MEDDELELSER OM GRØNLAND
UDGIVNE AF
KOMMISSIONEN FOR VIDENSKABELIGE UNDERSØGELSER I GRØNLAND
Bd. 192 · Nr. 7

GRØNLANDS GEOLOGISKE UNDERSØGELSE
Bulletin No. 104

A LICHENOMETRICAL STUDY OF SNOW PATCH VARIATION IN THE FREDERIKSHÅB DISTRICT, SOUTH-WEST GREENLAND,

AND ITS IMPLICATIONS FOR STUDIES OF CLIMATIC AND GLACIAL FLUCTUATIONS

BY

G. T. KEITH PITMAN

WITH 10 FIGURES AND 5 TABLES

KØBENHAVN
C. A. REITZELS FORLAG
BIANCO LUNOS BOGTRYKKERI A/S
1973

Abstract

This report describes firstly the methods used to determine local growth rates of the species *Rhizocarpon geographicum* and the confidence that can be put in such estimates of substrate age based on lichen diameters. Secondly, mean *Rhizocarpon geographicum* diameters in former snow patch zones were sampled and non-random patterns of colonization were observed. Two models were constructed to explain these colonization patterns in terms of the change of the perennial snowline with height against time. Hence mean annual temperatures back to 1680 were predicted from the models for Frederikshåb. Lastly a correlation is shown between local mean annual temperature changes in the historical period, glacial fluctuations, and estimates of temperature obtained from the lichen colonization models.

ISBN 87 421 0084 4

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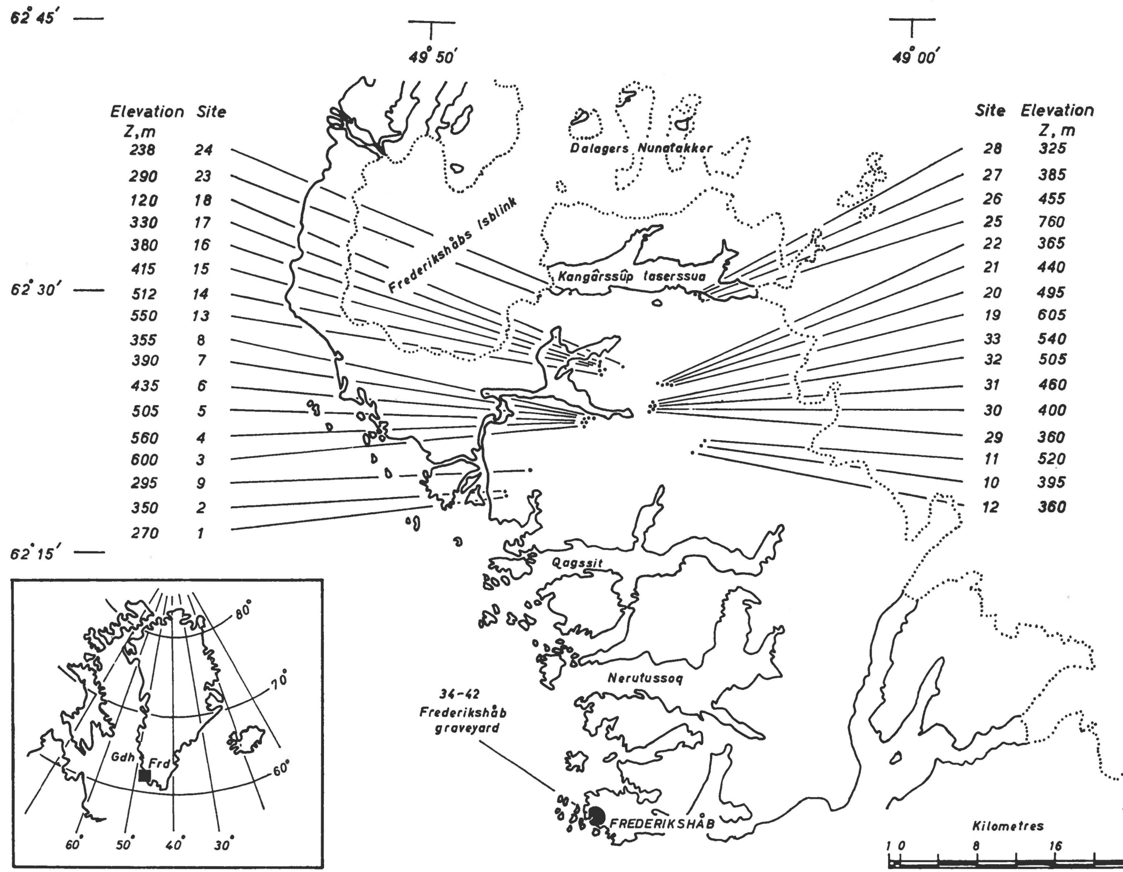

Fig. 1. Frederikshåb district: location of sampling sites 1968.

INTRODUCTION

The field work which forms the basis of this paper was undertaken in the summer season of 1968 during the mapping of the superficial deposits for the Geological Survey of Greenland in the north Frederikshåb district. It was subsequently submitted as part of studies for the B. A. Honours degree in Environmental Sciences at the University of Lancaster, England, 1969.

Theory and development of lichenometry

Initially developed by BESCHEL (1950, 1957, 1958) the method of lichenometry permits absolute dating of the underlying substrates from a knowledge of the local lichen growth rates. The complete method and its justification is summarised by BESCHEL (1961). The assumptions made in lichenometry have been reassessed by ANDREWS & WEBBER (1969), following the criticisms put forward by JOCHIMSEN (1966) regarding the linearity of growth rates: provided that sufficient care is taken in the method their reexamination demonstrated that the technique was valid.

The following characteristics of lichen growth are fundamental to the method. Firstly, the newly exposed rock surface becomes sprayed by diaspores from the atmosphere which subsequently grow, providing that the limiting conditions for growth are met. Consequently the largest lichen will reflect the 'age' of the substrate. Secondly, very slow growing species, such as the crustose *Rhizocarpon geographicum*, have constant growth rates for a very long time after an initial exponential 'spurt' of growth. The rate of growth in this period is a function of the hygro-continentality of the environment (BESCHEL, 1961, 1965; GAMS, 1932; ANDREWS & WEBBER, 1964). Consequently growth will vary in space, i.e. with distance inland from the coastal regions, and in time, if the climatic variations have been sufficiently large. However, as the present diameter is representative of the integrated growth variations no methods exist to examine and eradicate time variations of climate and it will be assumed that growth has been constant with respect to time.

Scope of the work and sampling procedure

The present study was carried out to examine the field observation that in Greenland there was a zonal distribution of maximum lichen diameters in snow patch areas (Kelly, personal communication, 1968). Firstly, it is suggested that these variations reflect areas occupied by the perennial snow in the past and hence provide an index of climatic change. Secondly, that such inferred climatic change from snow patch lichen data should be capable of correlation to recent climatic change monitored by other means: meteorological observations and glacier margin fluctuations.

