Tellus (1994), 46B, 294–303
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TELLUS
ISSN 0280–6509

Pattern of annual snow accumulation along a west Greenland flow line: no significant change observed during recent decades

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(Manuscript received 12 March 1993; in final form 14 March 1994)

ABSTRACT

At 10 positions on a traverse along a West Greenland flow line, shallow drillings and pit studies were performed in summer 1990. Continuous in situ hydrogen peroxide analyses on these samples allowed the seasonal firn stratigraphy to be established and thus to collect seasonally adjusted subsamples from the core in the field. The mean annual accumulation rate decreases from about 440 mm water equivalent at the western sites T9 and T13 to about 250 mm at the central positions T41 and Crête. Most of the prominent inter-annual changes of the surface mass balance appear to be well preserved over the area investigated. A comparison of the accumulation rates of the last decades with earlier measurements along the same Greenland flow line shows no significant change in accumulation rates during the last forty years. Further, there is no significant evidence for a pronounced increase in the Greenland surface mass balance as suggested by satellite altimetry.

1. Introduction

Within the programme of the "Expédition Glaciologique International au Groenland" (EGIG) several snow and ice studies were performed (mainly in the years 1958/59 and 1967/68) along a West Greenland flow line. At some sites, annual snow accumulation rates have been determined.

In 1990, the Geodetic Institute TU Braunschweig performed a traverse from Summit to T1 (Fig. 1) in order to remeasure the positions of the markers that had been placed along the 1959 EGIG traverse. Two glaciologists joined this traverse to determine the accumulation distribution over the Greenland ice sheet during the last decade.

To perform the drillings, two different types of augers were used. The first three firn cores were drilled with an electromechanical auger providing a core diameter of 50 mm. The auger (Inventor Co., Switzerland) operates at a power of about 100 W, which was provided by solar panels. After the loss of the auger at T41, the core drillings were performed by using a hand auger of the "Sipre" type providing a core diameter of 75 mm.

A total of 11 shallow firn cores, which reached a depth of about eight to ten metres, were drilled between Summit and T1. The drillings were performed about every 50 km. Hydrogen peroxide (H_2O_2) and snow density measurements were made along one fraction of the firn cores in the field. With the remaining parts of the firn cores, stable isotope and chemical analyses were done in the laboratory at the University of Heidelberg. Because of high solar radiation during the day, drilling and packing of the firn cores had to be done during the night.

The annual accumulation rate for each year and each site was calculated by using the measured density profile of the firn cores and the annual

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snow layer thickness, which had been determined by the H_2O_2 signal. The age of the bottom part of the firn core could be readily determined by counting annual layers from the H_2O_2 signal.

The mean annual accumulation rate can be determined by using any seasonally varying species such as $\delta^{18}O$ or H_2O_2 or by identifying special snow horizons caused by volcanic eruptions or radioactive fallout. Earlier determinations of mean annual accumulation rates along the western part of the EGIG line have been made by Aegerter et al. (1969), Ambach and Dansgaard (1970), Benson (1962), Bourton (1979), Clausen et al. (1988), Merlivat et al. (1973), Reeh et al. (1978), Reeh and Gundestrup (1985), Seckel (1977) and Stober (1986).

