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THE EFFECTS OF WIND ON $\delta(^{18}O)$ AND ACCUMULATION GIVE AN INFERRED RECORD OF SEASONAL δ AMPLITUDE FROM THE AGASSIZ ICE CAP, ELLESMERE ISLAND, CANADA

by

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ABSTRACT

Wind plays an important role in determining accumulation and $\delta(^{18}O)$ on some ice caps. Three surface-to-bed cores spaced about 1 km apart have been taken on a flow line of the Agassiz Ice Cap, Ellesmere Island. The A84 core comes from the top of a local dome. The A79 core is 1200 m down the flow line, but very close to the ridge through the local dome. The A77 core is 1100 m from A79 and well away from the ridge. The ridge causes wind turbulence, which removes or scours the soft winter snow from the A84 and A79 sites. No snow is scoured from the A77 site. Because of scour the retained accumulation and average $\delta(^{18}O)$ are different. The accumulations are 17.5, 11.5, 9.7 cm/a (ice equivalent) at A77, A79 and A84 respectively and the corresponding surface δs are −30.40, −27.90 and −27.05‰. The core records were dated by annual layer thicknesses and by identification of electrical conductivity measurement (ECM) acid peaks. With the three cores accurately aligned we examine the $(\delta_{A84}-\delta_{A77})$ and $(\delta_{A84}-\delta_{A79})$ time series. Significant variations in these difference series are interpreted as being caused by changes in the seasonal δ amplitude, which is then explained by changes in sea-ice cover. A seasonal δ amplitude series independently obtained from the Devon Island ice cap δ noise record is consistent with that from the Agassiz Ice Cap sites.

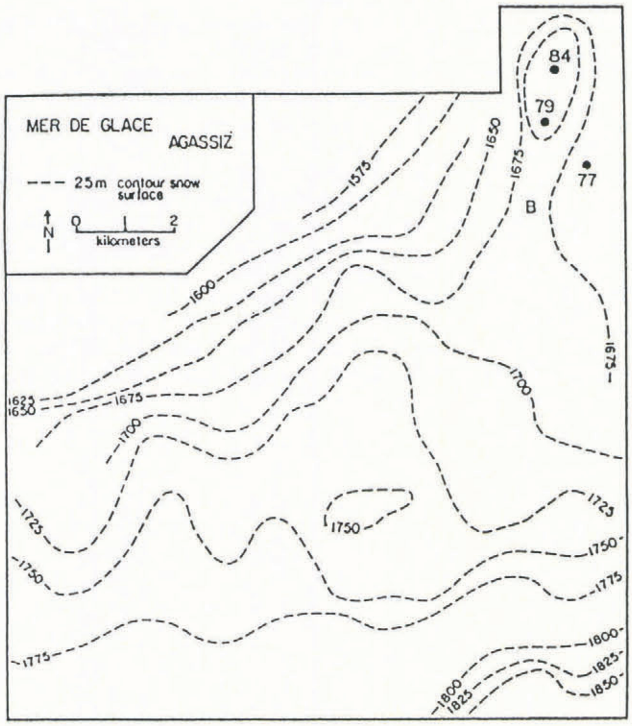

Fig.1. Surface contours of part of the Agassiz Ice Cap, showing the three bore holes drilled in 1977, 1979 and 1984 and referred to as A77, A79 and A84.

INTRODUCTION

$\delta(^{18}O)$ and accumulation rate λ measured on the Agassiz Ice Cap are intimately connected by some common meteorological variables. The influence of air temperature on δ has been discussed by many authors (e.g. Dansgaard and others 1973, Merlivat and Jouzel 1979). Temperature, water-vapour input and sea-ice cover through the whole water cycle have been examined by Fisher and Alt (1985) and Joussaume (1985). Little attention has been given to wind velocity and turbulence in affecting these variables at ice-cap sites. This paper reports on the results from three bore holes on nearly the same flow line on the Agassiz Ice Cap and demonstrates that wind is important in determining both the $\delta(^{18}O)$ of precipitation and λ. The time history of δ and the history of the δ difference between sites is shown to be related to wind scour and time variations in the seasonal δ amplitude, S.

The Agassiz Ice Cap δ amplitude history is compared to that deduced from the Devon Island ice cores, using the known δ noise time series for that site.

THE BORE HOLES AND ICE CAP

An ice cap, roughly 16 000 km^2 in area, covers the central part of Ellesmere Island between latitudes 79°45' and 81°N. Its surface topography is complex and there are nunataks even in the highest parts. Three cores were recovered from the northern part, the Agassiz Ice Cap, in 1977, 1979 and 1984 (Fig.1). Cores and sites are referred to as A77, A79 and A84 respectively. Summer melting as shown by ice layers in the firn (averaged over 1000 a) is 3% of the annual precipitation of 0.175 m a^{-1}. Table I gives the details for the three bore holes.