The forty-two sites sampled included a detailed examination of twenty-eight annual and former perennial snow patch sites characterized by their vegetation communities. The location and elevation of these sites is shown in figure 1. At these sites a total of over 10,500 measurements were made of the lichen *Rhizocarpon geographicum.*

It was decided to use the lichen *Rhizocarpon geographicum* for the following reasons:

(i) it has a very slow growth rate so that the effects of short term climatic change will be minimal.

(ii) the life form is easily recognizable – a bright yellow-green thallus and black hypothallus.

Undoubtedly using just this one species introduces errors inherent in assuming growth conditions to be constant. Consequently, statistically significant samples were taken at each snow patch site in order to account for these as far as possible. Even so the questionable nature of this assumption must be borne in mind.

A two tiered sampling procedure was adopted. Firstly blocks 2 by 2 km were located randomly on the map and the north facing slopes within each block were sampled for snow patches. Thus the sampled snow patches were located in a two co-ordinate vertical plane, the ordinate being height above sea level, X m, and the abscissa being the distance from the coast, D km.

The constraint that the snow patches be on the north facing slopes was in order to eliminate the microclimatic variations (effect of aspect, insolation and humidity gradients) as far as possible.

The second sampling stage was within each lichen zone in the snow patch area. A strip 10 m by 2 m divided into ten 1 m by 2 m quadrats was extended from the centre of the snow patch area outwards under the following constraints:

(i) that the sampling line be at 45° to the direction of maximum slope, thus avoiding the effect of melt water influencing growth rates.

(ii) that where possible material liable to mass movement be avoided: this would cause discrepancies in the age of the substrate.

(iii) that all vertical surfaces and large boulders be avoided. It was observed that large size variations occurred on adjacent vertical and horizontal substrates which were attributed to differential snow cover and contact ablation crevasses. Further, the variations on the boulders were due to their projecting above the surface layer, thus allowing continued lichen growth.

It was found that 'random' samples under these conditions could be satisfactorily taken by throwing handfuls of grit/grass/matchsticks into the air and measuring the lichens on which they fell.

Lichen thalli by virtue of their metabolism (HALE, 1959, 1967) are generally almost circular. However, non-circular forms were common and to compensate for this the largest and smallest 'widths' were taken and the mean recorded. Using dividers measurements could be recorded $\pm$ 0.5 mm. Thus from each quadrat 25 random samples were measured, making a total of 250 for each snow patch site.

The altitude of each snow patch was measured by hand altimeter (aneroid) set from sea level if the camp was sufficiently low or from the altimeters of the helicopters when available. Corrections were made to all heights by a 'loop' correction at the end of the day. By this method altitude was given to $\pm$ 10 m.

Distance from the coast was taken directly from 1:50000 enlargements of the Geodetic Institute 1:250000 sheet, each snow patch being projected onto a line normal to the coast.

The statistics for the analysis are those given by JOHNSON & LEONE (1964) and EZEKIEL & FOX (1965) unless otherwise stated.

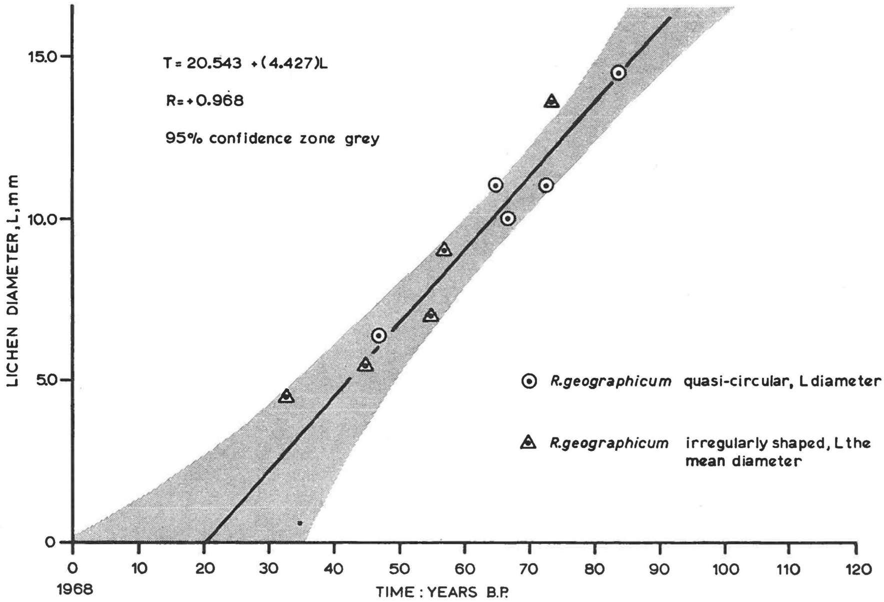

Fig. 2. The relationship of the diameter of *Rhizocarpon geographicum* to time. Frederikshåb, 1968.

RESULTS

Lichen growth rates

The determination of characteristic local growth rates was made by measuring *Rhizocarpon geographicum* growing on dated gneiss substrates: monuments and tombstones from 1884 to 1936 in the graveyard in Frederikshåb. The largest lichen diameters were plotted against time and an approximately linear distribution was noted (fig. 2).

Hence it was assumed that lichen diameter: time relationships could be represented by linear equations of the form:

$$L = aT + b \pm \xi$$

$$T = a'L + b' \pm \xi'$$

where L = diameter of *R. geographicum* in mm.

T = time in years before present.

a, a' = gradients of the lines.

b, b' = values at the intercept when $T = 0$, $L = 0$.

ξ, ξ' = random, normal error term.

Subsequently the two least squares' regression equations were obtained:

$$L = -3.8045 + 0.2140\,T \qquad (1)$$

$$T = 20.543 + 4.4267\,L \qquad (2)$$

The standard error of the estimate of equation 2 after correction for the small sample size and addition of measuring error was:

$$S = \pm\ 5.78 \text{ years}$$

with the correlation coefficient

$$R_{TL} = +0.9676$$

significantly different from zero at $p = 0.005$.

In effect the results from equation 2 mean that the lichen growth in the first 20.54 years is measurably zero: this period will include the lag-time for colonization and the very smallest initial growth. Further it indicates that *Rhizocarpon geographicum* grows approximately 1 mm every 4.4 years.

However, as the regression equation 2 is obtained on the basis of 10 samples it is necessary, in order to use the equation predictively, to give a measure of confidence that can be attached to time determinations from lichen diameters.

If T_0 is the time predicted from diameter $L = L_0$, then the 95 % confidence limits for a time prediction T_p is given in table 1 according to the sampling theory of regression analysis (Spiegel, 1961). The results are shown graphically in figure 2.

Table 1. *95 % confidence limits on lichen–time predictions:* $T_p = T_0 \pm \xi_{95\%}$

L_0 mm	5	10	20	30	40	50	60
T_0 years	42.68	64.81	109.08	153.34	197.61	241.88	286.14
$\xi_{95\%}$ years	11.37	9.95	14.79	25.50	35.46	45.97	57.86

Thus for a given lichen diameter the age of the substrate with confidence limits can be determined. However, it must be remembered that these equations are only strictly valid for the period represented when extrapolating, though the viability of linearity and homoscedasticity for much older lichens is currently acceptable (Beschel, 1961).