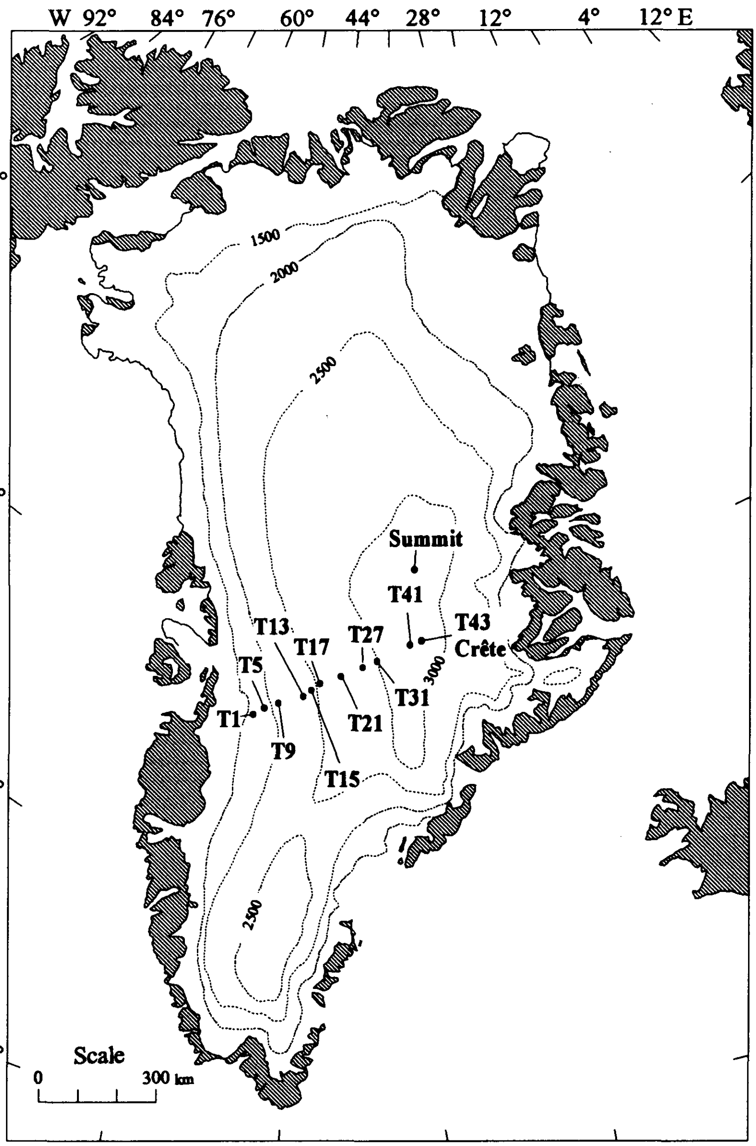

Fig. 1. Map of Greenland showing the location of the drilling sites. The traverse started in Summit and ended in T1.

An advantage of determining the annual accumulation rate by detection of H_2O_2 is that these measurements can be done continuously and easily while still in the field. The seasonality of H_2O_2 in the snow is due to changing H_2O_2 concentrations in the atmosphere. The seasonal atmospheric H_2O_2 variations are mainly based on photochemical effects. The concentration has a maximum in late summer and a minimum during the polar night (Logan et al., 1981). However, the H_2O_2 analysis shows a clear seasonal signal only in natural cold firn with little or no surface melting. At locations with high solar summer radiation surface melting disturbs the H_2O_2 signal (Sigg, 1990) and the seasonality of the H_2O_2 signal gets lost.

On the traverse along the EGIG line we identified annual layers at the locations from Summit to T5, i.e., at locations with a mean annual temperature of less than $-19°C$. At the site T1, which has a mean annual temperature of $-13°C$, the seasonal H_2O_2 signal gets lost due to high summer surface melting.

The H_2O_2 signal in the firn smoothes out with depth and the seasonal signal only survives the firnification process at locations with a high annual accumulation rate (Sigg and Neftel, 1991) (accumulation higher than about 260 mm water eq. year^{-1} (Sigg, 1990)). For Summit (accumulation 230 mm water eq. year^{-1}) the seasonal signal is lost below a depth of about 20 metre. For the sites from T31 to T1, where the annual accumulation rate is more than 260 mm water equivalent, the seasonality of the H_2O_2 signal is expected to survive the firnification process.

2. Methods

Cores could only be retrieved if the snow density was above 300 kg/m^3, i.e., beneath 0.5–1 m below the snow surface. The density and the H_2O_2 profile of the upper layers were determined by pit studies with a vertical resolution of 0.1 m for the density and 0.05 m for the H_2O_2 profile. The density profile of the drilled firn core was measured by weighing cylindrical pieces of the core. The accuracy of both the density and the H_2O_2 profile is about 5%.

