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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±2% per millenium 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.

Résumé. *Tendances séculaires des vitesses d'accumulation pour trois stations groenlandaises.* Les profils d'épaisseur des niveaux annuels le long de 400 m de trois carottes de glace sont transformés en registrements de vitesse d'accumulation. On trouve une diminution linéaire de 3±2% par millénaire dans le centre du Groenland. Des variations de durée intermédiaire (périodes de durée supérieure à 120 ans) autour de cette tendance linéaire sont de moins de 5% dans le centre du Groenland mais atteignent 11% à Dye 3 autour des années 1700 à 1400 de notre ère. Des oscillations de durée courte (périodes entre 120 et 30 ans) sont en général en phase à Milcent et à Crête.

Zusammenfassung. *Der säkulare Verlauf der Akkumulationsraten bei drei Grönlandstationen.* Die Dickenprofile der Jahresschichten längs dreier 400 m Bohrkerne werden in Akkumulationsraten umgerechnet. In Mittel-Grönland ergibt sich eine lineare Abnahme von 3±2% pro Jahrtausend. Mittelperiodische (über mehr als 120 Jahre) Abweichungen vom linearen Verlauf sind geringer als 5% in Mittel-Grönland, erreichen aber 11% bei Dye 3 um die Jahre 1700 und 1400. Kurzperiodische (zwischen 120 und 30 Jahren) Schwankungen in Milcent und Crête weisen im allgemeinen Gleichzeitigkeit auf.

A year-by-year dating of an ice core is identical with establishing a record of *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 λ_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 $\delta(^{18}O)$ 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 $\dot{\epsilon}_H$ to be -1.32×10^{-4} and $-1.14\times10^{-4}\,a^{-1}$ up to 8 km east and west of the ice divide, respectively. The average value, $\bar{\dot{\epsilon}}_H = -1.23\times10^{-4}\,a^{-1}$, is assumed to have been constant throughout the last 1 426 years spanned by the Crête δ record. Correcting the 1 426 annual layer thicknesses accordingly leads to a λ_H time series, which shows a small linear trend of $-4\pm2\%$ per millenium, the mean λ_H value through the last millenium being (0.289 ± 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. Gudmandsen). 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 λ-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 λ_H values (using Benson's (1962) λ_H gradients combined with our own surface λ_H mean values at Milcent and Crête), and the relative deviations are interpreted as a climatic information. Assuming $0 < h < 330$ m, the linear λ_H trend comes out as (0.0 ± 3.5)% per millennium,

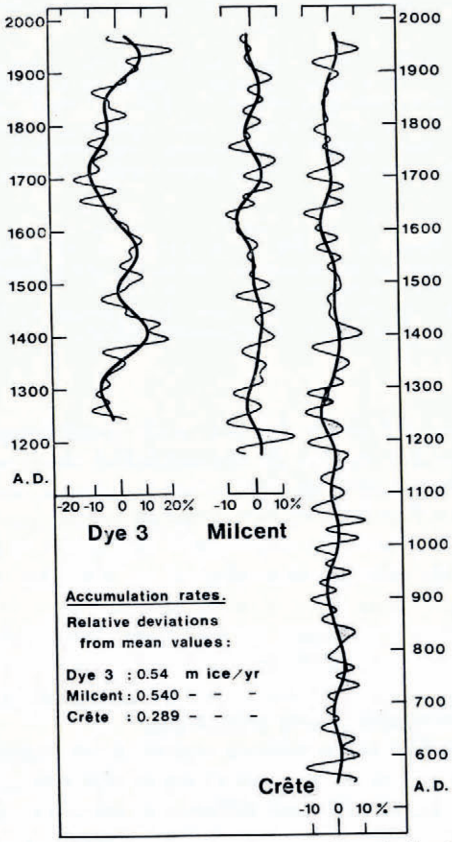

Fig. 1. Accumulation-rate records from three Greenland ice-sheet stations, determined mainly from seasonal $\delta(^{18}O)$ cycles. The annual accumulation data series have been smoothed by digital low-pass filters with cut-off periods of 120 years (heavy curves) and 30 years (thin curves).

