Supplement of The Cryosphere, 16, 799–806, 2022
https://doi.org/10.5194/tc-16-799-2022-supplement

The Cryosphere
Open Access

Supplement of

Brief communication: Application of a muonic cosmic ray snow gauge to monitor the snow water equivalent on alpine glaciers

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1 Measurement setup

Figure S1 displays the measurement setup on the Glacier de la Plaine Morte. For further information on the sensors apart from the muonic cosmic ray snow gauge see Gugerli et al. (2019).

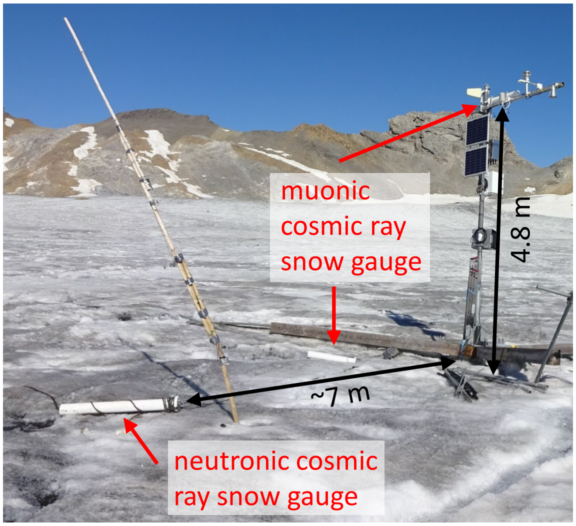

Figure S1. Measurement setup on the Glacier de la Plaine Morte with the sub-snow neutronic cosmic ray snow gauge and the top and sub muonic cosmic ray snow gauge. [Photo courtesy: M. Huss]

2 Gap filling of snow depth measurements

Two periods with invalid snow depth measurements were identified in winter 2020/2021. These are due to the large snow amounts. The ultra sonic ranger requires a minimal distance between the snow surface and the face of the transducer of at least 50 cm (Campbell Scientific, 2016). With the large snow amounts, the measured surface was too close, and these measurements are thus invalid.

Following the gap filling approach described in Gugerli et al. (2019) and Gugerli et al. (2020), we complemented the gaps with measurements from a station of the Intercantonal Measurement and Information System network (SLF Data, 2015). The station Gandegg/Lauchernalp (SLFGA2, 46°26' N, 7°46'E) at an altitude of 2717 m a.s.l. showed the highest correlation to daily changes in snow depth. For the first gap between 14 March 2021 to 22 March 2021, the snow depth was adjusted by 11.2 cm. During the second data gap between 5 May 2021 and 4 June 2021, the adjustment amounted to 37.5 cm.

3 Lake experiment with muonic cosmic ray snow gauge

In an independent experiment, the muonic cosmic ray snow gauge was descended into a lake in the USA. The Cochiti Lake is located in New Mexico at an elevation of 1702 m a.s.l. By descending the device into the lake, the overlying water depth is measured alongside the decreasing muon count number.

By dividing the initial count rate by the count rate with increasing water depth, the relative count rate is derived. This is fitted to the water depth, and results in two exponential equations with mainly different slopes. For shallow waters (< 100 cm), the fit results in

$$SWE = -275.35 \cdot \ln \frac{\mu_i}{\mu_0} - 0.40. \tag{1}$$

For deeper water (> 100 cm water depth), we fit

$$SWE = -811.76 \cdot \ln \frac{\mu_i}{\mu_0} - 239.79 \tag{2}$$

to relate the relative muon count rate to water depth (in cm).

Figure S2 shows the measured water depth as a function of relative count rates. Both fits agree well with the empirical data. The transition between the two fitted functions seems to occur between 1000 and 1500 mm water depth.

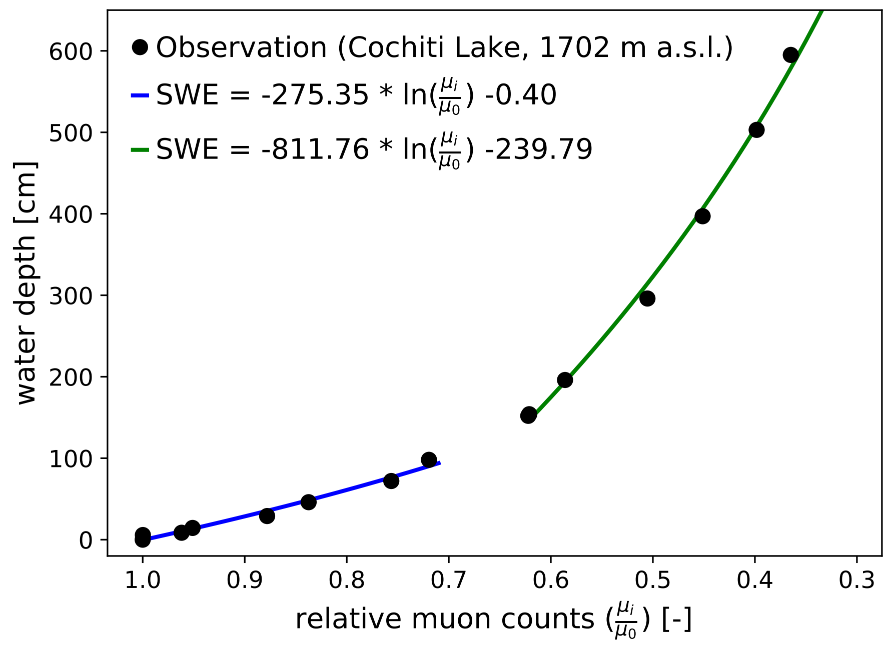

Figure S2. Empirical results from descending a μ-CRSG into a lake. Black dots depict the observations and the blue (green) curve show the fit for shallow (deep) water.