The samples for H_2O_2 analysis were collected in polystyrene tubes with a volume of 15 ml. The H_2O_2 analyses were performed in a tent to protect the equipment from wind, snowfall and snowdrift. The samples (in their polystyrene tubes) were melted in a hot water bath and subsequently analysed in a box with a stabilised inside temperature of about $+15°C$.

The H_2O_2 concentration of the melt water was measured by "Continuous Flow Analysis" (Sigg and Neftel, 1988) and plotted on a XY-recorder. H_2O_2 was analysed by using the enzymatic-fluorometric technique described by Lazrus et al. (1986) and Sigg (1990). A self built filter fluorimeter was used as detector. Reagents were added continuously to the sample stream using peristaltic pumps and calibrations were made regularly after about 20 samples.

Only a small segment of the firn core was used for the H_2O_2 measurements. The remaining parts of the firn core were cut into aliquots in the field based on the recorded H_2O_2 cycles. In this way seasonally synchronised bulk samples were obtained for subsequent chemical and isotopic analyses with a resolution of four to eight samples per annual layer. These core aliquots were carefully cleaned of surface contamination by a double microtome plane and sealed in polyethylene bags for shipping. For logistical reasons, melting of the snow samples during transport to the laboratory can not be excluded.

In order to agree with the hydrological year lasting from the first of October to the end of September of the following year, we determined annual accumulations between autumn snow layers. The autumn layer was assumed to be midway between the summer maximum and the following winter minimum of the H_2O_2 signal. Doing this, we assumed a constant distribution of the accumulation over the year.

3. Results

All the drill sites are located along the EGIG line of the 1959 expedition (Fig. 1), except for Summit. Summit is about 150 km north of Crête and is the highest location of the Greenland ice sheet. The coordinates and elevation of each site are presented in Table 1.

Although each investigated firn core shows seasonal variations (Fig. 2) the seasonality of the H_2O_2 profile at the two sites T1 and T5 is strongly disturbed due to their high summer temperatures,

Table 1. *Geographical location and elevation of the investigated sites measured on the 1990 and 1991 traverses by GPS (Kock and Homann, personnel communication)*

Site	Latitude	Longitude	Elevation
	north	west	(m)
T1	69°44′	48°08′	1680
T4	69°49′	47°31′	1848
T5	69°51′	47°15′	1905
T9	70°00′	46°18′	2107
T13	70°14′	45°01′	2375
T15	70°18′	44°34′	2447
T17	70°22′	44°06′	2530
T21	70°33′	43°01′	2692
T27	70°46′	41°33′	2868
T31	70°55′	40°38′	
T41	71°05′	37°55′	3150
Crête	71°07′	37°19′	3174
Summit	72°35′	37°38′	3230

which causes percolation of melt water that refreezes in deeper layers. Melt layers can strongly influence the original H_2O_2 concentration (Sigg and Neftel, 1988) introducing additional noise to the record. Therefore we exclude the location T1 in the following discussion. For the remaining sites a clear identification of annual layers can be made.

The calculated annual accumulation rates are given for each drilling site in Table 2. The error for a single annual accumulation rate is estimated to be less than 30 mm water equivalent. Most of the uncertainty is due to the estimate of the "October" snow horizon. For some parts of the firn core the quality was too bad to make a reliable density determination. To get a full density profile at each site, we interpolated the missing intervals using a spline function.

For Summit, there is no detailed density data set available for the ten metre deep firn core. The stratigraphy of the upper metre of the Summit firn core was disturbed by the drilling procedure leading to an underestimation of the annual accumulation rate for the years 1987/88 and 1988/89. We assume that the firn density profile of the two sites Summit and Crête are similar because they are both at nearly the same elevation, and the mean annual temperature differs only about 2°C. Therefore we used the density profile of the Crête firn core to calculate the annual accumulation rates at Summit. To establish a reliable H_2O_2 and density profile (and with this a reliable determination of the annual accumulation rate) beginning right below the snow surface we performed detailed pit studies of the upper metre at all other sites.

