Research Report 233

ACCUMULATION PATTERNS ON THE GREENLAND ICE SHEET

by
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JULY 1967

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

DA Task 1VO14501B52A02

PREFACE

This paper was prepared by S. J. Mock, geologist. It constitutes an interim report accomplished in conjunction with U. S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) research project, Surface Movement Studies on the Greenland Ice Sheet (Snow and Ice Branch, Research Division, James A. Bender, Chief).

The author would like to express his appreciation to the members of the Research Division of USA CRREL for providing many helpful criticisms. SP/4 Roger Doescher capably handled the tedious task of processing the data.

USA CRREL is an Army Materiel Command laboratory.

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SUMMARY

All available mean annual accumulation data on the Greenland ice sheet (excluding the Thule Peninsula) have been collected and analyzed using multiple regression techniques to develop equations capable of predicting mean annual accumulation. The analysis was carried out for north Greenland, south Greenland, and for the transition zone between the two major regions. The resulting equations show that mean annual accumulation can be predicted from the independent parameters, latitude, longitude and elevation.

The patterns of accumulation are shown in a series of isohyetal maps (contours of accumulation in terms of water). The major feature shown is a well defined asymmetry in accumulation; a pronounced east slope maximum in south Greenland and an equally pronounced west slope maximum in north Greenland. Poleward of 69°N, isohyets decrease in elevation to the north. Mean annual accumulation ranges from > 90 g/cm^2 in southeast Greenland to < 15 g/cm^2 in northeast Greenland.

A brief discussion of mass balance estimates of the Greenland ice sheet and of the relevance of this study to them is included.

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INTRODUCTION

The mean annual accumulation over the large ice sheets is a fundamental factor in determining their mass budgets. A knowledge of the distribution of mean annual accumulation, on an areal basis, is also of fundamental importance in ascertaining the climatic patterns affecting an ice sheet. Further, the gross form which an ice sheet assumes is, in part, governed by both the amount and distribution of mean annual accumulation. The present paper is an analysis of the distribution of mean annual accumulation over the Greenland ice sheet utilizing multiple regression techniques to develop trend surfaces of accumulation.

PREVIOUS WORK

Estimates of mean accumulation over the Greenland ice sheet were made by Loewe (1936) in an attempt to determine the mass budget. Since 1950 there has been a sufficiently large increase in the number of locations (sites of snow pit studies) where accumulation rates have been determined to allow the construction of isohyetal maps. These maps, beginning with Diamond (1960) and extending to Benson (1962) and Bader (1961), have increased in validity with the availability of new data. Large blank areas still exist, accounting for at least 20% of the ice sheet. These have been contoured on the basis of educated guesses.

In a previous paper, Mock and Weeks (1966) used multiple regression techniques to derive equations capable of predicting snow temperatures at 10-m depth (approximately the same as mean annual air temperature) on the Greenland ice sheet from the parameters latitude and elevation. Essentially the same techniques have now been used to construct trend surfaces of accumulation.

METHOD OF ANALYSIS

It is assumed that the mean annual accumulation, in g/cm^2 of snow (1 g/cm^2 = 1 cm of water), at any site can be characterized by an equation of the form

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \ldots\ldots b_n X_n$$

where Y is the predicted mean annual accumulation, X_1, X_2, ..., X_n are independent or powers of independent variables and the b's are multiple regression coefficients. In normal trend surface analysis X_1 and X_2 are usually map or grid coordinates and the remaining X's quadratic or higher order powers of X_1 and X_2. Ordinarily no causal relationship is implied between Y and the X's, although this is dependent upon the particular X's chosen.

In the present study several models were used in the initial stages of analysis in an attempt to approximate functional relationships, but limited success and difficulty in interpretation led finally to the decision to confine the study to predictor type models only. The independent variables were simply the spatial coordinates of the particular point, i.e., latitude, longitude and elevation, and the initial model a second degree equation in these three variables.

