradient of snow temperature and density in the upper 1 m of the snowpack, measured at 10 cm intervals. In all cases there was a clear gradient to colder temperatures with depth. The greatest gradient (11°C) was found in snow pits 5, 7, and 8. In the latter two the temperature over the top 10 cm was -5°C; this fell to -16°C at 1 m depth, suggesting that even in these warmer areas the cold content at the end of June was still high. The smallest thermal gradient was found in snow pits 1, 2, and 6. The former two profiles had gradients of -6°C and -8°C, respectively, and were from sites located at high elevation and latitude. In these two profiles the surface

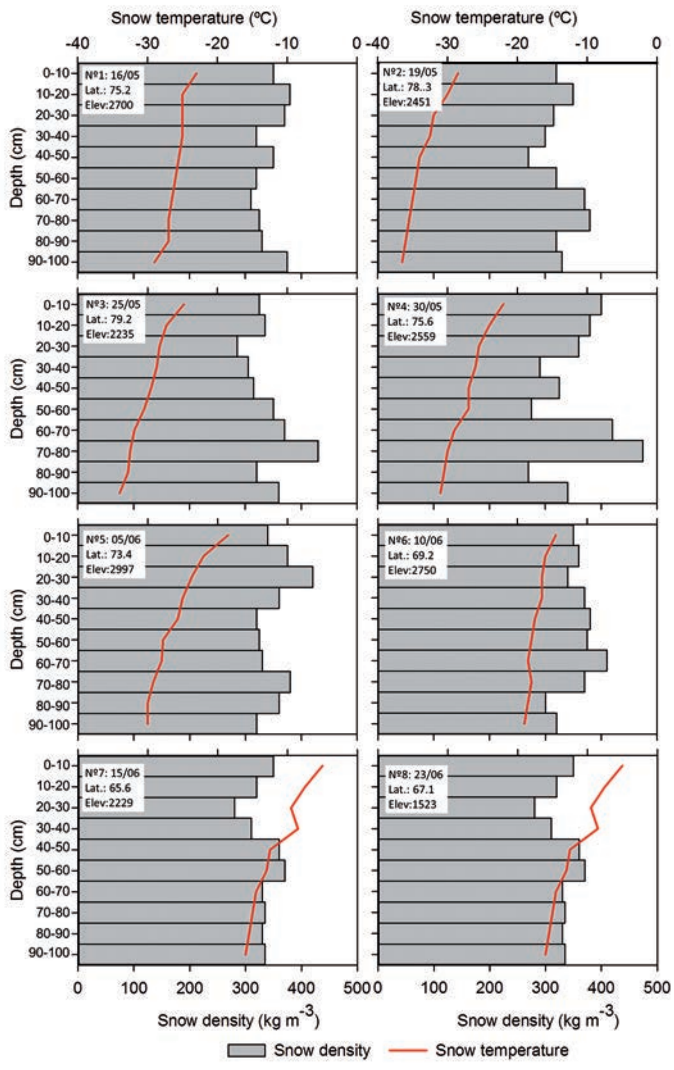

Figure 8. Vertical gradient of snow temperature and density at 10 cm intervals in the upper 1 m of the snowpack.

temperature was very low (-22°C and -29°C, respectively), and declined to < -30°C at 1 m depth. Snow pit 6 had the lowest gradient (-4.5°C; range: -14.5°C to -19°C), and was located at a relatively low latitude (67°N) but at one of the highest elevations among sites (2750 m a.s.l.). The most common pattern in the vertical gradients of snow density was a slight decrease in density from the surface to 60 cm depth, and an increase in density from 60 to 80 cm depth. This pattern was particularly characteristic of those sites where ice layers were present. As mentioned previously, the ice layer was typically at approximately 70 cm depth. For snow pit 1 there was a relatively constant increase in density over the top the 1 m, whereas for snow pits 7 and 8 the snowpack was denser in the interval 40-60 cm, probably corresponding to a more recent melting event. The snow density in the eight pits was very similar below 70 cm depth, with values ranging from 325 to 375 kg m^{-3}.

4. Conclusions

Snow depth measurements on ice sheets can be difficult to interpret. Depending on the particular study site the measurements can reflect the depth of the seasonal snowpack during the previous year, while in accumulation zones it can provide information about the presence of ice layers or the degree of compaction of the snowpack. In the main accumulation zone on the Greenland ice sheet the local variability of the snowpack at a scale of 100 m^2 was relatively high (coefficients of variation: 0.75-1), mostly because of the presence of a consistent ice layer located at approximately 70 cm depth. This layer may be associated with the melting event that occurred in July 2012, which affected 98% of the ice sheet. In many cases the snow probe could not penetrate this layer during measurements. However, when the ice layer was penetrated, depths of 4-5 m (the length of the snow probe) could be reached, and indicated a relatively high rate of densification at these sites. In areas characterized by higher temperatures and more frequent melting events, the snow depth was relatively constant at approximately 1.5 m, and the local variability of the snowpack was very low (coefficients of variation approximately 0.3).

The average temperature in the upper 1 m of the snowpack was closely correlated with the average atmospheric temperature over the previous 15 days, with these variables having an almost linear relationship ($r^2 = 0.97$). With few exceptions, at the majority of sites the snow density in the upper 1 m of the snowpack was very homogeneous, and ranged from 300 to 390 kg m^{-3}. These values are consistent with the results of previous studies carried out in Greenland. The spatial homogeneity of these values during the 49 days of the circumnavigation suggests that compaction of the snowpack occurred simultaneously with or immediately following snowfall, as a consequence of wind-driven effects. The subsequent densification process was relatively slow in the upper part of the snowpack.

Analysis of the temperature and density profiles from the snow pits indicated that the snowpack was increasingly cold from the surface to 1 m depth. The majority of profiles had very low temperatures, even late in the season, and only those pits that were at relatively low elevations and latitude, and were analyzed at the end of the expedition, were relatively close to isothermal conditions. The gradient was particularly steep (shallow) for snow pits located at the warmest (coldest) sites. The snow density profile was characterized by greater density at 60-80 cm depth, coinciding with the depth of the ice layer thought to have been formed during the July 2012 melt event. A denser layer, found closer to the surface in pits dug at the warmest sites, may correspond to a more recent snow melt event, as these sites were in the ablation zone, where the snowpack can be considered seasonal.

Polar expeditions typically provide only a snapshot in time of the snow characteristics. However, they commonly involve very large areas and relatively short timeframes, reaching places that are extremely inaccessible to most researchers, so it has an undeniable interest from a scientific point of view. In this context the Windsled offers a very promising tool for exploring and studying polar areas because of its flexibility in transporting research equipment, its speed and versatility in such complex terrain, and because it is environmentally friendly. The information collected needs to be carefully interpreted because of its temporal character, but can be very useful for developing and testing various hypotheses, for validating climate and cryospheric models, and to provide useful data for calibrating remote sensing products, which are currently the main source of information on changes in the mass balance of the cryosphere in Polar Regions.

Data accessibility and more information. Data on temperature and relative humidity collected during the circumnavigation, as well as information on the snow depth, temperature, and density are available to all interested researchers. Please contact the corresponding author for queries related to accessing the data. For more information concerning the Windsled, and to suggest new experiments for the next polar expedition, contact Tierras Polares (www.tierraspolares.es).

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