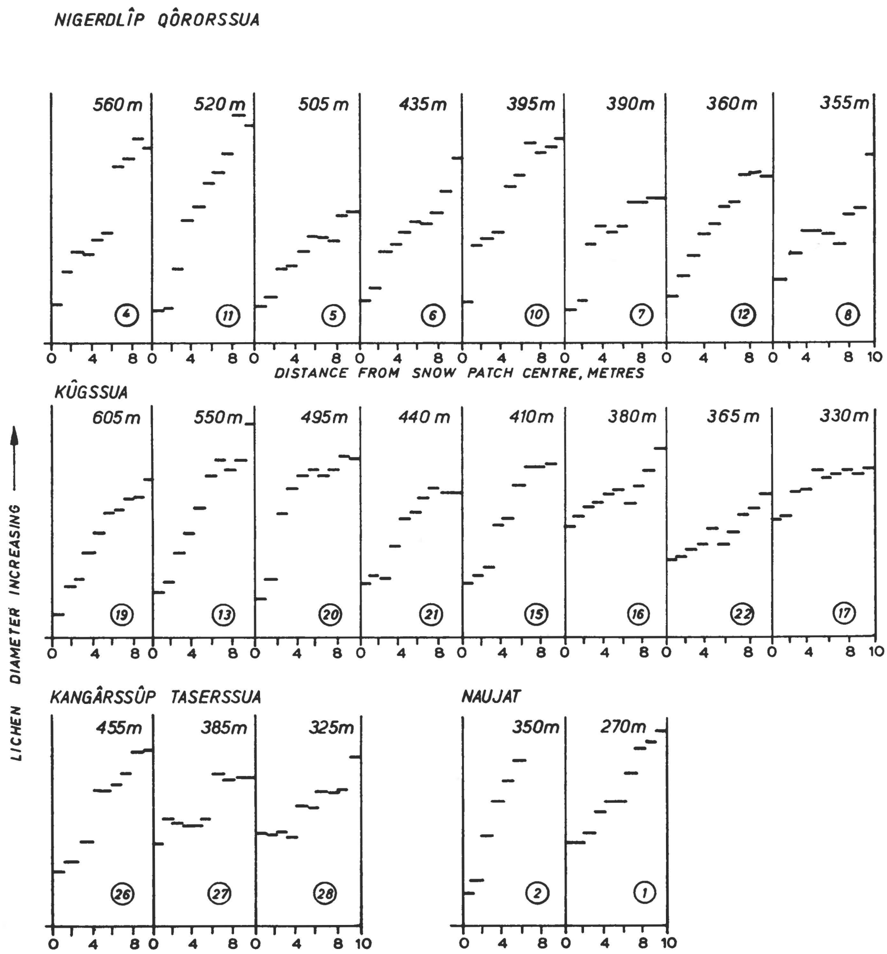

Fig. 3. Mean diameter of *R. geographicum* by quadrats for selected sites.

In order to assess the influence of changes in hygrocontinentality on growth rates lichen diameters were measured at two sites (24 and 28) 14 km apart on the highest strandline of the ice dammed margin lake Kangârssûp taserssua. This shoreline is considered to date from the 1876 advance of Frederikshåbs Isblink (Weidick, 1959). A χ^2 test of the resulting two samples showed that there was no significant difference in lichen diameters at the lake and strandline between the two sites.

Consequently it will be assumed that the rate of growth calculated for Frederikshåb is applicable to all sites regardless of distance from the coast. However, this one test should not be taken as conclusive because of the small number of sample sites.

Snow patch data

In order to examine the variation of lichen diameter within and between snow patches the mean diameter was calculated for each quadrat and plotted against the distance of the quadrat from the centre of the snow patch. Figure 3 gives examples from Nigerdlîp qôrorssua, Kûgssua, Kangârssûp taserssua and Naujat; the snow patches are identified by the ringed number in the bottom right hand corner of each site plot. The number in the top right corner gives the elevation of the site.

On examination of the distribution two features become apparent:

(i) the mean lichen diameter in the innermost quadrat shows an inverse relationship with height.

(ii) at each site the mean diameter can be seen to form discontinuous discrete curves with the lichen diameter increasing with distance from the centre.

Tests of randomness were applied to the data (Kershaw, 1964; Lindgren & McElrath, 1959) and it was found that the distributions observed were not random i.e. the lichen growth varies systematically according to its distance from the centre of the snow patch.

INTERPRETATION OF THE DATA

The two models outlined below show that the systematic variation within and between the sites as shown in figure 3 can be explained by

(i) a gradual rise in mean annual temperature

and (ii) a fluctuation in mean annual temperature about the long term trend.

From the use of these models the theoretical equations which describe the relationship between climate and associated lichen and snow patch characters are derived.

Hypothetical models of snow patch – climate relationships

The models are based on the following simplifying assumptions:

(i) that each snow patch has an equilibrium radius, X_n, at a mean annual temperature, t_n, and mean annual precipitation, p_n.

$$\text{i.e. } X_n = f(1/t_n, p_n)$$

Unfortunately precipitation, mostly in the form of snow, is extremely difficult to measure in mountainous terrain (ARMSTRONG & STIDD, 1967; DRISSEL & OSBORN, 1968) due to drifting, and its variation with time (VIBE, 1967). Thus any model incorporating p_n cannot be tested against actual observations. Consequently, because of lack of information to the contrary, it will be assumed that precipitation in time and space has been constant for the height and distance ranges considered: 400 m and 35 km respectively.

It has been noted by several observers (BONACINA, 1947; HAWES, 1947; MANLEY, 1939) that the mean annual temperature is an important parameter in snow patch studies as it offsets the potential summer ablation against the 'reservoir of winter cold' in the snow patch.

Hence:

$$X_n = \varphi(1/t_n)$$

Thus an increase in t_n will cause a decrease in X_n.

(ii) that lichens die after a prolonged covering of snow. This assumption was tested by observations of perennial snow patches and lichen growth, sections being dug from the edge of the snow patch to the centre. In all cases all lichen thalli 50 cm or more from the edge appeared to be dead. A few examples of *Rhizocarpon geographicum* collected *in situ* were subsequently proved dead in laboratory tests.

(iii) that decreases in snow patch radii are accompanied, after a suitable lag period, by lichen colonization, the largest lichens being indicative of the time passed since shrinking.

(iv) that the effect of variations in length of growing season with distance from the centre of the annual snow zone can be assumed to be negligible.

Model 1. The increasing temperature model.

Consider three snow patches on a north facing slope as illustrated in figure 4. Each snow patch has a radius, X_n, in equilibrium with the mean annual temperatures at that height, t_0 °C at Z_2 for snow patch 2 and at t_1 °C at Z_1 for snow patch 1.

If the temperature increases from t_1 to t_2 °C in a period $T_2 - T_1$ the radii of the snow patches will shrink to maintain thermal equilibrium. In the case of snow patches 3 and 2 it would shrink from X_3 to X_4 and X_2 to X_3 respectively, and snow patch 1 melts away entirely. Hence the substrate exposed in the centre of the snow patch area is ready for lichen colonization.