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_1^2 + b_5 X_2^2 + b_6 X_3^2 + 2b_7 X_1 X_2 + 2b_8 X_1 X_3 + 2b_9 X_2 X_3$$

where X_1 = latitude in degrees and hundredths

X_2 = longitude in degrees and hundredths

X_3 = elevation in meters.

The data were processed on a digital computer using a multiple regression program prepared for this study (Mock, 1966). The following were calculated:

$\overline{X}_i$	mean of each X variable
$\overline{Y}$	mean of Y
$\sigma_{\bar{x}_i}$	standard deviation of each X variable
$\sigma_{\bar{y}}$	standard deviation of Y variable
r	matrix of simple correlation coefficients
b_{simp}	simple regression coefficients
R	multiple correlation coefficient
b_0	multiple regression intercept
b_i	multiple regression coefficients
S	standard error of estimate
F	F value
S_{b_i}	standard error of b_i
t_{b_i}	t value for each b_i.

The results were then examined critically and further work done according to the following criteria:

1. F values, used to test the null hypothesis that all the true multiple regression coefficients were equal to zero, had to be sufficiently large to allow rejection of the null hypothesis at the 1% significance level.

2. t values, used to test the null hypothesis that an individual regression coefficient was equal to zero, had to be sufficiently large to allow rejection of the null hypothesis at the 5% significance level.

If criterion 1 had not been met, the model would have been discarded, an event which did not occur. Where criterion 2 was not met, a second program was used which deleted those variables whose associated coefficients were rejected and recalculated the various multiple regression statistics on the basis of the reduced data array. The process was continued until the model was completely acceptable.

DATA

The data consisted of some 127 stations where accumulation has been determined by stratigraphic techniques in pits (Koch and Wegener, 1930; Langway, 1961; Lister, 1961; Benson, 1962; Ragle and Davis, 1962). As shown in Figure 1, the distribution of data points is far from uniform. No attempts were made to correct for skewness in the distribution of the data. The data were taken directly from the compendium tabulated by Mock and Weeks (1966) without critical review. Certain aspects of this body of data should be kept in mind when considering the results of this study:

1. The majority of this work was done in the period from 1952 onward but a significant portion (35 stations) dates from 1912 (Koch and Wegener, 1930).

2. The mean annual accumulation is based on the number of years penetrated in a pit study. This may range from 10 years to only a single year, thus some values may be very poor representatives of the mean.

3. Since the time span of the studies is large, temporal changes in accumulation rates may have occurred.

4. In certain areas, particularly those with high accumulation, the possibility of error in stratigraphic interpretation is rather high.

For these reasons, if no other, the results must be viewed as indications of regional trends rather than as exact predictions.

REGIONAL ASPECTS

The Greenland ice sheet can be divided into two rather distinct regions based on topography, temperature and accumulation. Topographically the ice sheet divides into two domes – a higher, broader and larger northern dome separated from the smaller southern dome by a broad saddle centered at approximately 66°N latitude. The northern dome is considerably colder, receives less accumulation and would be considered relatively inactive in comparison with the southern dome.

The transition zone dividing the two domes happens also to be an area with a paucity of data. Thus the decision to analyze the two domes separately on the basis of physical and environmental characteristics was further encouraged by the distribution of data. In order to study the transition zone itself it has been necessary to use data from both north and south Greenland. A final study was then made for the entire body of data covering all Greenland. The areal breakdown is shown in Figure 1.

The Thule Peninsula has not been included within the present study as a report of detailed investigations in that area is in press (Mock, in press).

RESULTS

The results in the form of predictor equations for each area are shown in Table I along with pertinent statistical information.