* Dividing the mean λ_H value by the ice thickness $H = 3\,150$ m (Gudmandsen, 1973), gives a mean vertical strain-rate of $\bar{\dot{\epsilon}} = -0.914 \times 10^{-4}\,a^{-1}$ through the last millennium, i.e. 74% of $\bar{\dot{\epsilon}}_H$. If we assume a horizontal velocity profile of the type given by Hammer and others (1978, p. 22, equation (10)), $\bar{\dot{\epsilon}}/\bar{\dot{\epsilon}}_H$ can be shown to be equal to $p/(p+1)$, i.e. $p = 2.9$ for $\dot{\epsilon}/\dot{\epsilon}_H = 0.74$, which is much less than the p-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.

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which does not disagree with the $(-4\pm2)\%$ obtained independently, practically speaking, with the Crête data. The relatively high uncertainty is due, first to the Milcent λ_H series being shorter and, secondly, to the vertical strain and the up-slope λ_H corrections being more complicated than in the case of Crête. The weighted mean linear trend in mid-Greenland is thus $(-3\pm2)\%$ per millenium. The mean λ_H value through the last 796 years has been (0.540 ± 0.004) 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 λ_H gradient is not well known, and (iii) the variability of the measured λ profile is high. This induces a high standard error on the long-term λ_H trend that can only be given as $(+2\pm6)\%$ per millenium, assuming $0 < h < 400$ m. Accordingly, the mean λ_H value through the last 728 years, has been (0.535 ± 0.015) m ice a^{-1} at Dye 3.

Intermediate-term variations. In Figure 1, the heavy curves show λ_H time series from Dye 3, Milcent and Crête. The linear trends have been removed, and the residuals have been smoothed by a low-pass digital filter that removes all λ_H oscillations with periods shorter than 120 years. The λ_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 Crête prior to A.D. 1800 and between all three curves prior to A.D. 1600. 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 Crête 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 δ (to be published elsewhere) and λ_H series. For example, the Dye 3 δ curve contains a broad minimum from A.D. 1500 to 1700, corresponding to the culmination of the "little ice age", whereas λ_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

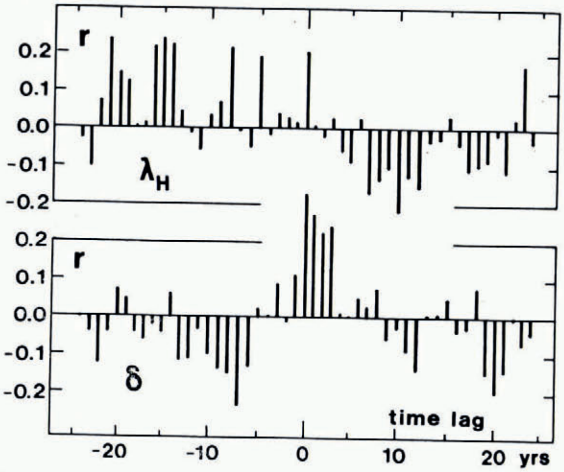

Fig. 2. Cross-correlation coefficients r between annual accumulation values at Milcent and Crête (top) and between the corresponding annual mean δ values (below) A.D. *1177–1276 for time lags between −24 and +24 years. Only zero time lag gives significant r-values for both the λ_H and the δ series, indicating concordant time scales along the two cores through the earliest century represented in the Milcent core. Similar checks were performed for the subsequent centuries.*

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 λ_H series smoothed by a 30 year low-pass digital filter. The deviations from the heavy curves correspond to λ_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 Crête: $R = 0.69$, 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 Crête ($R = 0.50$; $P > 95\%$). Nevertheless, the Milcent and Crête 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 Crête annual λ_H series (upper section) and mean annual δ 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 Crête 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 λ_H oscillations of up to 15 years is real.

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