4. Interpretation and conclusions

Stable isotope measurements, although performed at a lower spatial resolution, confirms the H_2O_2 profile (Fig. 3). Fig. 3 shows that both tracers lead to the same determination of the annual snow layer thickness. For our investigated sites, we assume that accumulation rates are approximately equal to the precipitation rates. However, drifting snow and evaporation might induce some bias to the precipitation rate determined in this way. Depending on the local topography, snow drifting can lead to an over- or an underestimation whereas evaporation always leads to an underestimation of the precipitation (Ohmura and Reeh, 1991). The meteorologically measured precipitation, however, is often smaller than the measured accumulation (Ohmura and Reeh, 1991). It is assumed that this is due to an incomplete capture of snowflakes by the snow gauge (Ohmura and Reeh, 1991; Ohmura et al., 1992).

The distribution of the annual accumulation over the Greenland ice sheet has been established by Ohmura et al. (1991). A comparison of his accumulation map with our accumulation data set shows a good agreement for the eastern parts (Crête to T17). For the more western sites (T13 and T9) our accumulation rates are about 10% lower than those given by Ohmura et al. (1991).

The results of this work show large variations of the local annual accumulation rates during the last decade (Table 2). The typical standard deviation of the annual accumulation at one location is about 10–25%. Annual precipitation records at West Greenland coastal stations have a standard deviation which is in the same range. For Søndre Strømfjord, for example, the standard deviation of the annual precipitation was 28%, for Egedesminde 17% and for Thule 20% during the last decade (Danish Meteorological Institute, 1969–82; 1990). Comparison of the changes of the annual accumulation rate at our investigated sites show a clear correlation between sites (Fig. 4). The hydrological year 1986/87, for example, shows a relatively high rate at all sites. At 4 out of 10 sites, it is the year with the highest accumulation rate of the last decade. Again, the hydrological year 1988/89 is the one with the lowest accumulation rate at six out of ten sites. The hydrological year 1983/84 is one with a relatively high annual accumulation and the years 1981/82 and 1984/85 show relatively low annual accumulations.

In Table 3, mean annual accumulation rates (averages over four to thirty years) as determined during earlier expeditions along the EGIG line are presented together with the results of this work. Most of the earlier expeditions determined mean