RELATIONSHIP BETWEEN WIND-SCOURING ACCUMULATION AND $\delta(^{18}O)$

We believe that the general circulation wind (and its turbulence) is mainly responsible for scouring on the Agassiz Ice Cap (Fisher and others 1983). Conditions for scour prevail near the ridge and down the steep slope

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TABLE 1. AGASSIZ ICE CAP NEAR-SURFACE PROPERTIES.

Site	elevation (m a.s.l.)	$\delta(^{18}O)$ 50 a average (‰)	Accumulation (m/a ice)	10 m temperature (°C)	Ice thickness (m)
A84	1730	−27.05	0.094–0.101	−21.88	127
A79	1700	−27.90	0.115	−22.33	139
A77	1670	−30.40	0.175	−24.52	338

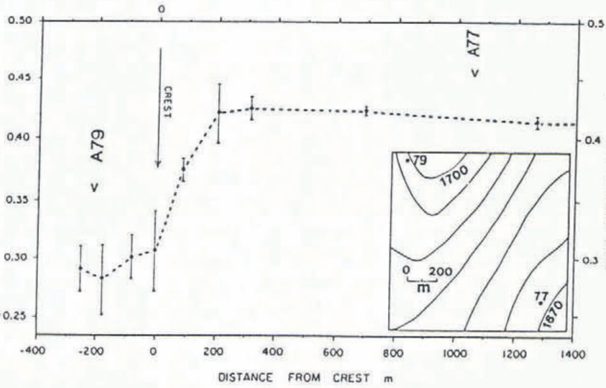

Fig.2. Detailed surface contours around A77 and A79 and an accumulation profile along a line between the sites. The scour zone is defined by low values of accumulation. The minimum is on the W or windward side of the ridge and scour stops quite abruptly about 200 m east of the ridge. Accumulation rate data are based on 6 years' measurements on a "stake farm" that encompasses the A77 and A79 sites.

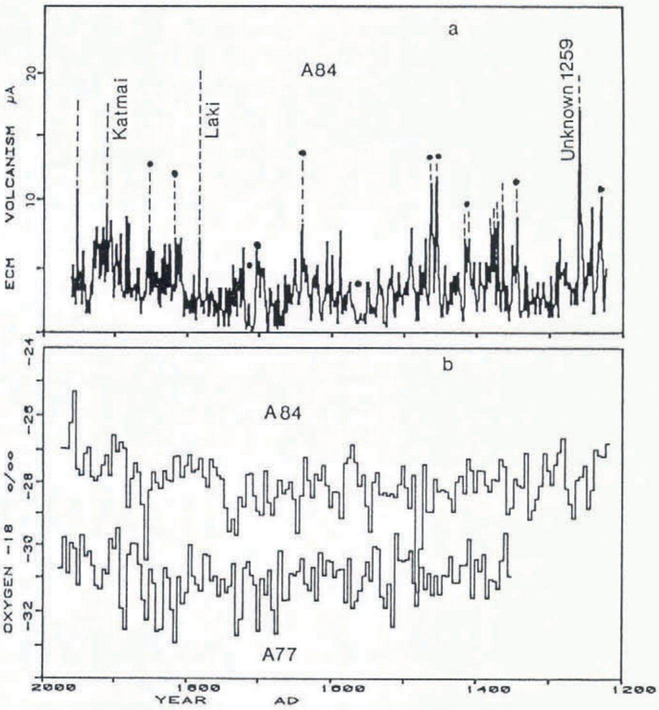

Fig.3. (a) Annual averages of the volcanic acid stratigraphy from electrical conductivity measurements (ECM) for A84. The larger peaks are extended to their maximum values. The time-scale assumes that these peaks can be identified with the Greenland stratigraphy. (b) Five-year averages of $\delta(^{18}O)$ for A84 and A77 on the same time-scale. Notice the 3‰ offset caused by wind erosion of winter snow from A84.

north-west of A79 on the windward side of the ridge (Figs. 1 and 2). We know that scour occurs more often in the winter, when snow grains are smaller and less efficiently sintered.

Accumulation measurements show a scour zone with a minimum accumulation slightly to the windward of the ridge (Fig.2). Accumulation decreases slightly from A79 to A84 at the top. On the lee there is a 200 m transition from scour zone to undisturbed zone. The unscoured zone extends for many kilometres and shows little variation in λ.