North Greenland

Two equations are shown in Table I for north Greenland. Equation 1 includes the data from the Koch and Wegener expedition of 1912 (Koch and

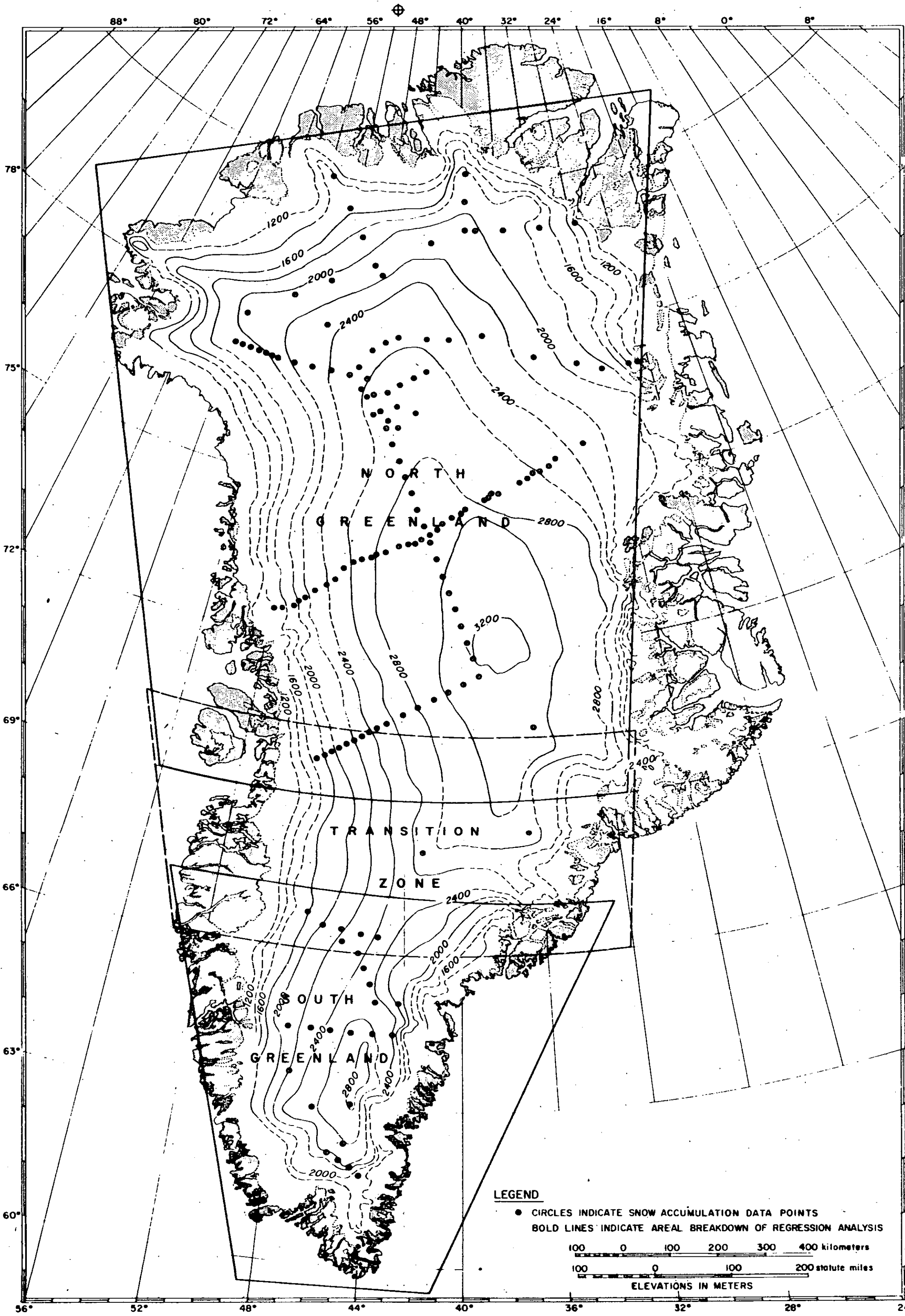

Figure 1. Geographic zones and location of data stations used in analysis.

Table I. Regression equations of Y_p (mean annual accumulation, g/cm^2) versus X_1 (latitude, degrees and hundredths), X_2 (longitude, degrees and hundredths), and X_3 (elevation, meters).