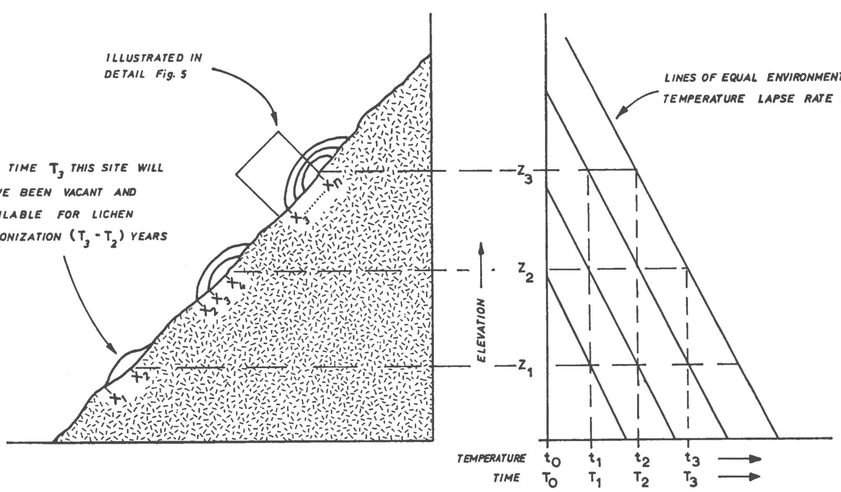

Fig. 4. General details of the increasing temperature model.

Snow patch 2 is now at a temperature lower than that of snow patch 1 by virtue of the environmental lapse rate of temperature, Γ_e, where

$$\Gamma_e = (t_2 - t_1)/(Z_2 - Z_1)\ ^\circ\mathrm{C} \cdot m^{-1} \tag{3}$$

The difference in temperature at the two levels is:

$$\Delta t = -\Gamma_e(Z_2 - Z_1) = (t_2 - t_1)\ ^\circ\mathrm{C}$$

If, however, later in time T_2, the temperature should increase by $\Delta t\,^\circ$C, snow patch 2 will disappear and snow patch 3 shrink to a thermal equilibrium radius X_1. Snow patch 2 substrate is now clear for lichen colonization.

At the time T_2 the lichens that have colonized snow patch 1 will have grown to a diameter, L. Hence at any later time, T_3, samples taken from the centres of the former snow patch sites would reveal a difference of lichen diameter, ΔL. A plot of lichen diameter in the first quadrats against height would reveal the inverse relationship found in figure 3 between the snow patches.

As the mean annual temperature will vary with increasing continentality it is necessary to take the distance from the sea, D, of the various snow patch sample sites into account.

If the inverse relationship of the mean lichen diameter in the innermost quadrat to height and distance inland is related by a function:

$$Z = f(L, D) \tag{4}$$

then the height, Z, above sea level can be related to temperature by the temperature lapse rate equation (BYERS, 1959):

$$t = \theta + \Gamma_e \cdot Z \tag{5}$$

where θ = datum temperature °C
t = actual temperature °C
Γ_e = environmental lapse rate °C $\cdot\, m^{-1}$
Z = height above datum m.

As the datum temperature is not known the differential form will have to be used. i.e.

$$\frac{dt}{dZ} = \Gamma_e \tag{6}$$

Hence on differentiating equation 4 for a constant D equation 6 can be substituted.

$$\text{i.e. } dZ = \beta(L)\, dL \tag{7}$$

and on substituting 6

$$dt = \Gamma_e \cdot \beta(L)\, dL \tag{8}$$

From equation 1

$$L = aT + b \pm \xi$$

$$\text{i.e. } \beta(L) \text{ becomes } \psi(T) \tag{9}$$

and $dL = adT$, $a = dL/dT$ = lichen growth in unit time.

$$\text{i.e. } dL = \frac{dL}{dT} \cdot dT \tag{10}$$

On substituting 9 and 10 into 8

$$dt = \Gamma_e \cdot \frac{dL}{dT} \cdot \psi(T)\, dT \tag{11}$$

Therefore the change in mean annual temperature in time period T_1, T_2 is given by:

$$\Delta t = \Gamma_e \cdot \frac{dL}{dT} \cdot \int_{T_1}^{T_2} \psi(T)\, dT \tag{12}$$

By formalizing the relationship $Z = f(L, D)$ and hence $\psi(T)$, obtaining values for the environmental temperature lapse rate Γ_e, and the lichen growth rate dL/dT, equation 12 can be solved numerically and tested against known trends. Furthermore equation 4 with D as a variable gives information on the height of the perennial snow line which can be related to the (higher) equilibrium line on glaciers and used to demonstrate its trends. Thus glacial fluctuations may provide an additional, indirect, means of checking equations 4 and 12.

Model 2. The fluctuating temperature model.

If figure 5 represents a hypothetical cyclic temperature fluctuation superimposed on the general trend of temperature increase then its effects on snow patch size and lichen population will be as shown by the lower two graphs.

Consider that at time T_6, the temperature is at t_6 and this gives an equilibrium radius X_6. However, if at time T_5 later the temperature drops to t_5, the snow patch, to maintain thermal equilibrium, will increase in radius to X_5. By time T_4 the temperature increases to t_4 and the snow patch melts to X_4. On the exposed substrate lichen colonization takes place, the difference between the maximum and minimum diameters L_5 and L_6 being proportional to the amelioration period $\Delta T_{5.4}$.

In the next time period, $\Delta T_{4.3.}$, the temperature decreases to t_3 and the snow patch expands to X_3. This overruns some of the previously colonized substrate and kills the lichens. The temperature then increases to t_2 at time T_2 and the snow patch again melts, opening up a new substrate for colonization.

