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Autonomous Ice Sheet Surface Mass Balance Measurements from Cosmic Rays

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Abstract. Observations of mass accumulation and net balance on glaciers and ice sheets are sparse due to the difficulty of acquiring manual measurements and the lack of a reliable remote sensing method. The methodology for recording the water equivalent accumulation of snowfall using the attenuation of fast neutrons generated by cosmic ray impacts was developed four decades ago and has been employed in large-network snowpack monitoring but has yet to be applied to glaciers and ice sheets. In order to assess this potential method, we installed a cosmic ray neutron sensing device at Summit Camp, Greenland in April, 2016. Hourly neutron count was recorded for ~20 months and converted to water equivalent thickness after correcting for variability in atmospheric pressure and background cosmic ray intensity. The daily accumulation estimates are analysed for noise level and compared to manual surface core and snow stake network measurements. We estimate the sensor's accuracy to be better than 1 mm for water equivalent thicknesses less than 20 cm, and better than 1 cm in up to 140 cm. Our observations agree with the surface core measurements with a standard deviation of 1.2 cm and a small negative bias that is explained by snow drifting, as supported by comparison to the snow stake network. Our observations reveal large temporal variability in accumulation on daily and greater scales, with consistently low accumulation in June/July and high accumulation in the autumn. Based on these results, cosmic ray sensing represents a potentially transformative method for measuring glacier and ice sheet mass balance.

1 Introduction

Ice sheets and glaciers gain mass from the accumulation of snow and lose mass primarily from meltwater runoff and iceberg calving, with smaller amounts from sublimation and basal melting. Accurate measurements of these terms are necessary for assessing the contribution of land ice to rising sea levels. All methods for estimating glacier and ice sheet mass balance, with the exception of satellite gravimetry, require observations or model estimates of the mass accumulated per time. Multiple remote sensing methods exist for measuring the of volume of accumulation, including repeat satellite or airborne altimetry and snow penetrating radar, but the density of the accumulation and, therefore, its mass are unknown. Mass accumulation rates are most commonly obtained through in situ sampling from snow pits and firn cores, typically with an annual resolution corresponding to identifiable seasonal layering. Such methods are laborious, logistically expensive and provide only a point measurement affected by local variability due to drifting and scouring. Active radar imaging of the upper snow surface has been employed successfully to measure mass accumulation, but the power and maintenance requirements of these systems, and their sensitivity to meltwater, make them currently impractical for long term (> 1 year) autonomous deployment in remote locations. Other methods typically used to monitor seasonal mountain snow packs, including snow pillows and mechanical scales, are ill suited to glaciers and ice sheets. Snow pillows require the transport or on site generation of 100's of kg of water and antifreeze to fill the pressure bladder, and will still freeze at polar temperatures. Both methods require a large, level surface for deployment and they may underestimate mass due to stress bridging by strong layers in the snowpack.

Cosmic ray neutrons are generated through collision of cosmic rays, high-energy particles generated from supernova, with the Earth's atmosphere. The hydrogen in water attenuates such neutrons, with attenuation increasing predictably with the mass of water surrounding a measurement sensor. In a series of experiments, Kodama et al. (1975; 1979) and Kodama (1980) designed and deployed passive sensors that used the attenuation of cosmic ray neutrons by accumulating snowfall to estimate time series of snow water equivalent thickness of mountain snowpack. These sensors were able to measure daily water equivalent thickness with an accuracy of 3-4% (Kodama, 1980). Additionally, the sensor is sensitive to snowfall over relatively large area (10's m2), providing an aerially averaged estimate. Further, since the maximum limit of observable water thickness is determined by the minimum number of counts required to provide a statistically significant mean, the method could ostensibly work in water equivalent thicknesses exceeding 10 m. Finally, since the sensor is passive and primarily consists of only polyethylene in a steel case, it is lightweight, compact, durable and has low power requirements. While this method was further refined and adapted successfully to monitoring soil moisture (Kodama, 1985), it was not widely applied to measuring snowpack until 1998 when the French electric utility installed a network of 40 cosmic ray snow gauges for hydroelectric monitoring (Paquet and Laval, 2005; 2008). An extensive comparison between snow cores and cosmic ray sensor estimates revealed accuracies in water equivalent thickness between 12 and 20%, with much of the discrepancy due to spatial variability in the snowpack between the cores and the sensors, as well as a significant uncertainty due to variations in soil moisture. Accounting for these differences resulted in hourly swe estimated with accuracies better than 5% (Paquet and Laval, 2008), consistent with the results of Kodama (1980).