Area	Model	Equation	Mult Corr Coef R	$\underline{F}$	Stand Err of EST S
North Greenland	(1)	$Y_p = -497.57 + 12.566317\,X_2 + 0.33867771\,X_3 + 0.074529118\,X_1^2 - 1.515708\times10^{-5}\,X_3^2 - 0.153967222\,X_1X_2 - 0.0036881834\,X_1X_3$	.907	87.88	5.87
	(2)	$Y_p = -3480.17 + 65.819\,X_1 + 36.290\,X_2 + 0.341326\,X_3 - 0.28029\,X_1^2 - 0.04107\,X_2^2 - 0.40165\,X_1X_2 - 4.55656\times10^{-3}\,X_1X_3 - 3.74029\times10^{-4}\,X_2X_3$	.987	354.4	2.36
South Greenland	(3)	$Y_p = -21688.02 + 4.05496\times10^2\,X_1 + 4.18657\times10^2\,X_2 - 1.90657\,X_1^2 - 2.155708\,X_2^2 - 3.69714\,X_1X_2 - 13.9924742\times10^{-4}\,X_1X_3$	.902	14.6	10.31
Transition Zone	(4)	$Y_p = 14358.6 - 473.38772\,X_1 + 98.250275\,X_2 + 3.5329395\,X_1^2 - 1.2868113\,X_2^2 - 1.79500378\times10^{-5}\,X_1X_3$	.853	16.1	9.50

Wegener, 1930), while equation 2 is the result without these data. On the basis of the statistical tests shown, it is tempting to discard equation 1 completely. Koch and Wegener's data, however, are the result of very meticulous studies of snow stratification observed in pits, essentially the same techniques generally used today, and their interpretation of the observed profiles seems valid. While deep pit studies (Bader et al., 1955; Mock, in preparation) show no significant changes in accumulation between the 1905-12 period and the post-1952 period at 77°N latitude it is possible that what is shown does represent a change in accumulation rate.

Figure 2 shows contours of accumulation predicted by equation 1. Immediately obvious is the pronounced west slope accumulation maximum and the equally pronounced northeast slope minimum of accumulation. This suggests that the waters to the west of Greenland, Baffin Bay and Melville Bay, are the chief sources of moisture for north Greenland. Major storm tracks extend up the west coast of Greenland through Davis Strait and Baffin Bay and cyclonic disturbances frequently cross the ice sheet in north Greenland (Hamilton, 1958). Curvature of isohyets southeastwards may indicate that waters lying southeast of Greenland are a secondary source of moisture.