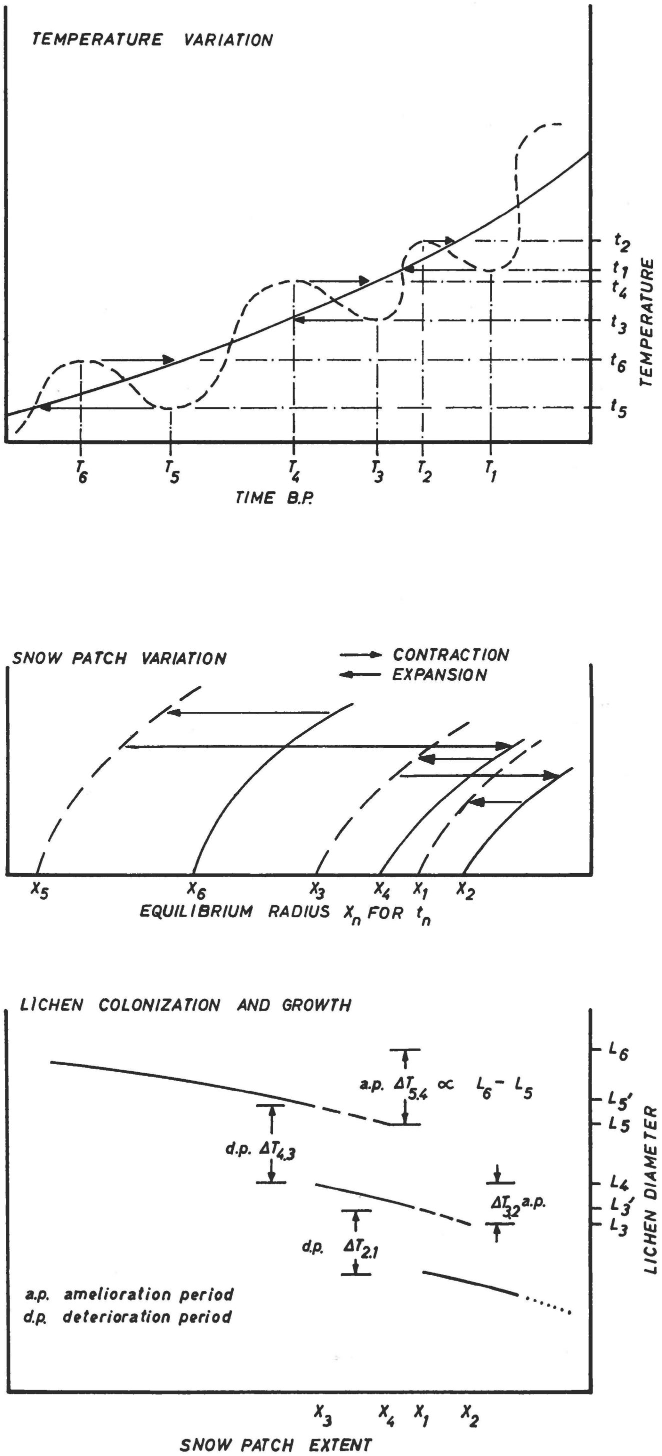

Fig. 5. Hypothetical model for cyclical temperature fluctuations.

Consequently, the discontinuity L_5' to L_4 is equal to a deterioration of temperature for the period $\Delta T_{4.3}$; according to the model this exaggerates the length of cooling by $L_5' - L_5$ units. However, for simplification of interpretation of these discontinuities this will be neglected.

Thus the discrete discontinuous curves shown in figure 3 can be explained by alternate warming and cooling around an upward trend of temperature.

The analysis of the above observations can only be undertaken for the length of period of lichen growth and discontinuities between the lichen growth periods. Hence estimates of periods of warming and cooling can be made but no estimates of the range of temperature responsible for these fluctuations.

In order to test whether these observed discrete mean value curves could be shown by a continuous population as a result of a continuous upward trend of temperature, a parametric analysis of variance was made using a model discussed in the section on temperature fluctuations.

Temperature trends 1680 to 1948

Figure 3 shows the variation in lichen diameter in the innermost quadrat with site elevation. According to model 1 this should record the trend of mean annual temperature change over a period, the data of which can be found from the known lichen growth rates. These gave ages of 1680 and 1948 for largest and smallest diameters in figure 6.

Evaluation of the terms in equation 12 would enable this $Z:L$ plot to be converted into a temperature:time plot. In order to do this Z, D and L were plotted graphically and possible empirical relationships found.

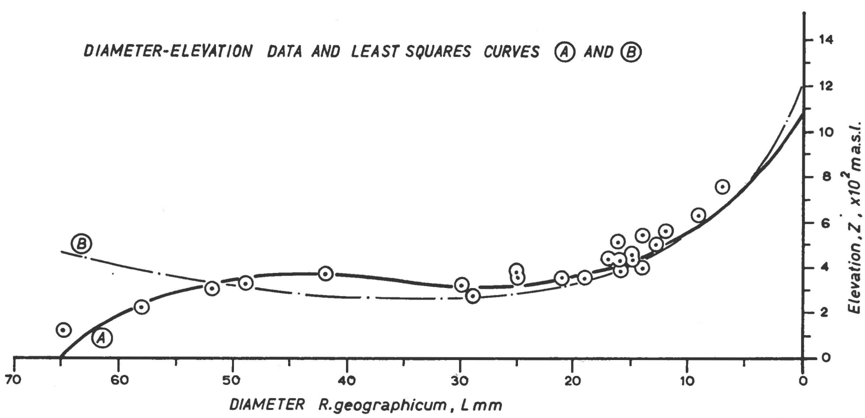

Fig. 6. Lichen diameter data plotted against elevation of occurrence and best fitting polynomials.

A linear plot was observed between Z and D. The relationship $Z:L$ was seen to be curvilinear which could be represented by various functions of L, L_φ, as follows:

$$L_\varphi = \varphi\ [1/L, L, L^2, L^3, \log_{10} L]$$

Hence it was thought that:

$$Z = f[D + L_\varphi] \tag{13}$$

as in equation 4. The regression equations were calculated using an ICL 1902 computer.

It was found that the best fitting multiple curvilinear regression equation (curve A, fig. 6) was:

$$Z = 1067.745 + (1.267)D - (69.722)L + (2.057)L^2 - (0.019)L^3 \tag{14}$$

with $R_{Z.DL} = 0.9283$ significant $p = 0.005$
and a standard error of estimate

$$S_{Z.DL} = \pm 34.83 \text{ m}$$

Equation 14 left 13.82 % of the variance unaccounted for.
A second equation (curve B, fig. 6):

$$Z = 1234.430 + (1.381)D + (0.108)L^2 - (711.090) \log_{10}L \tag{15}$$

was found to have

$$R_{Z.DL} = 0.9069$$
$$S_{Z.DL} = \pm 38.16 \text{ m}$$

and 17.74 % of the variance unaccounted for.

These two curves are plotted in figure 6, after correction for distance from the coast making the stipulation: $D = 0$.

Equation 14 was selected because of its slightly better fit. However, it must be noted that this is due to there being a small number of data points at the large diameter end of the diagrams, so that great caution must be employed when examining the temperature result during and before this corresponding period.

The only unknown in equation 12 is the environmental temperature lapse rate, Γ_e. This was calculated using radiosonde data from Egedesminde (68°42′ north, 52°52′ west), supplied by The Danish Meteorological Institute for the period 1951–1960. The monthly mean temperature lapse between the surface and 850 mb was analysed and the following results were obtained:

$$\Gamma_e = 0.3069°\text{C} / 100\text{m with } \sigma_e^2 = 0.00159°\text{C} / 100\text{m}.$$