Cosmic ray sensing therefore provides a potentially effective method for measuring mass balance in the accumulation zones of ice sheets and glaciers. Since the cosmic ray neutron count rate is only sensitive to the mass, and not the density, of the firn, it integrates the processes of snowfall, sublimation, deposition, and vertical vapor and meltwater fluxes into a single measurement of local mass balance. Glaciers and ice sheets are also particularly suitable to cosmic ray sensing because, firstly, neutron counts increase with altitude and latitude, due to decreasing atmospheric attenuation, which increases the accuracy and resolvable maximum thickness for a given temporal resolution. Secondly, the sensor's effective cone of measurement provides an aerial average that is less sensitive to spatial variability caused by drifting. Thirdly, the sensor is portable and solid state, providing ease of deployment and durability. It is also passive and, therefore, has a relatively low power requirement.

Here we assess the potential for cosmic ray sensing of glacier and ice sheet mass balance through deployment of a cosmic ray neutron sensing instrument at Summit Camp (72.57°N, 38.46°W), located 3216 m above sea level in center of the Greenland Ice Sheet. We describe the deployment setup, the characteristics of the raw neutron count data, the correction and calibration datasets and compare the raw to the corrected count data and water equivalent accumulation estimate. We present our daily and monthly accumulation rates at Summit Camp and then compare those estimates to manual observations of snow accumulation for validation.

2 Instrument Deployment

Summit Camp was chosen for its continuous power supply and climate-controlled instrumentation housing. This, and the year-round presence of support staff to troubleshoot if needed, simplified this initial deployment and reduced the risk of instrument failure, allowing the focus to be only on assessment of the cosmic ray counting methodology. The support staff were also able to perform the validation surveys. Summit Camp has annual water equivalent accumulation of 24 cm and an average surface density of 0.35 cm g cm-3 (Alley et al. 1993). Snowfall occurs throughout the year, with some uncertainty about the seasonality of accumulation (Dibb and Fahnestock, 2004).

We installed a Hydroinnova Snowfox™ cosmic ray neutron-sensing instrument at Summit Camp on April 30th, 2016. The Snowfox™ is a 0.81-m long and 0.2 m diameter tube that was placed horizontally in a shallow trench in the firn so that the top of the Snowfox™ was ~0.20 m below the surface (Fig. 1). The trench was then allowed to fill with wind-blown snow, burying the sensor. A 100 m long power and communications cable connects the sensor to a data logger, telemetry modem and continuous power supply housed in the climate-controlled Main Science Facility (MSF) at Summit Camp. The sensor recorded hourly counts of neutron impacts, as well as hourly average barometric pressure and temperature.

3 Count Rate Correction and Conversion

To obtain an estimate of the water equivalent thickness of accumulation, hw, from hourly counts of neutrons recorded by the sensor, N, corrections must be applied for background variability in background cosmic ray activity and atmospheric water vapor. Background cosmic ray variability is corrected using atmospheric pressure-corrected count data from a second, reference neutron sensor located above the surface. The relative calibration count rate N_r^* is obtained from the reference sensor count rate N_r as:

$$\boldsymbol{N_r^* = 1 + \beta\left(\frac{N_s}{N_r} - 1\right)}, \tag{1}$$

where N_s is the reference count rate and β is a distance-dependent scaling parameter. For application to summit station, we use the neutron monitor located at Thule (THUL) Greenland operated by the Bartol Institute at the University of Delaware and distributed via the Neutron Monitor Database (www.nmdb.eu/nest/). The correction for atmospheric water vapor is applied using barometric pressure recorded at the sensor, P as:

$$\boldsymbol{P}^* = \boldsymbol{exp}(\boldsymbol{\alpha}[\boldsymbol{P_0} - \boldsymbol{P}]), \tag{2}$$

where P_0 is a reference pressure for the elevation of Summit Camp and α is a scaling constant. The solar and pressure-corrected relative count rate is then:

$$N^* = P^* N_r^* \frac{N}{N_0}, \tag{3}$$

where N_0 is the reference count rate at the surface obtained prior to burial of the sensor. The water equivalent accumulation thickness, h_w, is then obtained from the corrected, normalized count rate N^* as:

$$h_w = -\Lambda^{-1} \log N^*, \tag{4}$$

with:

$$\Lambda = \frac{1}{\Lambda_{max}} + \left(\frac{1}{\Lambda_{max}} - \frac{1}{\Lambda_{min}}\right)\left(1 + exp\left[\frac{a_1 - N^*}{a_2}\right]\right)^{-a_3}, \tag{5}$$

