SECULAR TRENDS OF ACCUMULATION RATES AT THREE GREENLAND STATIONS

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ABSTRACT. The annual layer thickness profiles along three 400 m ice cores are transferred into accumulation-rate records. A linear decrease of \(3 \pm 2\%\) per millennium is found in mid-Greenland. Intermediate-term (periods longer than 120 years) deviations from the linear trend lines are less than 5% in mid-Greenland, but reach 11% at Dye 3 around A.D. 1700 and 1400. Short-term (periods between 120 and 30 years) oscillations are generally in phase at Milcent and Crête.

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A year-by-year dating of an ice core is identical with establishing a record of \(\text{in situ}\) annual layer thicknesses that can be turned into an accumulation-rate record by correcting for (1) density variations, (2) accumulation-rate deviations up-stream, and (3) total vertical strain since the time of deposition. The first correction never causes any problem, and the second one is zero at the summit of an ice sheet and usually negligible close to ice divides. In other cases, up-stream variations in annual accumulation \(\lambda_H\) must be corrected for by using the present surface distribution.

As to the total vertical strain of a given annual layer at a considerable distance from the bottom, it may be calculated from a directly measured surface strain-rate if it is reasonable to assume a constant vertical strain-rate since the time of deposition. Otherwise, the correction implies two- or three-dimensional flow modelling.

Hammer and others (1978) have measured annual layer thicknesses, mainly by \(\delta^{18}\text{O}\) analyses along three 400 m ice cores recovered under the Greenland Ice Sheet Program (GISP) from Crête (on the ice divide) and Milcent in mid-Greenland, and from Dye 3 in South Greenland (see figure 4 facing p. 12). Below, their data will be transformed into series of accumulation-rates as outlined above.

Long-term trends. A surface strain net has been measured at Crête by Karsten and Stober (1975). Using their raw data, we find the vertical surface strain-rate \(\varepsilon_H\) to be \(-1.32 \times 10^{-4}\) and \(-1.14 \times 10^{-4}\) a\(^{-1}\) up to 8 km east and west of the ice divide, respectively. The average value, \(\varepsilon_H = -1.23 \times 10^{-4}\) a\(^{-1}\), is assumed to have been constant throughout the last 1426 years spanned by the Crête \(\delta\) record. Correcting the 1426 annual layer thicknesses accordingly leads to a \(\lambda_H\) time series, which shows a small linear trend of \(-4 \pm 2\%\) per millennium, the
mean $\lambda_H$ value through the last millennium being $(0.289 \pm 0.002)$ m of ice per year,\(^*\) the uncertainty including an estimated dating error of 0.5\%.

Unfortunately, no data for calculating surface strain-rates are available from Milcent. Instead, we assume that the flow pattern up-slope from Milcent is consistent with Hammer and others' (1978, p. 7) equation (2), $h$ being proportional to the ice thickness $H$ that has been measured by radio-echo sounding (private communication from P. Gudmansen). Philberth and Federer's (1971) procedure leads to an estimate of $h = 330$ m at Milcent, which is most likely to be an upper limit for $h$, since orientation of the c-axis in favour of easy glide has not been allowed for. A two-dimensional flow model is then used to interpret the measured $\lambda$-profile in terms of accumulation rates at the up-slope sites of formation of the individual core layers. These accumulation rates are finally compared to the present up-slope $\lambda_H$ values (using Benson's (1962) $\lambda_H$ gradients combined with our own surface $\lambda_H$ mean values at Milcent and Crête), and the relative deviations are interpreted as a climatic information. Assuming $0 < h < 330$ m, the linear $\lambda_H$ trend comes out as $(0.0 \pm 3.5)$ % per millennium.

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* Dividing the mean $\lambda_H$ value by the ice thickness $H = 3150$ m (Gudmansen, 1973), gives a mean vertical strain-rate of $\dot{e} = -0.914 \times 10^{-4}$ a$^{-1}$ through the last millennium, i.e. 74\% of $\dot{e}_H$. If we assume a horizontal velocity profile of the type given by Hammer and others (1978, p. 22, equation (10)), $\dot{e}/\dot{e}_H$ can be shown to be equal to $\rho/(\rho + 1)$, i.e. $\rho = 2.9$ for $\dot{e}/\dot{e}_H = 0.74$, which is much less than the $\rho$-value (c. 10) that appears by integrating Glen's law at Crête. This may reflect the dominance of longitudinal stresses close to an ice divide.
which does not disagree with the $(-4\pm2)\%$ obtained independently, practically speaking, with the Crète data. The relatively high uncertainty is due, first to the Milcent $\lambda_H$ series being shorter and, secondly, to the vertical strain and the up-slope $\lambda_H$ corrections being more complicated than in the case of Crète. The weighted mean linear trend in mid-Greenland is thus $(-3\pm2)\%$ per millenium. The mean $\lambda_H$ value through the last 796 years has been $(0.540\pm0.004)$ m ice a$^{-1}$ at Milcent.