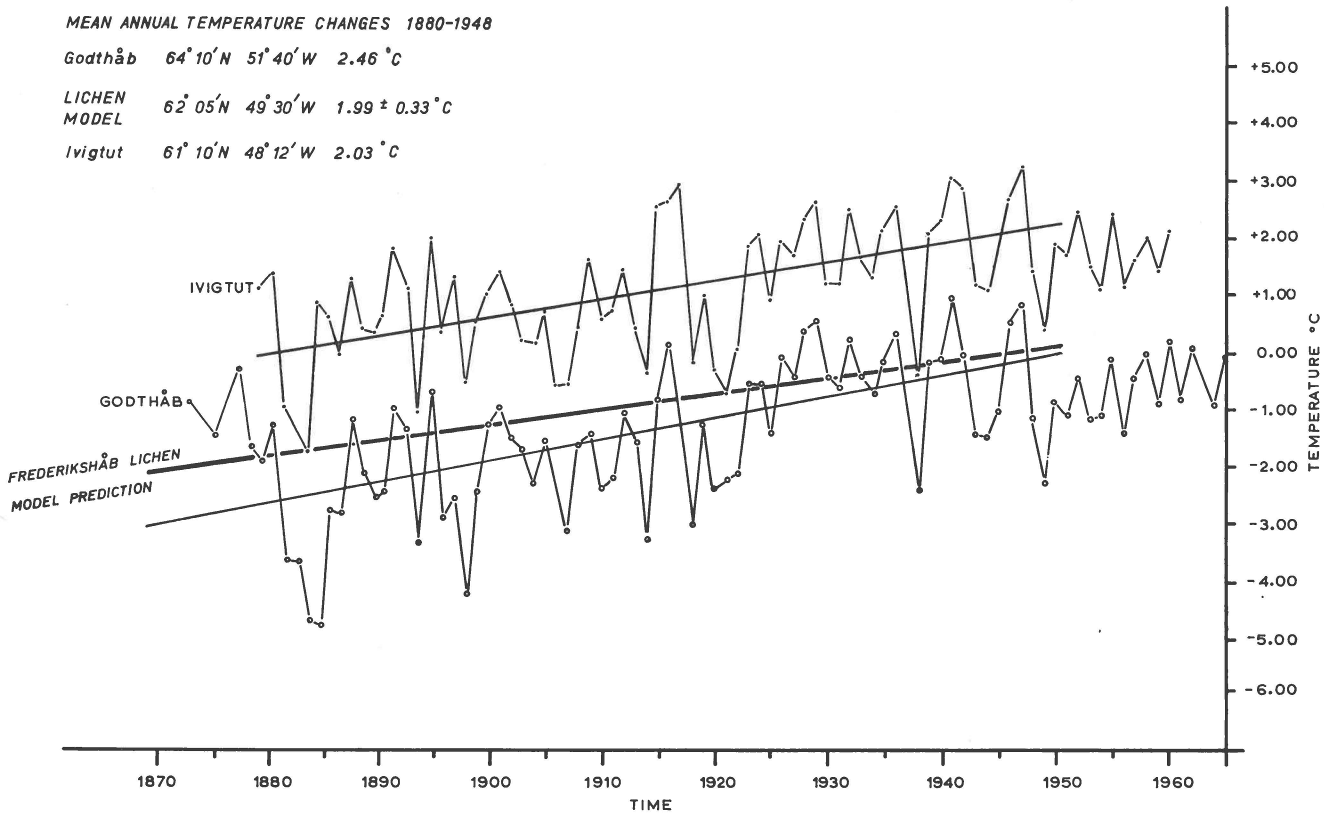

Fig. 7. Mean annual temperature for Godthåb, 1875–1965, and Ivigtut, 1879–1960 with trends 1880–1948. Lichen model prediction superimposed.

Hence the change in mean annual temperature in the time period $T_2 - T_1$ is given on substituting the above result into equation 12 by:

$$\Delta t = (0.003069)\,(0.2140) \int_{T_1}^{T_2} [-(85.648) + (0.967)T - (0.00244)T^2]\, dT \pm \text{error term} \qquad (16)$$

Using equation 16, however, only gives values to the relative changes that have taken place. An attempt will be made to convert this relative change to an absolute value change.

Unfortunately, the temperature for Frederikshåb was first recorded only in 1949, hence there is little evidence on which to base a mean value for 1948. This difficulty was overcome by "forecasting" the 1948 mean annual temperature by regression analysis and checking this value relative to the adjacent stations of Godthåb and Ivigtut.

Consequently the temperature records of Godthåb and Ivigtut were subjected to a more rigorous analysis over a longer period: 1880–1948. Both time series were correlated and the linear trend between 1880 and 1948 was computed. This is shown in figure 7. The following results were obtained:

$$R_{Gd.Iv.} = +0.8927 \qquad \text{for } p = 0.005$$

For Ivigtut:

$$t_{Iv} = (0.02419) + (0.02945)T \qquad (17)$$

For Godthåb:

$$t_{Gd} = -(2.7576) + (0.03595)T \qquad (18)$$

It seems reasonable to assume that the mean annual temperature at Frederikshåb lies between these of Godthåb and Ivigtut.

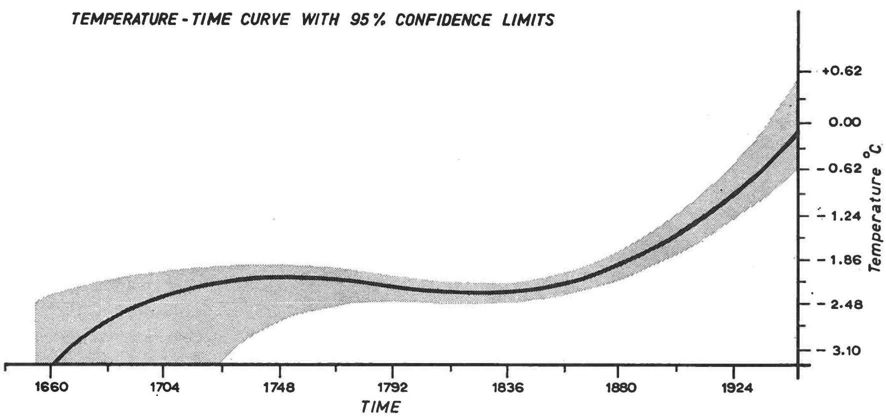

Fig. 8. Predicted mean annual temperature for Frederikshåb with 95% confidence limits for the period 1660–1947.

The means of the mean temperature for Ivigtut, Frederikshåb and Godthåb temperatures were then taken for the period 1949–1960. The Frederikshåb temperature was then expressed as the ratio of these two temperatures and from equations 17 and 18 the Frederikshåb temperature was predicted as +0.14°C.

All values for the temperature–time curves were then plotted relative to the 1948 temperature, as in figure 8, and values for the height of the perennial snow line and mean annual temperature are tabulated for the period 1681–1947 in table 2.

Table 2. *Predicted time variations in mean annual temperature and the associated perennial snow line levels in the northern Frederikshåb district of western Greenland.*

Date A.D.	Perennial snow level ma.s.l.	Mean annual temperature °C
1947	1067.8	+0.1
1925	708.2	−0.8
1903	557.5	−1.4
1881	420.6	−1.9
1859	344.1	−2.1
1837	313.5	−2.2
1815	314.4	−2.2
1793	332.7	−2.1
1770	354.1	−2.1
1748	364.3	−2.0
1726	349.2	−2.1
1704	294.3	−2.2
1681	185.6	−2.6

Temperature fluctuations 1680 to 1948

The following parametric model for the analysis of variance (ANOVA) was used to analyse the temperature fluctuations 1680 to 1948:

$$x_{ti} = A + B_t + Z_{ti} \qquad (19)$$

where x_{ti} is the observed value for the ith observation in the tth discrete group.

A is the weighted average of the group.

B_t deviations from A.

Z_{ti} random, normally distributed residual variable for the ith observation of the tth group.