4 Daily fluctuations analyzed with maximum daily wind speed

Hourly wind speed is measured at the station on the Glacier de la Plaine Morte from 20 October 2016 to 13 August 2021. The n-CRSG measurements in a deep snowpack are limited in their temporal resolution due to the counting rate statistics at this site. Hence, the following analysis is based on daily measurements.

Inter-daily fluctuations of n-CRSG and μ-CRSG correspond to the difference of the daily mean SWE from day 1 to day 0. If the change is positive (negative), an increase (decrease) in SWE is observed. Figure S3a shows the correlation of 0.64 between daily changes of n-CRSG and μ-CRSG.

Daily maximum wind speed is derived from hourly measurements of maximum wind speed. From 16 December 2020 to 13 August 2021, 238 days of daily maximum wind speed observations are available. On average, the daily maximum wind speed is 10.0$\pm$3.9 ms^{-1}.

Figure S3b shows a statistical summary of these daily differences as a function of maximum daily wind speed bins. If the daily maximum wind speed is lower 10 ms^{-1}, no change or a minimal decrease in SWE is observed by both CRSG's. For wind speeds higher 14 ms^{-1}, both devices show more days with increasing SWE amounts. Almost 80% of days with maximum wind speeds higher 14 ms^{-1} occur from December 2020 to April 2021. Please note that snow drift is not only a function of wind speed, but also of the snow density of the top layer of the snowpack. With our measurement setup and for a deep snowpack, however, we have no means of deriving a reliable snow density of the affected snow layer. With snow depth, only a bulk snow density can be derived.

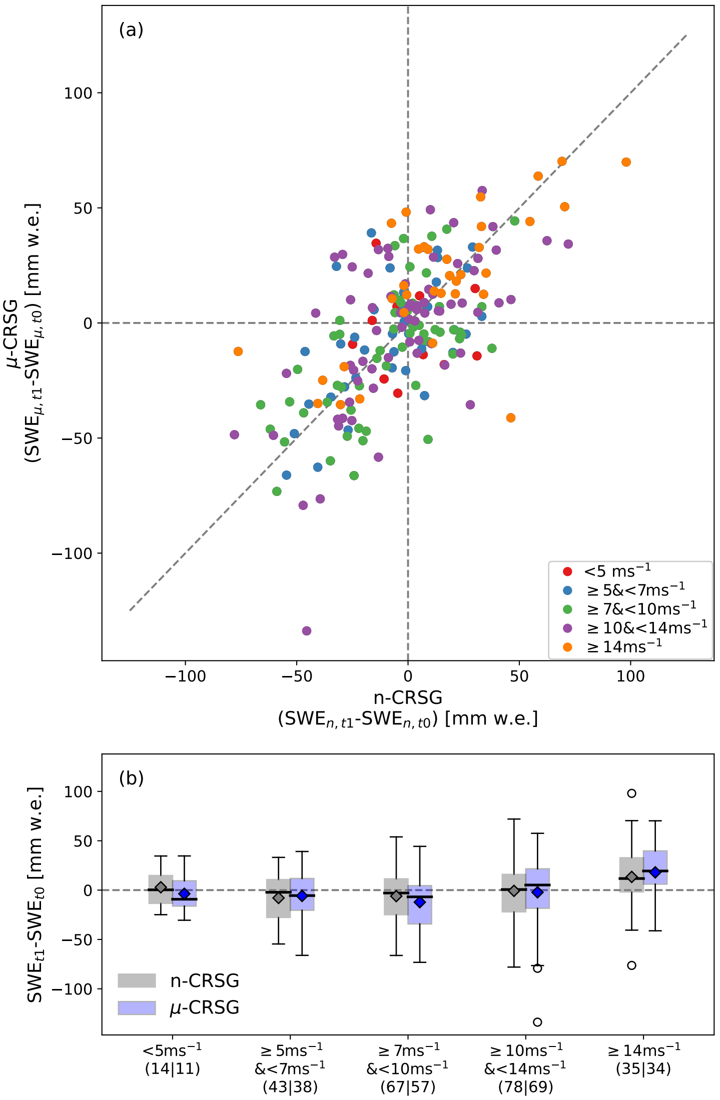

Figure S3. Daily changes in SWE are related to the daily maximum wind speed measured at the site. Panel (a) shows the correlation between daily fluctuations of the n-CRSG (x-axis) and the μ-CRSG (y-axis) with various wind speed bins in colors. Panel (b) shows the statistical summary of these daily fluctuations of the n-CRSG (grey) and the μ-CRSG (blue) as a function of wind speed. Diamonds represent the mean and the solid black lines show the median value. The numbers in the legend represent the number of days included in this analysis for the n-CRSG and μ-CRSG, respectively. These may differ according to the available measurements of the n-CRSG and μ-CRSG.

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