At Dye 3, either of the procedures described above is even more inaccurate, because (i) no surface strain data are available, (ii) the up-slope $\lambda_H$ gradient is not well known, and (iii) the variability of the measured $\lambda$ profile is high. This induces a high standard error on the long-term $\lambda_H$ trend that can only be given as $(+2\pm6)\%$ per millenium, assuming $0 < h < 400$ m. Accordingly, the mean $\lambda_H$ value through the last 728 years, has been $(0.535\pm0.015)$ m ice a$^{-1}$ at Dye 3.

Intermediate-term variations. In Figure 1, the heavy curves show $\lambda_H$ time series from Dye 3, Milcent and Crète. The linear trends have been removed, and the residuals have been smoothed by a low-pass digital filter that removes all $\lambda_H$ oscillations with periods shorter than 120 years. The $\lambda_H$ scales have been chosen so that a given amplitude corresponds to the same relative deviation from the mean in each curve. Maximum deviation from the long-term trend lines is 11%, 5% and 4%, respectively.

There is an obvious correlation between Milcent and Crète prior to A.D. 1800 and between all three curves prior to A.D. 1500. After A.D. 1600, Dye 3 and Milcent vary in antiphase. Any attempt to explain these variations should account for the facts (i) that the bulk of snowfall comes from south-east at Dye 3, but from south-west at Milcent, whereas Crète probably receives precipitation from either direction, and (ii) that the increasing occurrence of sea ice in the seventeenth century may have changed the general circulation pattern in the polar atmosphere.

No obvious correlation exists between the smoothed $\delta$ (to be published elsewhere) and $\lambda_H$ series. For example, the Dye 3 $\delta$ curve contains a broad minimum from A.D. 1500 to 1700, corresponding to the culmination of the “little ice age”, whereas $\lambda_H$ at Dye 3 decreases somewhat from A.D. 1550 to 1720. A possible explanation might be that in this period an increasing percentage of the cyclones moved into Davis Strait instead of going east of

![Fig. 2. Cross-correlation coefficients r between annual accumulation values at Milcent and Crète (top) and between the corresponding annual mean $\delta$ values (below) A.D. 1177-1276 for time lags between $-24$ and $+24$ years. Only zero time lag gives significant r-values for both the $\lambda_H$ and the $\delta$ series, indicating concordant time scales along the two cores through the earliest century represented in the Milcent core. Similar checks were performed for the subsequent centuries.](image-url)
Greenland. This is consistent with the maximum of accumulation at Milcent around A.D. 1700.

Short-term variations. The thin curves in Figure 1 depict the $\lambda_H$ series smoothed by a 30 year low-pass digital filter. The deviations from the heavy curves correspond to $\lambda_H$ series smoothed by a band-pass filter transmitting oscillations in the 30 to 120 year range. These deviations are in close correlation for Milcent and Crete: $R = 0.69$, significant at the $P > 99\%$ level with an estimated number of degrees of freedom $n = 25$ (supported by coherence calculations). The Dye 3 short-term deviations are less correlated with those at Milcent ($R = 0.30; P > 80\%$) and Crete ($R = 0.50; P > 95\%$). Nevertheless, the Milcent and Crete short-term curves are occasionally out of phase, for example around A.D. 1900, the sixteenth century, and A.D. 1180–1280, where the phase shift corresponds to 15 years. This should not be ascribed to dating errors: Looking at the time interval A.D. 1177–1276, Figure 2 shows cross-correlation coefficients $r$ between the Milcent and Crete annual $\lambda_H$ series (upper section) and mean annual $\delta$ series (lower section), plotted as functions of imposed time lags between the series ranging from $-24$ to $+24$ years. The standard deviation of $r$ is 0.1. Only zero time lag gives significant $r$-values in both series. We consider this as strong evidence that the Milcent and Crete time scales do not deviate from each other in the interval A.D. 1177–1276 and, consequently, that the phase difference between the intermediate-term $\lambda_H$ oscillations of up to 15 years is real.

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REFERENCES