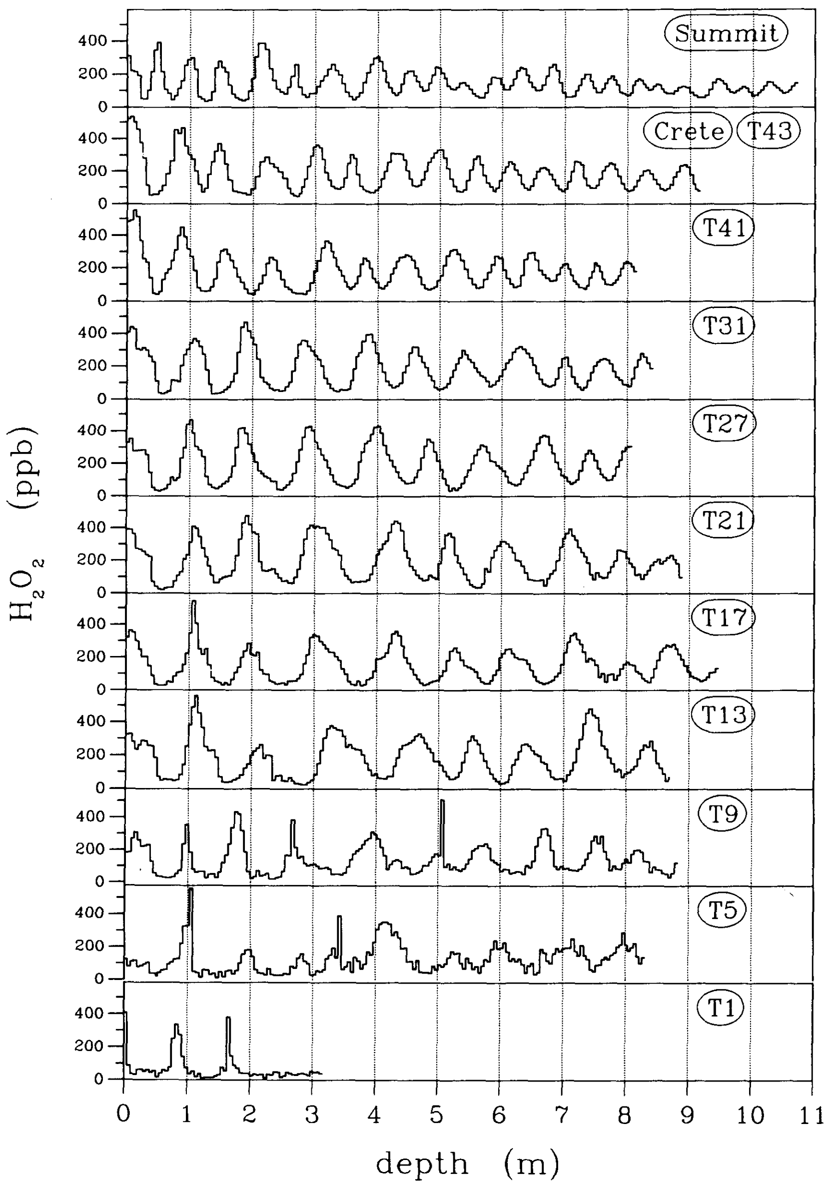

Fig. 2. H_2O_2 profiles versus snow depth at the different locations from Summit to T1.

Table 2. *Annual accumulation rate in mm water equivalent determined in this work for the different sites and mean annual accumulation rates during the interval available and during the interval 1982–1989*

Hydrological year	T5	T9	T13	T17	T21	T27	T31	T41	Crête	Summit
1988–1989	386	296	374	356	315	315	285	249	193	129
1987–1988	384	358	455	420	442	402	362	245	233	138
1986–1987	584	509	614	573	546	447	422	270	275	197
1985–1986	558	565	481	486	463	428	350	246	213	212
1984–1985	371	346	391	434	388	355	340	228	250	157
1983–1984	476	448	482	487	519	470	393	304	296	272
1982–1983	512	468	471	472	451	398	407	266	296	239
1981–1982		361		343	370		270	225	233	189
1980–1981							314	229	251	204
1979–1980								232	243	204
1978–1979								248	246	193
1977–1978									264	227
1976–1977									293	243
1975–1976										199
1974–1975										212
1973–1974										156
1972–1973										177
1971–1972										266
1970–1971										216
1969–1970										181
mean accumulation	467	419	467	446	437	402	349	249	253	201
standard deviation	88	87	72	70	72	49	50	22	30	37
mean accumulation from 1982–1989	467	427	467	461	446	402	366	258	251	192
standard deviation	88	97	78	68	78	53	47	25	40	53

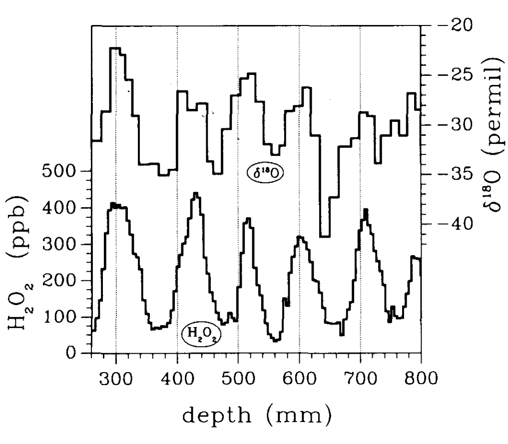

Fig. 3. Comparison of seasonal firn stratigraphy (site T21) as indicated by in situ H_2O_2 measurements with $\delta^{18}O$ results on sample sequences with lower resolution.