The empirical parameters Λ and *a,* as well as the reference and scaling factors in Eqns. 1 and 2, were determined through calibration and field validation experiments by the sensor manufacturer. Their values are listed in Table 1. The resulting time series of h_w is plotted in Fig. 2a. There is a gradual increase in h_w with decreasing N^* to h_w =34 cm, N^*/N_0 = 0.3. Below this N^*/N_0, h_w increases more steeply, rising to 200 cm at N^*/N_0 = 0.1, 300 cm at N^*/N_0 = 0.04 and 490 cm at N^*/N_0 = 0.01. Thus, as shown in Fig. 2b, the count rate is ~25 times more sensitive to variations in h_w at 10 cm than at 100 cm, and 50 more times sensitive than at 200 cm. Conversely, this implies a corresponding, nonlinear decrease in the resolution of h_W with increasing thickness, reaching 1 cm for 1 count per hour near 400 cm. However, the fractional change is such that the that resolution is better than 1% of h_w for thickness greater than 7 cm water equivalent. The true resolution, however, will also be a function of noise in the count rate.

4 Validation Datasets

In order to validate the cosmic ray sensor observations, water equivalent accumulation was measured manually every ~10 days beginning March 13, 2017 from a location approximately 10 m from the cosmic ray sensor. The manual observations utilized the "snow board" method in which a shallow, rectangular pit is excavated and a piece of plywood is placed at the floor of the pit. The pit is then allowed to fill with snow and settle over a period of ~2 weeks. A PVC tube is used to remove a core sample of the snow from the surface to the plywood, which serves as a depth reference for each subsequent sample. The sample is taken from a different location each time, as measured from flagged poles at the corner of the plywood, to provide an undisturbed sample. The surface snow core is then weighed to the nearest 0.1 g, the weight of the core tube is removed and the snow weight is divided by the cross sectional area of the core to give a measurement of h_w. For redundancy, the snow core sample is allowed to melt and the water volume is recorded to the nearest mL. This volume is divided by the cross sectional area of the core to give another measurement of h_w. The difference between these two measurements provides a check on the accuracy of the sample. For the 42 observations, the mean difference was 0.01 cm water equivalent thickness with a standard deviation of 1.63 cm. This standard deviation is larger than the uncertainty predicted by the measurement precisions and, therefore, may be due to unconstrained errors in the sampling procedure. We therefore assume ± 1.63 cm water as the error in h_w obtained from the surface cores. The length of the snow core is also measured to the nearest 0.5 cm, with the ratio of h_w to the snow depth giving the bulk sample density.

We additionally compare cosmic ray sensor h_w estimates to accumulation measured from a network of 120 stakes (i.e. the "bamboo forest") ~weekly at Summit Camp (Dibb and Fahnestock, 2003). Accumulation is estimated from the mean change in stake height above the surface, multiplied by a constant density of 0.35 g cm^{-3}. While the uncertainty of accumulation density, including an unknown amount of snow compaction, prevents a direct comparison with the cosmic ray estimates, the stake survey provides an estimate of average variability over a relatively large area as opposed to the point measurement provided by the surface core samples. This provides an assessment of the possible influence of spatial variability on surface core measurements relative to the cosmic ray sensor.

5 Results

Fig. 3a plots the time series of uncorrected hourly neutron counts recorded by the cosmic ray sensor. Starting from 7000 counts per hour (cph), when the sensor was exposed at the bottom of the firn trench, the count rate dropped to ~4200 cph over 16 days as the trench filled with snow. The count rate then held above 3000 cph until March, when it dropped to 2200 cph by May. The rate then stayed above 2000 cph through the end of the record (January). The daily standard deviation in hourly count rate in the uncorrected data was 32.1 cph. This provides a metric of relative noise level, since only a small change in counts due to snow accumulation (<< 1 cm) is expected during average weather conditions.

Corrections for solar activity, N_r* and atmospheric pressure P* are shown in Fig. 3b. An approximately 30-day oscillation with an amplitude of ±0.03 is visible N_r* , with larger, short-term events causing variability of up to ±0.5. There's a overall decline in N_r* over the period from 0.96 to 0.88. Relative variability, and thus the impact on count corrections, is larger for P*, with short term (days) variablity of up to ±0.1 and an annual cycle with an amplitude of ±0.12 and a maximum in July and minimum in January. Applying these corrections to the raw count data gives the corrected series shown in gray in Fig. 3a. The correction reduces the daily standard deviation of hourly counts to 15.5 cph and results in a more linear decline of ~1000 cph between July 2017 and January 2018. The initial corrected count rate when the sensor was uncovered (3571 cph) was then used as N_0 to give the corrected relative count rate and snow water equivalent thickness, h_w, shown in Fig. 3c. The initial, rapid 8 cm increase is consistent with infilling of the 20 cm trench assuming a density of wind packed snow of 400 kg cm^{-3}. From June to September, h_w remains near constant before increasing to 30 cm by the following spring. Another stable period of h_w occurs in the summer 2017, followed by another 20 cm increase between October and January.