A77 is in the unscoured zone and pit studies show that no seasons are missing in the δ profile (Fisher and others 1983). Most of the winter snow is removed from A79 and A84, representing 35 and 44% respectively of the total undisturbed accumulation. Not much more winter snow *can* be removed. Also, since only very light winds are needed to remove the loose winter snow in the scour zone (Koerner 1966), we think that the inter-site differences in λ and δ are constant, assuming a fixed-ridge geometry. Wind is needed for scour to produce the differences in λ and δ but these differences are probably insensitive to variations in the wind speed over a wide range. The consistency of this assumption will be tested later.

TIME-SCALES FOR THE THREE AGASSIZ ICE CAP CORES, VOLCANIC STRATIGRAPHY

The initial time-scales based on models and measured annual-layer thicknesses are used to date tentatively the electrical conductivity measurements (ECM) of volcanic peaks (Hammer 1980, Fisher and others 1983). The large peaks are then cross-identified between the Agassiz Ice Cap cores and further referenced to the large peaks in the Greenland ECM stratigraphy (Hammer 1984, Hammer and others 1980).

ECM measurements on the three cores were made with brass electrodes spaced 25 mm apart, across which 1250 V d.c. was applied. However, the conditions of measurement and record quality vary from core to core. Measurements on the A77 core were made in the laboratory at −10°C 1 year after drilling, those on A79 were made in the field at too warm an ambient temperature, and the A84 cores were analyzed in the field at −18°C on newly drilled cores. In all cases half-cores were examined after at least 5 mm of surface ice had been removed with a clean stainless-steel knife. The A84 ECM record is probably the most reliable and A79 the least. Major features are apparent in all the records.

Great care was taken to align the ECM and $\delta(^{18}O)$ stratigraphies and the alignment error is 10 cm at most. Annual averages of the A84 volcanic stratigraphy are presented in Figure 3a, along with the δ record for A84 and A77 (Fig.3b). All these records have been dated using the volcanic record. Peak ECM values for major peaks are shown as dashed extensions of the annual average. All the dashed peaks and features marked by dots in Figure 3a were used to align the three Agassiz Ice Cap cores. The firn part of the ECM record goes down to 46 m, which is 500 years old. Thus the background trends in the upper 500 years should be viewed with caution.

RELATIONSHIP BETWEEN ANNUAL δ, SCOUR AND SEASONAL δ AMPLITUDE ON THE AGASSIZ ICE CAP

Assume that the same seasonal δ pattern is represented at two sites (A77 and A84, for example), and for simplicity let the annual unscoured average ($\bar{\delta}$) be equal to 0‰. Let the undisturbed seasonal δ variation be given by

$$\delta = S\cos(2\pi z/12) \qquad (1)$$

where S is the seasonal amplitude, i.e. $(\delta_{\text{summer}} - \delta_{\text{winter}})/2$ and z is the month of the year.

Now if a fraction f of the unscoured annual accumulation is removed from the coldest part of the winter snow, then the annual average of the snow left behind will be

$$\bar{\delta}_S = S\sin(\pi f)/((1 - f)\pi) \qquad (2)$$

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The difference between scoured and unscoured annual δ is simply

$$\Delta\bar{\delta} = \bar{\delta}_s - \bar{\delta} = \bar{\delta}_s$$

Using the Agassiz Ice Cap A84 and A79 accumulation and $\bar{\delta}$(^{18}O) data from Table I, one can use Equation 2 to compute the amplitude S of unscoured snow; S = 5.53‰ ± 0.5. This compares well with S = 5.1‰, which was obtained from the upper 2 years of the detailed δ record from a pit beside the unscoured A77 site (Fisher and others 1983).

The Agassiz Ice Cap seasonal δ amplitude seems too small when compared with the values for Devon Island and Camp Century, but in fact it fits into the Northern Hemisphere pattern of seasonal δ amplitudes for high-elevation ice-cap sites in Greenland and Arctic Canada (Fig.4). There is an increase in S from south Greenland to latitude 76°N, then a sharper decrease north of 76°. The rise in S up to 76°N is probably related to the seasonal march of sea ice in Baffin Bay and Davis Strait (Fisher and Alt 1985). The decrease in S north of 76°N is probably caused by the decrease in survival distance of water vapour with latitude, coupled with the distance of sites from local water-vapour sources south of them. There may also be some Arctic Ocean influence (Fisher and Alt 1985).