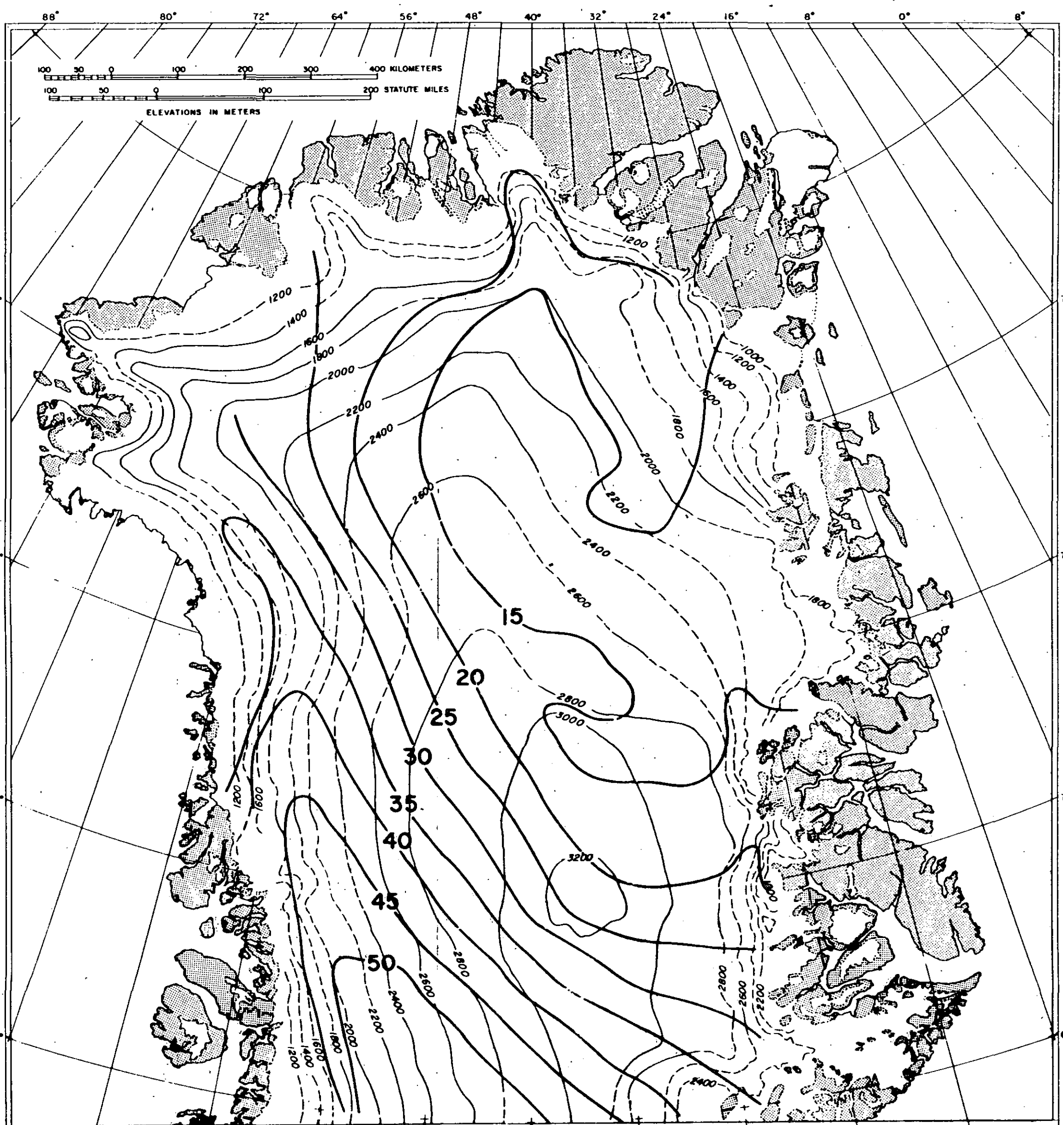

Figure 2. Isohyetal map of north Greenland. Bold contours in g cm^{-2} of snow.

Figure 2 also shows the well developed zone of maximum accumulation on the west slope, and its decline with elevation towards the north.

South Greenland

Figure 3 shows isohyets for south Greenland predicted by equation 3. In contrast to north Greenland, a pronounced east coast accumulation maximum is indicated with a general decrease in accumulation to the west. The high values on the east and south coasts can be attributed to circulation around the semi-permanent Iceland low but the pronounced low accumulation area on the west coast seems somewhat anomalous, particularly when contrasted with the higher accumulation at similar altitudes further north.

It should be pointed out that a far larger range of observed accumulation occurs within a smaller area in south Greenland than in north Greenland. In addition warmer temperatures and high accumulation make the possibility of interpretive error in pit studies more likely. The high value of the standard error for equation 3 reflects the variability of accumulation.

Transition zone

Isohyets for the transition zone are shown in Figure 4. A greater degree of symmetry is shown here than in the regions to the north and south, although an east coast maximum still exists. The beginning of the change-over to a west coast maximum is visible. The multiple correlation coefficient R of equation 4 shows that the model is not as successful as a predictor for this area as for the preceding regions.

