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CHARACTERISTICS OF MAGNETIC DISTURBANCE AT THE CANADIAN ARCTIC OBSERVATORIES

Part I: Cyclic Field Changes on Quiet and Disturbed Days
Part II: Transient Field Changes

BY

K. WHITHAM AND E. I. LOOMER

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CONTENTS

PART I—CYCLIC FIELD CHANGES ON QUIET AND DISTURBED DAYS

Illustrations and Tables

PART II—TRANSIENT FIELD CHANGES

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Characteristics of Magnetic Disturbance at the Canadian Arctic Observatories

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PART I: CYCLIC FIELD CHANGES ON QUIET AND DISTURBED DAYS

ABSTRACT

A selection has been made of three classes of days at Resolute Bay* (geomagnetic latitude = 83°N) and Baker Lake (geomagnetic latitude = 73.7°N) corresponding to "local disturbed", "local quiet", and "local very quiet" conditions at a time of sunspot minimum. The disturbance daily variation has been harmonically analysed, and the statistical properties of the cyclic disturbance waves examined.

Well inside the polar cap, it has been demonstrated that the form of the disturbance field remains substantially constant independent of the intensity of disturbance and the season, and can be well represented by 24-hour waves only. The 12-hour waves are only very partially persistent and higher harmonic waves are random. The results from Resolute Bay are in excellent agreement with a simple atmospheric dynamo model, but modifications of the theory lead to contradictions, and the plausibility of the model is thus in doubt.

In the transitional region to the north of the auroral zone, diurnal disturbance is much more complex and variable, changing form as the disturbance increases. The persistent properties of the waves are discussed in connection with a number of theories of auroral zone magnetic disturbance, and it is shown that none of these theories satisfactorily explain the observations.

INTRODUCTION

The quiet day solar daily variation and the disturbance daily variation in moderate and low latitudes have been widely analysed and the findings discussed in detail by Chapman and Bartels (1940, Chs. 6, 7, 9, 23). Until recently the observational material available from polar regions has been very limited and it has been only partially discussed. The Dominion Observatory has operated two magnetic observatories in the Canadian Arctic since 1948. One of these is situated at Resolute Bay, Cornwallis Island (latitude 74.7° N, longitude 265.1° E) and the other at Baker Lake, Northwest Territories (latitude 64.3° N, longitude 264.0° E). The geomagnetic coordinates of these observatories are $\Phi = 83.0°$ N, $\Lambda = 289.0°$ E and $\Phi = 73.7°$ N, $\Lambda = 315.3°$ E respectively, assuming 78.5° N, 291° E for the position of the north geomagnetic pole. Resolute Bay observatory is thus well situated for the study of magnetic phenomena found within the geomagnetic polar cap, and so far as is known to the authors, it is the only permanent observatory besides Thule in continuous operation well inside the auroral zone. Magnetic disturbance at Baker Lake is representative of disturbance found in the transitional region to the north of the auroral zone. Again permanent observatories in these latitudes are few in number: Calm Bay (Tikhaya) magnetic observatory located in Franz Joseph Land at geomagnetic latitude 71.5° N should be comparable.

An analysis of the outstanding features of magnetic disturbance at Resolute Bay and Baker Lake observatories is described in this paper. Part I refers to cyclic field changes on quiet and disturbed days whereas in Part II the transient storm disturbances are discussed. The statistical techniques used have been largely those tried for low and

*A recent decision by the Canadian Board on Geographical Names has assigned the single name 'Resolute' to this location.

moderate latitude stations with certain modifications and additions. Wherever possible the results obtained have been compared with the predictions of different theories: however, with two stations only this is often an ambiguous process. A similar analysis for a denser network of Arctic observatories would be more valuable and such a treatment may become possible after the IGY. However, the results discussed in these two papers are of great value to any comprehensive discussions of magnetic disturbance because of the position of the observatories.

THE SELECTION OF DAYS

Continuous photographic registration of three magnetic elements has been carried out at Baker Lake since 1950 but at Resolute Bay since mid-October 1953 only. In order to use records in three components for the same period of time at both observatories, days were selected from the period November 1953 to March 1955. At the time these investigations began, data were not available beyond March 1955. The number of months in each of the solstitial and equinoctial periods is different, but this is thought to be unimportant since the period is almost centred about the sunspot minimum of April 1954. The results obtained should be representative of sunspot minimum: the amplitudes of the cyclic changes found are probably only about 70 per cent of the mean for a complete sunspot cycle.