annual accumulation rates during the fifties and the sixties. There is also a data set of Reeh et al. (1978), which contains a mean annual accumulation value over the last 1400 years for Crête and 800 years for T15. If we compare this data set with the results of our work we notice a weak but not significant decrease of the annual accumulation rate, which is still within one standard deviation of the results from this and earlier expeditions.

Boutron (1979) determined mean annual accumulation rates at the sites T12, T20 and others. In this work we compare the results from Boutron with our results in T13 and T21, ignoring the fact that there is a distance of about 10 km between these neighbouring sites (from T12 to T13 and from T20 to T21). We assume that on the Greenland ice sheet the accumulation rate changes only slightly within 10 km distance. Earlier determinations of annual accumulation rates in T13 and

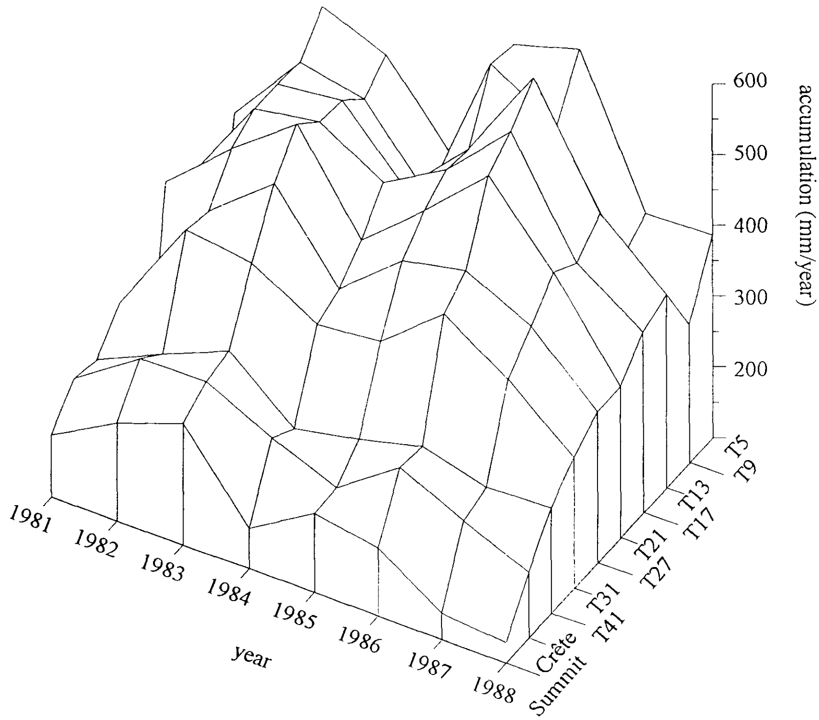

Fig. 4. Mean annual accumulation rates at different sites. The year 1988, for example, indicates the hydrological year 1988/89. There is a close correlation among the annual accumulation rate changes of the different sites.

Table 3. *Annual accumulation rates during different time intervals; a comparison of the mean annual accumulation rate determined by this work and investigations of earlier expeditions*

Time period	T4	T5	T9	T13	T15	T17	T21	T27	T31	T41	Crête	Summit	ref.
1982–1989		467	427	467		461	446	402	366	258	251	192″	0
1950–1954	560	580	550	540	510	470	450	400	355				1
1959–1974		529	433	499		471	438	377	328	238	231		2°
1959–1974	561			498*			437*		343		253		3
1943–1973					486						273	240	4
1959–1968		481	450	476		471	424	377	330	230	221		5°
1959–1968	547				492				329		243		6
1948–1967	570												7
1950–1960					462				371		289		8
1953–1959					500				330		230		9
		(mean acc. of 800 a)			495			(mean acc. of 1400 a)			265		10

* Accumulation in T12, T20, respectively. ″Slightly underestimated, see text. °Density data set from this work.