Since we believe that the fractions f removed from A79 and A84 sites are not very sensitive to wind speed, we are left with explaining changes in $\Delta\bar{\delta}$ by changes in amplitude S. Figure 5 shows $(\delta_{A84}-\delta_{A77})$ and $(\delta_{A84}-\delta_{A79})$ for the last 700 years. We see there are intervals of time with above-average inter-site $\Delta\bar{\delta}$ values, e.g. (A.D. 1977–1800), and periods of below-average $\Delta\bar{\delta}$, e.g. (A.D. 1670–1450). If the $(\delta_{A84}-\delta_{A77})$ variations are all attributed to S variations, then the S history can be read off the $\Delta\bar{\delta}$ difference record using the right-hand scale of Figure 5, which is obtained using Equation 2. In the above-average S interval (A.D. 1977–1800) S = 6.0‰, and in the minimum S interval (A.D. 1670–1450) S = 3.5‰. Using Figure 4 one can change the Agassiz Ice Cap S from 6 to 3.5‰ by shifting the S latitude pattern south by 3.5° of latitude.

RELATIONSHIP BETWEEN SEASONAL δ AMPLITUDE AND δ NOISE ON THE DEVON ISLAND ICE CORES

If two or more δ records are available from closely adjacent sites, if they suffer no scouring and can be aligned exactly, then their δ difference history is a time series of $2e_n$, where e_n is the areal or drift noise (Fisher and others 1985). The standard deviation σ_n of e_n in the Northern Hemisphere ice caps has also been related to the seasonal amplitude S (Fisher and others 1985) by

$$\sigma_n(\delta) = 0.08S \tag{3}$$

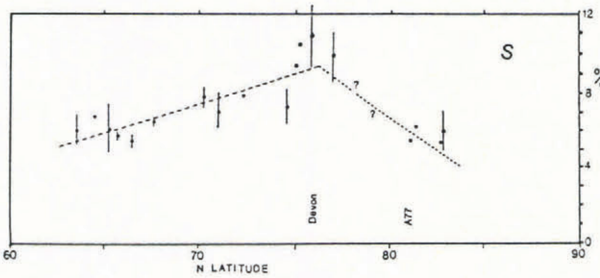

Fig.4. Seasonal δ(^{18}O) amplitude S = $(\delta_{summer}-\delta_{winter})/2$ for high-elevation ice-cap sites in Greenland and Arctic Canada. Because of diffusion only the upper 2 years of δ profiles are used to determine S. Sites within half a degree of latitude of each other are averaged together. A least-squares line fits the points between 60° and 76°N and the slope of this line matches that for sea-level stations (Fisher and others 1985).

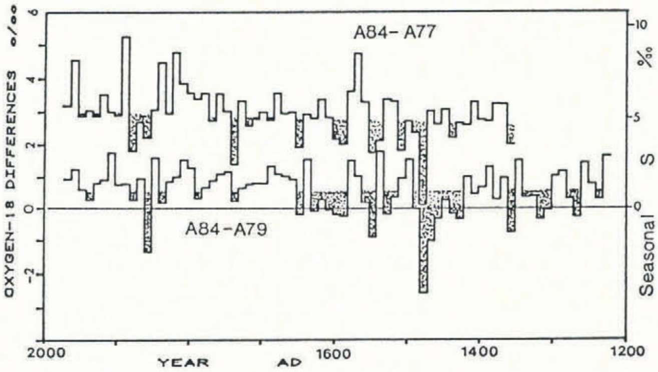

Fig.5. Time series of $(\delta_{A84}-\delta_{A77})$ and $(\delta_{A84}-\delta_{A79})$. The ‰ scale is on the left. The $(\delta_{A84}-\delta_{A77})$ record can be translated into a seasonal δ amplitude record, S, by using the right-hand scale. During the Little Ice Age S is smaller by a few per mille, suggesting that winter sea ice was farther south at that time.

Two such annual δ time series, obtained from cores taken 27 m apart on the Devon Island ice cap (Paterson and others 1977), provide such an annual-drift noise series (Fig.6c). Figure 6a and b shows the Devon Island (^{18}O) and summer melt record respectively. The "coldest" parts of the δ and melt records clearly contain the least drift noise. The left side of Figure 6c gives $\sqrt{2}\ \sigma_n$ and this is transformed into S in ‰ (on the right side of Fig.6c) by means of Equation 3. Using the right-hand S scale of Fig.6c, the average Devon Island S in the interval (A.D. 1960–1800) is 8.7‰. The modern S value as taken from the least-squares line of Figure 4 is 9.2‰ ± 1.0. In the (A.D.