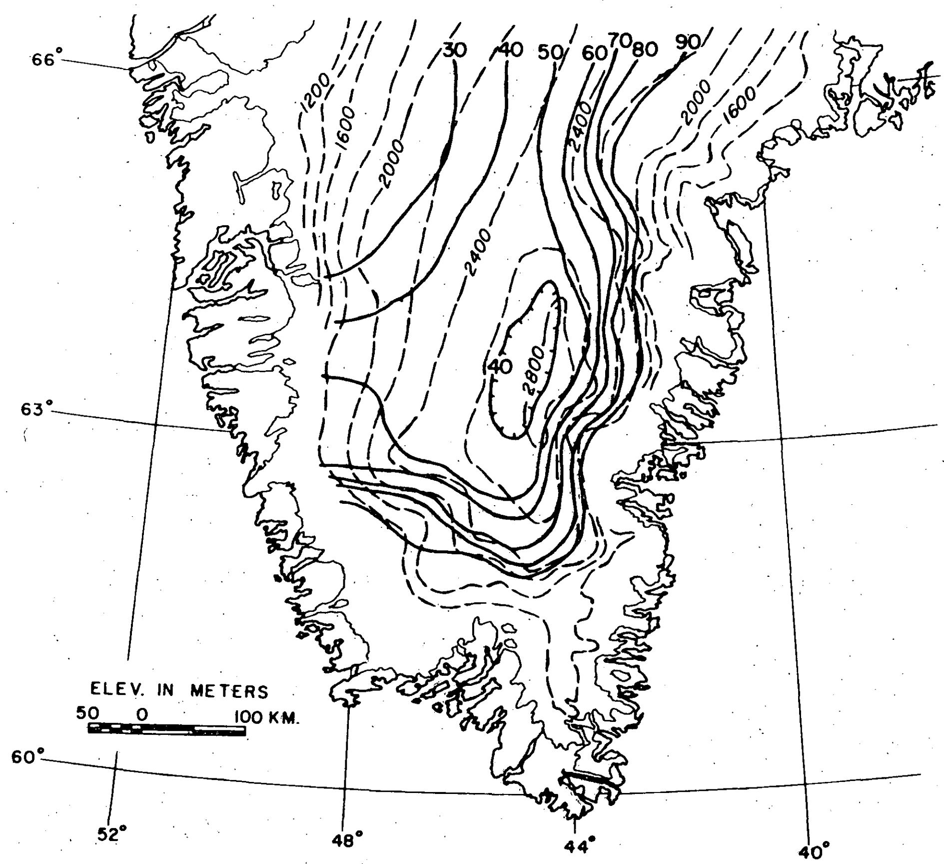

Figure 3. Isohyetal map of south Greenland. Bold contours in g cm^{-2} of snow.