This will be used to test the Null hypothesis that there is greater variation within the discrete groups than between them. If the Null hypothesis is rejected the second stage will be to relate the largest lichen diameters in each discrete group to its mean to give the time at which the substrate was uncovered.

All lichen discontinuities greater than 10 mm between the plotted mean data were taken as dividing lines and the number of occurrences in each group analyzed in detail. The results of the analysis are tabulated in table 3.

Table 3. *ANOVA results.*

Source of variation	Sum of squares	Degrees of freedom	Variance estimate
Between samples.......	480,342.0	10	48,034.20
Within samples........	225,082.0	4,410.0	51.04
Total.................	705,424.0	4,420.0	

As Snedecors 'F' ratio proved to be extremely significant, the Null hypothesis was rejected and the groups were taken to be independent estimates of differing populations for each amelioration period.

In order to put an upper boundary to these mean value continuous sections the distributions of one of the group were selected at random and its statistical parameters calculated.

Table 4. *Temperature fluctuations 1686 to 1948*

Periods of positive change from ANOVA	Godthåb record analysis	Type of change warm/cool
1923 +	1926–1935 +	warm
1876–1886 +.............	1876–1885 +	cool/warm
1718–1871 +.............		?
1686–1710 ?		warm

The largest lichen diameters were 1.78 standard deviations from the mean of the observed distribution. This confidence limit was calculated for all the independent groups, and their upper bounds considered to represent the beginning of the amelioration period. Equation 2 was applied to this upper limit and the diameters reduced to absolute dates with an error term. The application of the error term reduced the original eleven independent groups to five as in table 4.

TESTS OF CLIMATIC IMPLICATIONS

The above results, based upon the developments from the hypothetical model, can be tested on a local scale by comparing with known temperature trends directly, and indirectly by comparison with glacial fluctuation data.

Historical temperature records

From an analysis of the regression equations 17 and 18 for Ivigtut and Godthåb respectively the changes in mean annual temperature for the period 1880–1948 were computed and compared with that predicted from the model (equation 16) for Frederikshåb as shown in figure 7. Table 5 shows that despite all approximations and assumptions made the results are remarkably similar; further that the temperatures predicted for Frederikshåb by the ratio method all fall within the confidence limits for equation 16.

Table 5. *Temperature changes 1880 to 1948.*

Station	Temperature change (mean annual)°C
Godthåb	+ 2.46
Frederikshåb	+ 1.99 ± 0.33°
Ivigtut	+ 2.03°

As a result of the above temperature–time test model it is felt that the trends back to 1680 may be accepted but with caution, there being no reliable record for west Greenland before 1875 against which to test this model.

In order to test the predicted fluctuations it was necessary to analyse the Godthåb record in much greater detail than before. The method used by Liljequist (1943) for the reduction of the Stockholm temperature series to assess the severity of winters was applied to the decadal monthly means from 1875 to find periods of significant temperature change.

It was found that the major causes of this upward trend were significant increases in the January and December temperatures of 1906–

1925, followed in the period 1926–1935 by significant increases in all summer temperatures. A much smaller change took place at the beginning of the period 1876–1885. It is interesting to note that this recent climatic pattern has been observed over the whole northern hemisphere (Callender, 1961). However, for the purpose of testing the lichen record, the slight (though not significant) warming of 1876–1885, and the dramatic increase in 1926–1935 may be correlated with episodes shown in table 4.

Thus a quantitative comparison of the predicted trend and a qualitative comparison of the predicted fluctuations with local meteorological data does, as far as the tests are valid, substantiate the model predictions.

Historical glacial fluctuations

The historical trim line zone (Weidick, 1968) is very well marked throughout the northern Frederikshåb district. Consequently the deposits at the eastern end of Kangârssûp taserssua are taken to be representative of the area. In order to make direct comparisons with the model predictions the moraine system was dated using *Rhizocarpon geographicum* (Andrews & Webber, 1964) and a tentative history of glacier fluctuation constructed.

Before lichen dating the moraine system, a traverse $T - T'$ was made across the thrust moraine and dead ice zone to check for lichen growth on exposed erratics. The morphology of the area is shown in figure 9. No lichens were found and hence it was assumed that the lichen age of the moraine substrate is from the date of ice retreat.

The youngest moraine is a very small pressure ridge approximately 5–50 m from the present ice margin. The largest diameter thallus of 50 randomly selected samples gave a date of 48 years before 1968 i.e. 1920 ± 10 years. Locally this represents a thinning ΔS, of 5 m.

The higher moraine was dated from the largest thallus of 250 thalli randomly selected and gave a date 74 years before 1968 i.e. 1894 ± 10 years. This date was further checked by dendro-chronological analysis of two samples of *Salix glauca*. They gave counts of 40 and 35 annual rings respectively (not counting half rings and missing rings), thus indicating a minimum age of at least 40 years. From the studies of Beschel & Webb (1963) this might be indicative of a substrate twice this age. From altimetric evidence $\Delta S \approx 25$ m, the former ice margin varied from 100 m beyond its present position in Kangârssûp taserssua to approximately 1 km to the west of Avangnardleq. Throughout the area the variations appear to be of the same order.