We expect the noise level in h_w to increase as N* decreases (and h_w increases) because the noise in N* becomes larger relative to N^*/N_0 , so that the signal to noise ratio decreases. This is visible in the curves in Fig. 3c. We assess the increase in noise by plotting the daily mean of hourly h_w estimates to their standard deviation (Fig. 4). The standard deviation increases from under 0.1 cm at h_w = 15 cm to 0.5 cm at h_w = 50 cm. The best fit line predicts a standard deviation of 0.013 cm + 0.007 cm per cm of h_w , so that the standard deviation reaches 1 cm by h_w = 140 cm. The lower range of daily standard deviations corresponds closely to the depth-dependent resolution of hourly h_w measurements shown Fig. 2b, and the best fit of the standard deviations is three to five times larger (Fig. 4). This indicates that errors in h_w due to noise in the count rate are of similar order of magnitude as, but larger than, the resolution errors. In relative terms, the standard deviation drops below 1% for h_w larger than 5 cm, declining to 0.7% for h_w greater than 30 cm. The increasing noise however, increases the uncertainty of change measurements, given by the root sum of two times the squared deviations, or 0.01 cm per cm of h_w, assuming daily errors are uncorrelated. Thus the standard deviation in daily change measurements is 0.5 cm in 50 cm of h_w and 1 cm in 100 cm of h_w .

The mean daily water equivalent accumulation rate was 0.078 cm with a standard deviation of 0.356 cm (Fig. 5). The maximum single day of accumulation was 2.1 ±0.4 cm on 15 September, 2017, while the maximum negative accumulation (ablation) was -1.1 ±0.4 cm on 18 September, 2017. After the period of infilling of the trench in which the cosmic ray sensor was deployed, including two days with near 2 cm/day of accumulation on 14 and 15 May, 2016, there was a sustained period of low deviation in daily rates from June to October, 2016, followed by increasingly large scatter after. We expect increasing noise in these data due to a declining relative neutron count rate and such is apparent when plotting the change in h_w as a percentage of h_w (Fig. 5b), where a daily ± 2% variation is consistent throughout the record. We would also expect variability to correspond with wind strength due to the effect of drifting and scouring. While some anomalously high accumulation rates, such as on the 15 September, 2017, occurred on days with high winds (Fig. 5c), the correlation between mean or maximum (not shown) daily wind speed and accumulation rate is not significant, indicating that the much of the variability is due to noise and other factors.

Overall, the rate of accumulation was 26.2 ±0.3 cm yr^{-1} from 16 May 2016 (after burial of the sensor) to 14 January 2017. The single year accumulation to 16 May 2017 was 23.1 ± 0.5. We plot the monthly accumulation rate, calculated as the change in monthly mean h_w, normalized for days in each month, in Fig. 6. The monthly accumulation rate shows large variability, with a standard deviation of 58% of the 2.1 cm per 30-day mean. In both 2016 and 2017 the lowest accumulation rate was in June/July, with the June/July 2016 accumulation rate totalling only 0.06 cm, or 3% of the mean rate. The highest accumulation rate in 2016 was recorded in October/November, while the highest in 2017 was in September/October. For the 7 months (June through December), measured in both 2016 and 2017, those measured in 2017 had higher accumulation rates in all but July/August, with more than double the 2016 rates in September/October and October/November.

6 Validation

For validation we compare the change water equivalent accumulation thickness, Δh_w , estimated from the cosmic ray sensor to surface core and snow stake observations (Fig. 7). Since both the surface core and snow stake observations have a one day timestamp, we compare these data to the daily means of the hourly cosmic ray estimates. The mean difference in Δh_w from surface core measurements is -0.77 cm with a standard deviation of 1.21 cm. The r^2 between variations in the surface core and cosmic ray measurements is 0.97 (Fig. 8a) . The three largest outliers occur on 19 September 2017, 9 November 2017 and 17 January 2018 and all after large (> 2 cm) accumulations recorded by the surface core. The difference then goes to near or greater than zero in the next one or two core measurements. The cosmic ray sensor estimated approximately one standard deviation lower Δh_w than the snow cores in June 2017, moving back to zero difference by the end of August.