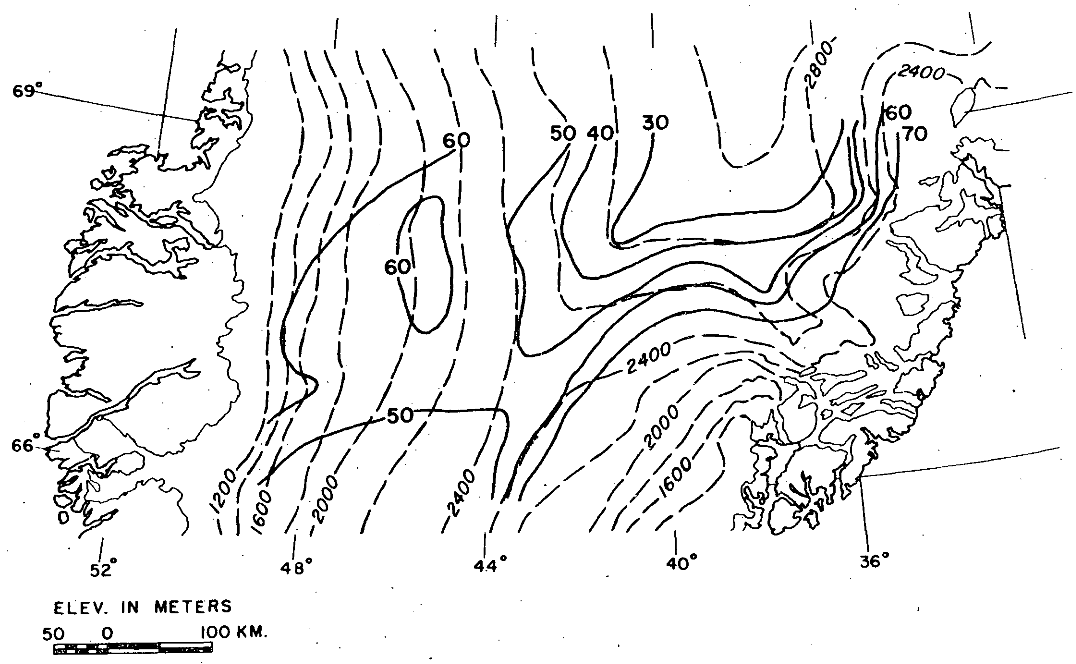

Figure 4. Isohyetal map of transition zone. Bold contours in g cm^{-2} of snow.

DISCUSSION

Figure 5 shows isohyets for all Greenland derived by combining the results of the three separate areas. In combining, isohyets were smoothed and changed somewhat to bring about a smooth transition between regions. The resultant map shows clearly the asymmetric nature of the accumulation pattern. It seems quite evident that this asymmetry is a product of the shape of the ice sheet, of the circulatory pattern existing in this region, and of the distribution of available moisture source areas.

One of the major questions yet to be satisfactorily answered is whether the mass budget of the Greenland ice sheet is presently in balance. Several authors (Loewe, 1936; Bauer, 1955; Benson, 1962; and Bader, 1961) have estimated the mass balance by the traditional method of equating input (snow accumulation) against output (melt in the ablation zone and iceberg calving). The results have ranged from Bauer's moderately negative budget to Bader's strongly positive assessment. The present study enables a more reliable estimate of the input term to be made, but of course adds nothing to our knowledge of the output terms. For Greenland there are very little data on which to base estimates of calving and melt, hence the range of mass balance estimates.

Shumskii (1965) and Bauer (1966) have used a different approach based on surface strain rates. Their calculations indicate that strongly negative conditions prevail in central Greenland.