Refs.: 0 results of this work; 1 Benson (1962); 2 Stober (1986); 3 Boutron (1979); 4 Clausen et al. (1988); 5 Seckel (1977); 6 Merlivat et al. (1973); 7 Ambach and Dansgaard (1970); 8 Quervain (1969); 9 Aegerter et al. (1969); 10 Reeh et al. (1978)

T21 (Seckel, 1977; Stober, 1986) seems to justify this assumption since their calculations are similar to those of Boutron in T12 and T20. However, Benson (1962) determined an annual accumulation rate at the site T13, which is significantly higher than those from Seckel (1977) and Stober (1986). Also at the sites T5 and T9, the determinations of Benson (1962) are 20–30% higher than the results from this work and the results from Stober (1986) and Seckel (1977). Benson (1962) calculated the mean annual accumulation rate as an average of 4 years (1950–1954), which is a rather short interval for the determination of annual accumulation rates, especially in the lower accumulation zone with strong surface melting during the summer inducing percolation of melt water.

Seckel (1977) and Stober (1986) indicate only mean annual snow layer thicknesses. To compare their determinations with the results of this work we first need to multiply their snow layer thicknesses with the corresponding snow densities. Since there are no density profiles for the corresponding times and sites available we use the density data sets of this work to calculate the annual accumulation in water equivalent. This is justified if the temperature distribution on the ice sheet is still about the same as 20 years ago. There is less than 10% deviation between the data sets of Seckel and Stober and the data set of this work.

The accumulation rates calculated in this work deviate 5–12% from the mean value of the earlier determinations. Since the standard deviation of the results from earlier expeditions is also about 10% we observe no statistically significant change of the annual accumulation rate over the last forty years.

Nevertheless, there is a change of the distribution of the annual accumulation rate between the sites T5 to Crête during the last forty years, with a significance at the 95% level as indicated by the t-test. For each investigated site, Fig. 5 shows the difference of the annual accumulation rate between the results of this work and determinations of earlier investigations (see Table 3) plotted versus the distance from the site T1. In our work the western sites (T5–T17) show in comparison with earlier investigations a smaller and the eastern sites (T17–T41) a higher annual accumulation rate during the last decade. The slope of the linear regression between these changes of accumulation rates is 0.26 mm accumulation/km with a standard deviation of 0.04 mm accumulation/km.

This suggests that the annual accumulation rate on the Greenland ice sheet is increasing in its central part and decreasing in mid and low elevation areas.