The mean difference in Δh_w from the snow stake network measurements, converted to water thickness assuming a constant density of 0.35 g cm^{-1}, is -0.22 cm with a standard deviation of 0.90 cm. The r^2 between variations in the surface core and cosmic ray measurements is 0.99 (Fig. 8b). The snow stake measurements, as with the cosmic ray measurements, tend to show smaller variability than the surface core measurements and do not show the large increases and decreases during the outler events mentioned above.

7 Summary and Conclusions

Cosmic ray neutron sensing offers a potential method for obtaining practical, autonomous, in situ mass balance measurements on glaciers and ice sheets. To test this potential, we deployed a cosmic ray neutron counting sensor at Summit Camp, Greenland between April 2016 and January 2018. Based on the the daily scatter in hourly measurements, we obtain a 1σ error estimate of 0.013 cm for 0 cm water equivalent, increasing with thickness at a rate of 0.0071 cm per cm of water equivalent, giving errors of 0.1, 0.5 and 0.7 cm in thicknesses of 10, 50 and 100 cm of water, respectively. We observed single day accumulation and ablation events of up to approximately 2.1 and -1.1 cm of water per day, respectively, with daily variability due to both increasing sensor noise with depth and wind drifting and scouring. Monthly accumulation rates show large month-to-month variability, exceeding 50% of the mean, with a minimum accumulation in July/August in consecutive years and a maximum in autumn, suggesting an annual cycle.

We validated the cosmic ray neutron measurement though comparison to repeat surface snow core and stake network measurements. The mean difference in Δh_w from surface core measurements is -0.77 cm with a standard deviation 1.21 cm, which is better than the estimated ±1.6 cm uncertainty of the core measurements. The negative bias arises from short-term, local scale variability measured by the surface core due to snow drifting that is areally averaged by the cosmic ray sensor. This is confirmed by the greater correlation to accumulation measured from the snow stake network which, like the cosmic ray sensor, did not show the large, temporary increases in accumulation. Thus, a challenge to further validation will be obtaining validation observations of high enough accuracy at a similar spatial and temporal resolution as the cosmic ray sensor.

Our test supports cosmic ray sensing's potential as an effective and practical method for obtaining, for the first time, continuous and autonomous measurements of surface mass balance within accumulation zones (i.e. where annual snowfall exceeds ablation). The very high accuracy of the instrument, exceeding 1 mm per hour, opens up the possibility of acquiring mass balance measurements over the low accumulation, but vast interior of the Antarctic Ice Sheet, where few direct measurements of surface mass balance exist and which represents among the largest sources of uncertainty in ice sheet mass balance measurements. These low accumulation, polar regions are also the most difficult to measure manually due to the limited precision of core samples and the lack of chronology in the upper firn. In areas with higher accumulation, the increase in noise and loss of resolution with depth can be mitigated by increasing the count period, so that the duration of autonomous sensor deployment would be most likely limited by the instrument power and communications (e.g. the height of the tower supporting the telemetry antenna and solar panels or the battery lifespan). This still could be several years in the case of very high accumulation, or decades in the case of polar deserts.

The portability, ease of deployment and low power of this passive sensor are ideal for measuring accumulation in remote locations, where manual measurements (i.e. cores and snow pits) are currently cost or logistically prohibitive. Combining the cosmic ray neutron sensor with observations commonly made by automated weather station observations, including temperature, wind speed and repeat measurements of surface height by echo sounder, wouled provide new information about the processes of wind redistribution and firn compaction, for which mass and density are currently unknown variables. This information is critical for obtaining ice sheet mass balance from repeat altimetry measurements, such as from NASA's ICESat missions. Finally, these measurements would inform regional and ice-sheet scale surface mass balance models for which direct water equivalent accumulation and wind distribution observations are currently sparse or non-existent.

Since our implementation requires burial in the underlying firn, the cosmic ray sensor is most applicable for measuring accumulation where meltwater infiltration is shallow enough that water does not infiltrate below the depth of the sensor. It is possible, however, that the sensor could be used to measure water transport at the surface or in the firn by observing the decrease in mass during periods of no precipitation, in a similar manner currently used for soil moisture measurements. Finally, borehole applications may exist for measurement of basal and englacial water transport.

Acknowledgments

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Table 1. Parameter Values Used in Correction and Conversion Equations.

P_0	763 mbar	Λ_{max}	$1.144\text{x}10^{2}$
α	$-7.7\text{x}10^{-3}$	Λ_{min}	14.11
β	1.191	a_1	$3.133\text{x}10^{-1}$
N_s	118 cph	a_2	$8.268\text{x}10^{-2}$
N_0	3571 cph	a_3	1.117

Figure 1. Photograph of Hydroinnova Snowfox™ cosmic ray probe exposed in firn trench on the first day of deployment. Inset shows the location of Summit Camp on the Greenland Ice Sheet, as denoted by the red circle. The red triangle shows the location of the THUL reference neuton monitor maintained by the University of Delaware Bartol Institute.