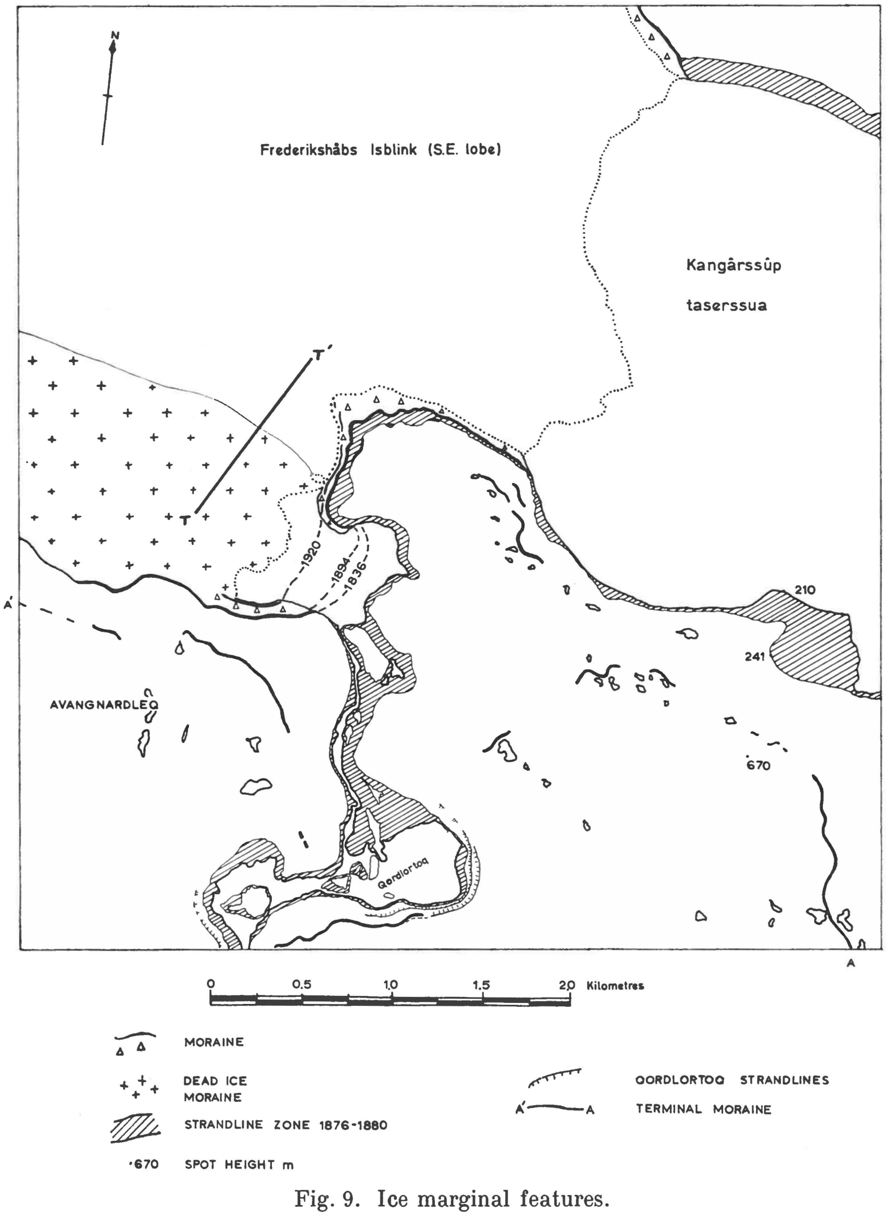

Fig. 9. Ice marginal features.

The upper, outer limit of the trim line zone has been dated from the largest of 50 thalli as 136 years before 1968 i.e. 1832 ± 20 years. It has $\Delta S \approx 30$ m and extends 20–100 m beyond the 1894 ice margin. There is no evidence for older historical ice advances beyond the 1832 trim line.

From the evidence of the LARS DALAGER 1751 expedition and JENSENS 1878 expedition (WEIDICK, 1959) there was possibly no net change in the ice margin. No mention is made of the extensively developed strandline around Kangârssûp taserssua. From lichen dates of the upper and lower limits of this strandline it appears that the lowering of the lake level occurred between 1876 and 1880. It is possible that this took place either by fluctuation of the ice barrier (THORARINSSON, 1939) or by pressure melting (GLEN, 1954).

The historical fluctuations can now be summarised:

1) Before 1751 there was a large advance (WEIDICK, 1959) that dammed Kangârssûp taserssua, both the date and nature of which are unknown.
2) After 1832 ± 20 years there was a retreat in the area, the extent of which is unknown.
3) Between 1832 ± 20 years and 1876 there was possibly widespread ablation. During this period, probably the latter part, the passage of a kinematic wave led to a stillstand or readvance of the Isblink reaching a climax in the 1880s.
4) After 1894 there was widespread ablation and the formation of of extensive dead-ice zones on the southern part of the Isblink in the region of the thrust moraines.
5) This widespread retreat was temporarily halted by a small advance in the 1920s.
6) After 1920 the retreat continued and, on some portions of the Isblink margin in the west, can be measured in tens of metres.

Figure 10 shows these phases and the temperature trend curve from the model.

The relationship of climatic change and glacial response can, in terms of the postulated changing perennial snow line, be explained as follows.

The advance before 1832 may be due to the very cold period in the late seventeenth century when the accumulation level was 822 m below the present level. The increase in height to the maximum of 1748 may be correlated with the retreat after 1832.

The very slight lowering of the level to the minimum of 1837 may have initiated the advance before 1894; it appears that the kinematic wave (NYE, 1960) must have been quite large not to have been affected by the increased ablation after 1850.

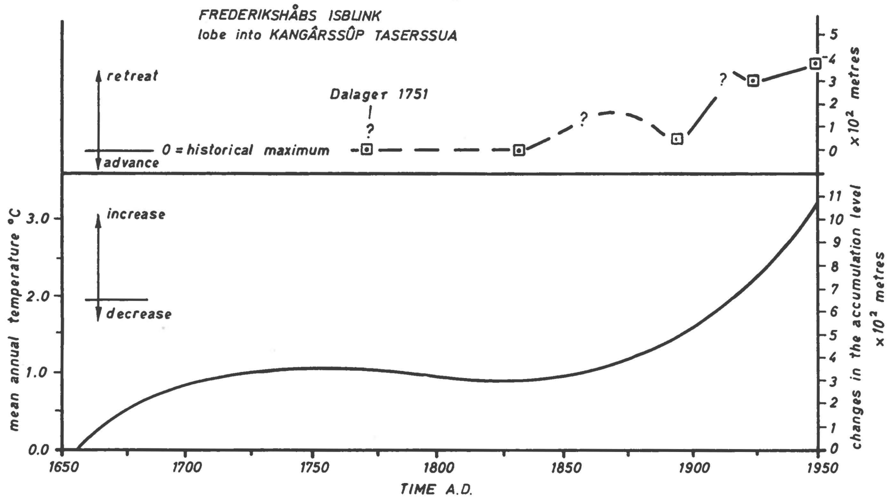

Fig. 10. Historical climatic and glacial variations 1650–1950.

After 1894 the retreat was probably due to the rapid increase in height of the perennial snow level and hence the equilibrium line and ablation, the small advance of the 1920s possibly being the result of the cool period of the early 1900s.

CONCLUSIONS

On the basis of the preceding discussion the temperature trends predicted by equation 16 are put forward as being representative of the recent climatic changes in the Frederikshåb district. From the various quantitative and qualitative tests applied and comparisons made, the predicted trend appears to be substantially correct within the testing period.

Smaller scale variations in lichen colonization, reflecting variation in snow patch size, appear to correlate with actual climatic variations recorded in the historic period. Earlier lichen records of snow patch variation are affected to a great extent by ecological factors, such as competition and growth conditions adjacent to snow patches, and are, consequently, not reliable.

It was shown that the model could be used to predict present and past perennial snow levels on the inland ice (equation 5, and table 2). Unfortunately no tests are available to check any forecasts made.

The assumptions that precipitation is constant in time and space leads to distortion of the temperature trends predicted, increased precipitation causing underestimates to be made, and decreases in precipitation causing overestimates. The slight temperature underestimation for the period 1880–1950 may be due to the time variation of precipitation shown by LAMB (1966), there having been a slight upward trend in precipitation since 1850 in the North Atlantic region.

Ideally the model should be tested in an area having long precipitation records to reduce the probability of error. In addition the reality of the assumptions could be tested by laboratory and field studies of lichen growth in snow patch microclimates.

ACKNOWLEDGEMENTS

The author wishes to thank the Director of Grønlands Geologiske Undersøgelse for permission to publish this report. I should also like to thank Dr. M. Kelly and Miss H. R. Storrow for invaluable suggestions and criticisms of the text, R. Brown for help and companionship in the field and The Danish Meteorological Institute for supplying the meteorological data. The outline map of fig. 1 is reproduced with permission (A. 649/72) of the Geodetic Institute, Denmark.

Department of Geology
University College
Gower Street
London WC1E 6BT
England

Revised manuscript received 21 June 1972

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Færdig fra trykkeriet den 10. august 1973.