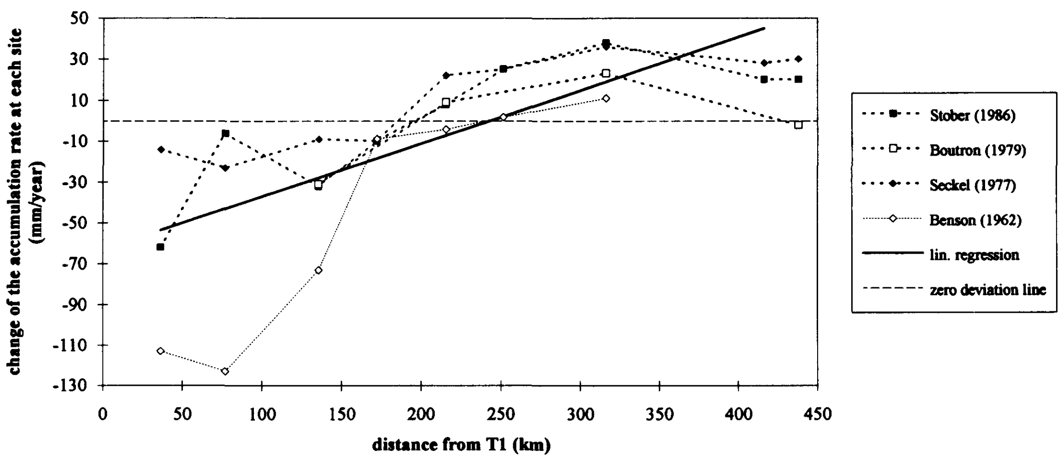

Fig. 5. Difference of the annual accumulation rate between the results of this work (containing mean annual accumulation rates of the last decade) and determinations of earlier investigations (containing accumulation rates within the time interval from 1943–74) plotted versus the distance from the site T1. The slope of the linear regression (0.26 ± 0.04 mm accumulation/km) indicates a changing distribution of the accumulation rate between the earlier periods and the present at the 95% significance level.

Thickness changes of the Greenland ice cap are a controversial subject. Results from Reeh and Gundestrup (1985) indicate an increase of the ice sheet at Dye 3 (65°11′N, 43°49′W) (South Greenland) of 30 ± 60 mm/year which could be caused by slowing of the ice flow due to the downward propagation of stiffer post-Wisconsin ice.

Based on satellite altimetry measurements by Zwally (1989), the Greenland surface elevation south of 72° N should be increasing by a rate of 230 ± 40 mm/year. This would require a 25–45 % excess ice accumulation over the amount required to balance the outward ice flow (Zwally, 1989). The results of this work show that the annual accumulation rate has changed less than 10% during the last four decades. A comparison of the modern accumulation rate with the long time mean accumulation rate at Crête (the last 1400 years) and T15 (the last 800 years) indicates that the accumulation rate has changed by less than 6% during the last millennium at these two sites. Since accumulation rate is a regional rather than a local parameter and since Crête and T15 are located far away from each other, their small change of accumulation rate during the last millennium indicates an equally minor change of accumulation rate (less than 10%) for the whole region between these sites. Reeh and Gundestrup (1985) proposed that the ice sheet is increasing due to the changing viscosity of glacial and interglacial ice layers. Since the viscosity profile in the ice sheet changes only gradually in time, a sudden change of the outward ice flow rate is unlikely. We can therefore assume that during the period of thousand years the annual rate of increase of the surface elevation resulting from changing ice viscosity has not much changed. Therefore, Zwally's results and the stability of the accumulation rates would imply that the ice sheet south of 72° N must have been growing with an approximately constant rate during the last 1000 years. With a rate of increase of more than 200 mm/year (Zwally, 1989) the altitude of the ice sheet would have raised about 200 m during the last millennium. Due to the increase of the surface altitude, the local mean temperature on the Greenland ice sheet would decrease in comparison with the global mean temperature. This should manifest itself by an increasing difference between ice sheet temperature records and land based temperature records. The temperature on the ice sheet can be reconstructed with the isotopic $\delta^{18}O$ record along an ice core. During the last 7000 years the isotopic temperature from Summit (Johnsen et al., 1993) and Dye 3 (S. J. Johnsen, personal communication, Copenhagen, DK) was very stable and changed less than 1°C during this time period, and, in particular, a comparison of the isotopic temperature from Summit and Dye 3 with long-term temperature records from Lake Michigan (Bernabo, 1981) and Central England (Lamb, 1977) show no systematic cooling or warming of these two Greenland stations during the last millennium.

Since there has been neither a significant drift of the Summit and Dye 3 surface temperature nor a pronounced change of the accumulation rate during the last millennium a present-day increasing surface with a rate of 230 ± 40 mm/year (Zwally, 1998) is rather unlikely and is not confirmed with the findings of this work.

5. Acknowledgements

We wish to thank J. Schwander for all the invaluable discussions and H. Kock and K. Obergfell from the TU Braunschweig for the organisation of the traverse. This work has been supported by the Swiss Nation Foundation and the Swiss Department of Energy.

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