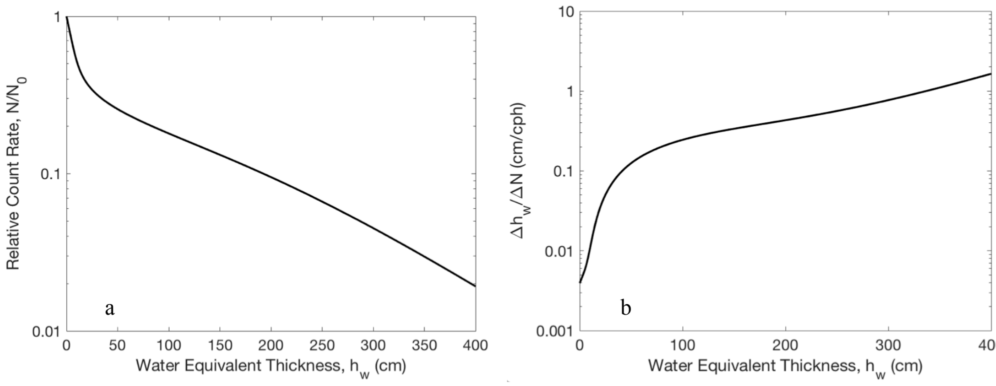

Figure 2. Water equivalent thickness of accumulation, h_w versus (a) the corrected relative count rate, N/N_0, measured at the sensor using Equations 4 and 5 and the parameters provided in Table 1, and (b) the change in h_w per change in hourly count rate N for N_0 = 3571 counts per hour.

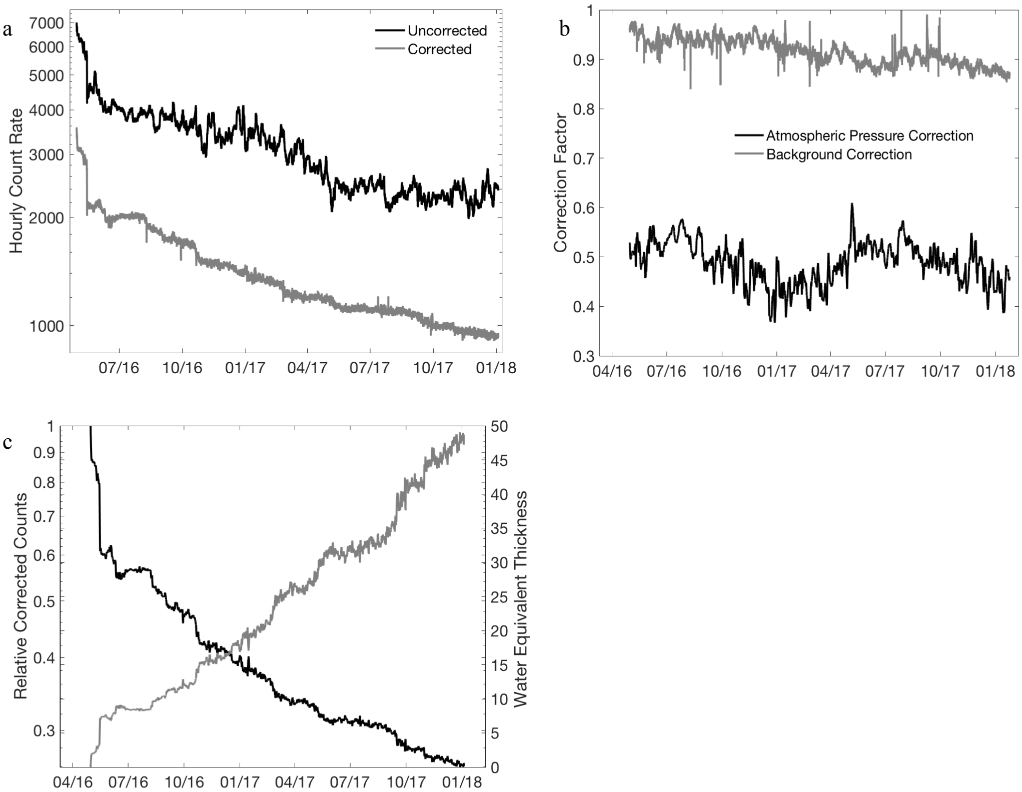

Figure 3. (a) (black) Uncorrected and (grey) corrected hourly neutron count rate measured at Summit Camp, Greenland by a cosmic ray sensor emplaced in the firn. (b) Count rate correction factors for (black) atmospheric pressure and (grey) solar activity, as derived from equations in Section 3 of the text and the Thule (THUL) neutron monitor for reference. (c) (black) Relative corrected counts and resulting (grey) snow water equivalent thickness accumulation from Equations 1-4 and the parameters in Table 1.