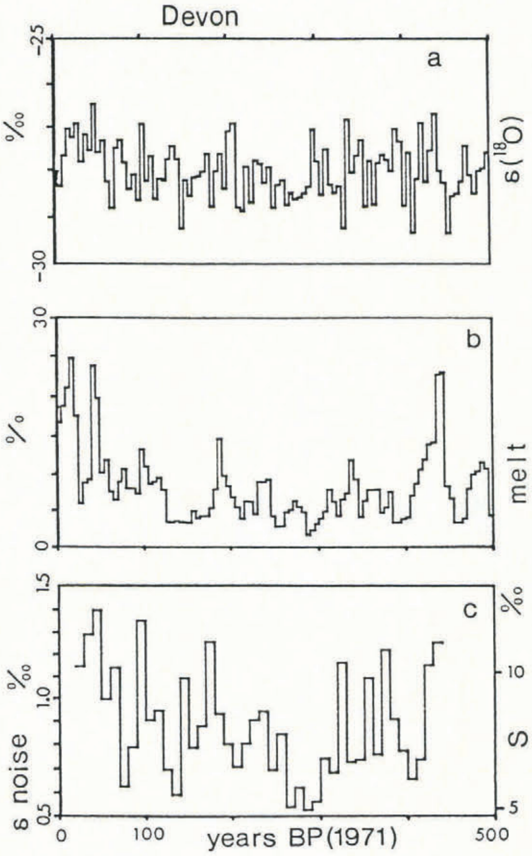

Fig.6. (a) The Devon ice cap δ(^{18}O) record in five-year averages. This record is obtained by averaging δ records from two 300 m holes 27 m apart (Paterson and others 1977), after first accurately aligning them. (b) The summer melt percentage obtained by averaging results from three Devon Island ice cores. (c) The record of areal or drift noise in two Devon δ records. The left-hand scale is $\sqrt{2}\ \sigma_n$, where σ_n is the standard deviation of annual average noise in a single δ record. One can see a strong tendency for areal δ noise to decrease during cold periods. The right-hand scale translates the σ_n record into variations in S, the Devon seasonal δ amplitude.

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1700–1520) interval S = 7‰. Using Figure 4 one can change Devon Island's S from 9 to 7‰ by shifting the S latitude relation south by 3.5°; it is the same shift needed to explain the scour-related change in the ($\delta_{A84}-\delta_{A77}$) record of the Agassiz Ice Cap (Fig.5). This agreement shows that the local-noise model (Equation 3) applied to the Devon Island site gives an S history that is consistent with that obtained from wind-scour model (Equation 2) applied to the Agassiz Ice Cap site, provided that the S latitude pattern shifts as we suggest.

SCOUR, δ AND SEA ICE

We have argued that $\Delta\bar{\delta}$ time series can be treated as records of the seasonal δ amplitude S. Further, S is related to latitude by the empirical relation shown in Figure 4 and the variations in S can be explained by shifting the S latitude relation north or south. Between 60° and 76°N the latitude dependence of S is probably caused by the 15° seasonal march of the sea-ice front (Fisher and Alt 1985). At 60° on south Greenland there is little or no sea-ice effect because in winter the ice front and local water are not very far away; here S = 4.5‰. At 76° the ice-cap sites "see" a maximum sea-ice effect and S = 9.5‰. Here the closest water is very far away in winter and nearby in summer. The full sea-ice contribution to S for sites at 76°N is 5‰ or about half S (Fisher and Alt 1985). The fall in S north of 76° is possibly due to the decreasing value of the survival distance of moisture (especially local Baffin Bay moisture), coupled with the increasing influence of the Arctic Ocean. To suggest moving the present S latitude pattern south implies cooling conditions with southward migration of the winter sea-ice front, combined possibly with shorter survival distances for water vapour. A northward shift of the S latitude pattern, as required to explain an increase in S at Agassiz Ice Cap, implies warming conditions, a shrinkage in winter sea ice and more penetration of southern moisture to higher latitudes.

SUMMARY AND DISCUSSION

We have shown how wind plays an important part in determining such significant ice-sheet properties as retained accumulation and δ(^{18}O). Through differential erosion of winter snow on the Agassiz Ice Cap we are able, by examining the $\Delta\bar{\delta}$ records, to infer a history of the seasonal δ amplitude S. We interpret changes in S as due to a shift in the S latitude relationship which we propose accompanies a migrating winter sea-ice front. Areal or snow-drift noise is also related to S and we have extracted a history of S for the Devon ice cap cores that essentially backs up the inferred S record from the Agassiz $\Delta\bar{\delta}$ records.

Little Ice Age S decreased by about 2‰ from present values, at sites north of about 75°. We argue that during this period the S latitude pattern was shifted about 3.5° southward, resulting in the decrease in S at Devon Island, Camp Century and the Agassiz Ice Cap.

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