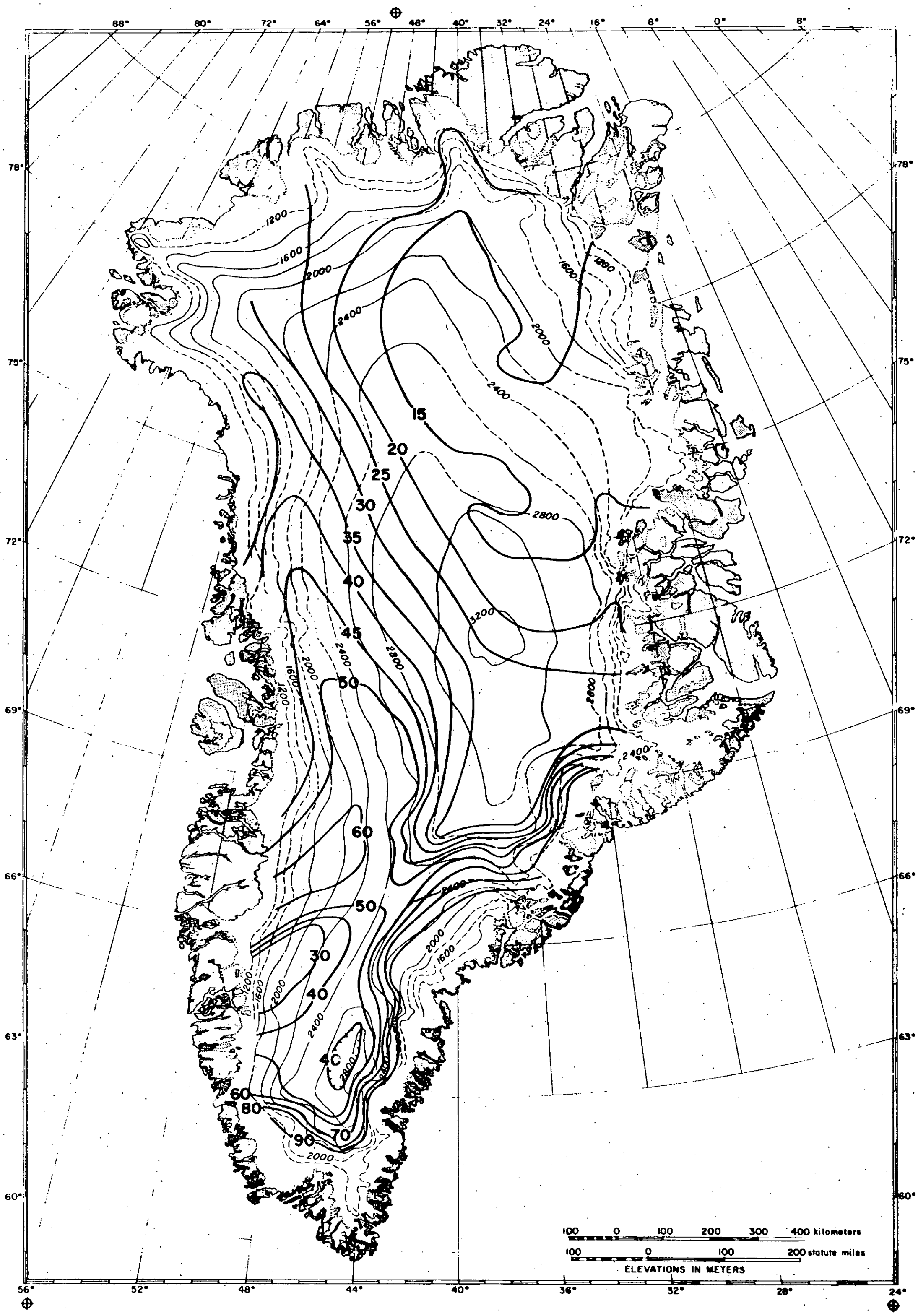

Figure 5. Isohyetal map of Greenland. Bold contours in g cm^{-2} of snow.

It appears that the use of strain and movement measurements provides a more promising approach to mass balance determinations, due largely to the difficulties in assessing the calving and melt factors. This study does nothing to remedy the problem; thus the temptation to add still another value has been resisted.

CONCLUSIONS

Mean annual accumulation at a point can be predicted with a fair degree of accuracy from the parameters latitude, longitude and elevation. Trend surfaces calculated from prediction equations indicate the regional accumulation patterns prevailing on the Greenland ice sheet. The ice sheet shows two major zones of high accumulation – the southern dome below 67°N latitude and the west slope of the ice sheet north to 77°N latitude. These zones are ultimately related to cyclonic storm tracks and the presence of moisture source areas along the storm tracks.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

ACCUMULATION PATTERNS ON THE GREENLAND ICE SHEET

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Research Report

5. AUTHOR(S) (First name, middle initial, last name)

Steven J. Mock

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1967	15	16

8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. DA Task 1VO14501B52A02 d.	9a. ORIGINATOR'S REPORT NUMBER(S) Research Report 233 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.

13. ABSTRACT

All available mean annual accumulation data on the Greenland ice sheet (excluding the Thule Peninsula) have been collected and analyzed using multiple regression techniques to develop equations capable of predicting mean annual accumulation. The analysis was carried out for north Greenland, south Greenland, and for the transition zone between the two major regions. The resulting equations show that mean annual accumulation can be predicted from the independent parameters, latitude, longitude, and elevation. The patterns of accumulation are shown in a series of isohyetal maps (contours of accumulation in terms of water). The major feature shown is a well defined asymmetry in accumulation; a pronounced east slope maximum in south Greenland and an equally pronounced west slope maximum in north Greenland. Poleward of 69°N, isohyets decrease in elevation to the north. Mean annual accumulation ranges from > 90 g/cm^2 in southeast Greenland to < 15 g/cm^2 in northeast Greenland. A brief discussion of mass balance estimates of the Greenland ice sheet and of the relevance of this study to them is included.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Glaciers--Mass balance--Greenland Snow cover--Distribution--Greenland Glaciers--Growth--Mathematical analysis Snow cover--Mapping Models (Glacier)						