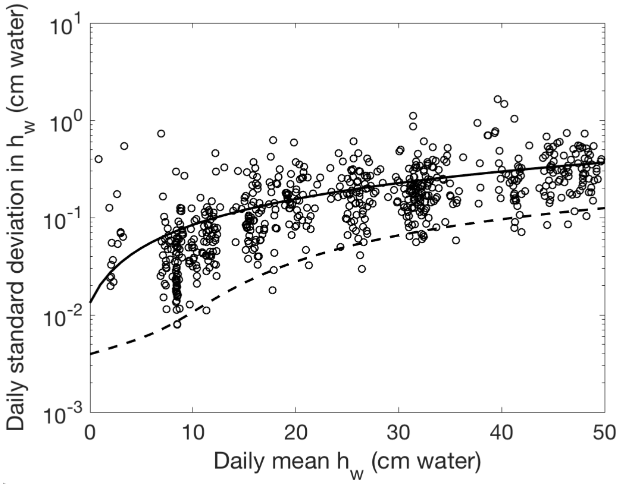

Figure 4. Daily means of hourly water equivalent accumulation, h_w, measured by the cosmic ray sensor, versus the daily standard deviation in hourly measurements. Solid curve is the line of best fit, with a slope of 0.0071 and a y-intercept of 0.0133 cm. Dashes are the change in h_w per change in hourly count rate N given by equation 4 (same as shown in Fig 2b).

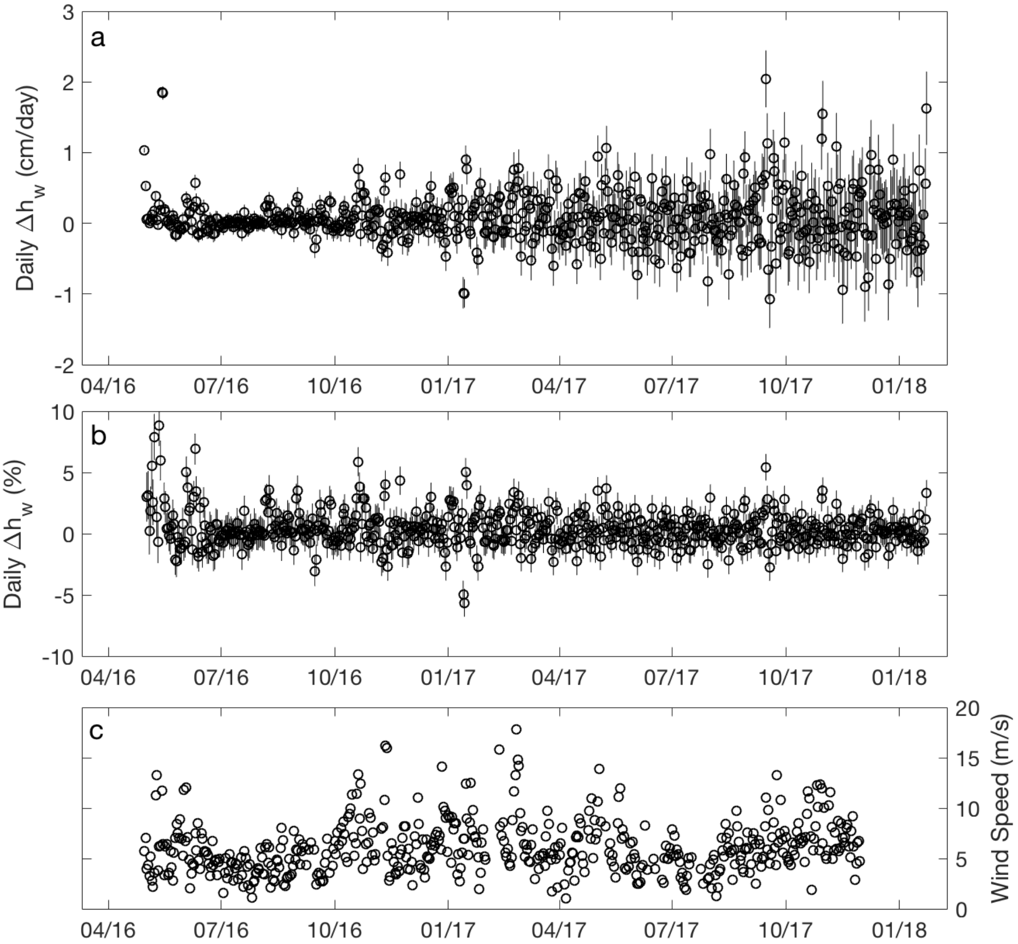

Figure 5. (a) Daily change in water equivalent accumulation, h_w, and (b) change as a percentage of h_w at Summit Station, Greenland, measured by the cosmic ray neutron sensor with 1σ error bars estimated from the fit in Fig. 4. (c) Summit Camp daily mean wind speed measured at the automatic weather station.

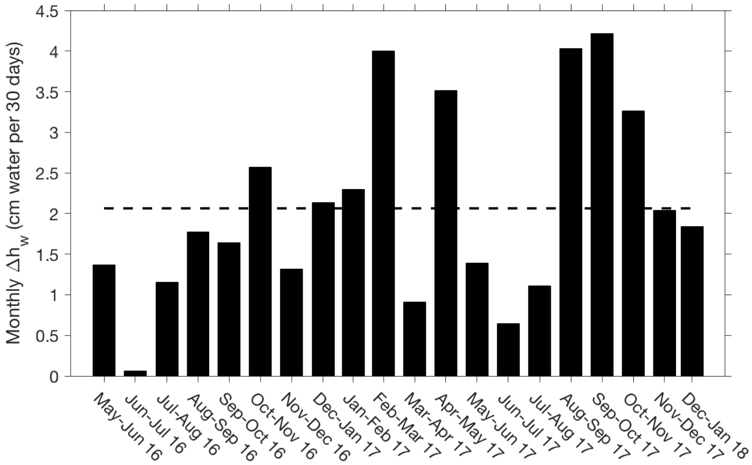

Figure 6. Monthly (30-day) water equivalent accumulation (h_w) at Summit Camp, Greenland as measured by the cosmic ray neutron sensor. Dashes are the average (2.1 cm per 30 days).

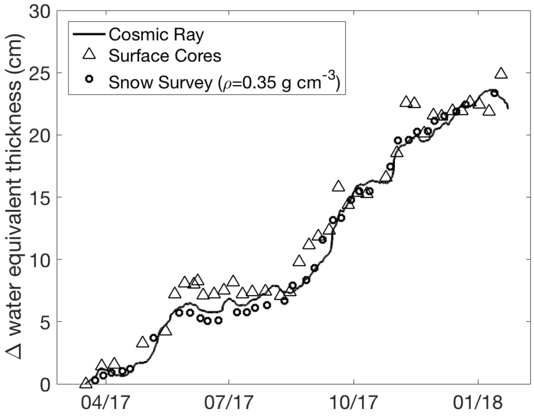

Figure 7. Time series of cumulative change in water equivalent thickness over the period of surface core sampling (17 March 2017 to 18 January 2018) from (solid curve) the cosmic ray sensor, (triangles) surface core samples and (circles) the "bamboo forest" snow stake network. The mean surface height change of the snow stakes is converted to water equivalent thickness change 5 assuming a density of 0.35 g cm^{-3}. The change is in addition to the 25.3 cm of water equivalent measured by the cosmic ray sensor between 30 April 2016 and 17 March 2017.

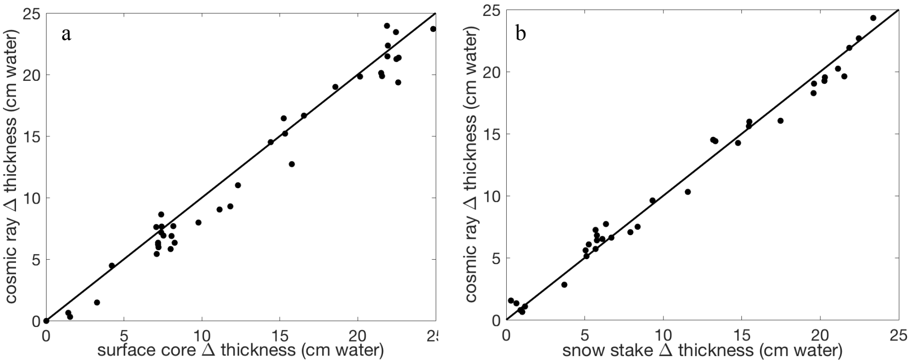

Figure 8. Cumulative water equivalent thickness change estimated from the cosmic ray sensor versus observations from (a) surface cores and (b) snow stake network assuming a density of 0.35 g cm^{-3}. The line shows unity for reference.