The method in current use for the selection of the international magnetically quiet and disturbed days in each month has been described by Bartels and Veldkamp (1955). Although the incidence of disturbance is world wide the relative intensity is not uniformly distributed. Consequently it seemed more reasonable to use the measured K indices for the two stations to select local quiet and local disturbed days, rather than the internationally selected days based on twelve observatories between geographic latitudes 47° and 63°. The working criterion adopted was the sum of K, and limits were set so that on the average throughout the interval approximately five days per month were disturbed and five quiet. However, in order to examine the data seasonally it was necessary to change the limits for the winter months at Resolute Bay corresponding to the decrease in the average K sum during the winter months.

Table I shows the relative number of days selected in each season for the observatories: at Resolute Bay the criterion of a disturbed day is approximately $\Sigma K \geq \overline{\Sigma K}_{AV} + 5$ and for a quiet day is $\Sigma K \leq \overline{\Sigma K}_{AV} - 5$. At Baker Lake the same K limits were chosen as for Resolute Bay, although the seasonal change of disturbance intensity is different at the two stations. As measured by the average sum of K in the three seasons, the summer is most disturbed in the polar cap whereas equinoctial peaks are found at Baker Lake as at middle and low latitudes. Winter is always least disturbed. The data in Table I also indicate that in the most disturbed season the average level of disturbance increases at the two stations, rather than the intensity of disturbance during the greatly disturbed days.

Some tests were made using the sum of K squared criterion for selecting days: during the winter 1953-54 fewer than one in eight days would be changed had this been adopted. This criterion modifies the selection of quiet days a little more than the selection of disturbed days. For the purpose of selection, it seems sufficient therefore to employ the sum of K test.

LLOYD'S SEASON	N° of MONTHS	$\overline{\Sigma K}$ ALL DAYS	N° of DISTURBED DAYS	$\overline{\Sigma K}$	N° of QUIET DAYS	$\overline{\Sigma K}$	N° of VERY QUIET DAYS	$\overline{\Sigma K}$
RESOLUTE BAY								
SUMMER	4	20.3	15 $\Sigma K \geq 25$	26.5	12 $\Sigma K \leq 15$	13.5	0 (No K>1)	
EQUINOX	5	19.7	21 $\Sigma K \geq 25$	26.8	25 $\Sigma K < 15$	11.0	3	
WINTER	8	14.3	43 $\Sigma K > 20$	24.9	68 $\Sigma K \leq 10$	7.2	12	
TOTAL	17	17.3	79	25.7	105	8.8	15	3.1
BAKER LAKE								
SUMMER	4	19.2	21 $\Sigma K > 25$	26.8	26 $\Sigma K \leq 15$	12.3	0 (Not more than 2 K's >2)	
EQUINOX	5	22.4	61 $\Sigma K > 25$	28.4	21 $\Sigma K < 15$	11.4	3	
WINTER	8	18.5	93 $\Sigma K \geq 20$	26.2	21 $\Sigma K \leq 10$	5.6	14	
TOTAL	17	19.8	175	27.0	68	10.0	17	4.3

TABLE I. Table of selected days at Resolute Bay and Baker Lake from November 1953 to March 1955.

A further selection of very quiet days was made from the selected quiet days: at Resolute Bay the criterion was that no K>1 during a very quiet day. Fifteen such days were found at Resolute Bay, twelve of which occurred during the least disturbed winter months and three during equinoctial periods. At Baker Lake only three days satisfying this criterion were found, and to increase the number of days, the criterion was relaxed to allow days with two K values equal to 2: seventeen days were found.

	Nº IN OUR SELECTION	MAX Nº WHICH COULD OCCUR IN 5 INT'L DAYS	Nº WHICH DO OCCUR	AGREEMENT RATIO	MAX Nº WHICH COULD OCCUR IN 10 INT'L DAYS	Nº WHICH DO OCCUR	AGREEMENT RATIO
	RESOLUTE BAY						
QUIET	71	34	29	0.85	52	47	0.90
DISTURBED	58	40	32	0.80			
TOTAL	129	74	61	0.82	92	79	0.86
	BAKER LAKE						
QUIET	49	35	25	0.72	47	38	0.81
DISTURBED	121	53	48	0.91			
TOTAL	170	88	73	0.83	100	86	0.86

TABLE II. Comparison of selected days at Resolute Bay and Baker Lake with international quiet and disturbed days, 1954.

It is informative to compare this selection of days with the internationally selected days, although a simple comparison is not possible. Table II shows the results. At both stations more than 80 per cent of the days selected which could be international days were in fact so. At Resolute Bay not one of the disturbed days selected is listed as an international quiet day (5 or 10 per month) and vice versa. At Baker Lake one of the quiet days is listed as an international disturbed day, and four of the disturbed days are listed as quiet days (10 per month). This suggests that in future comprehensive programs, it may be sufficient in the analysis of Arctic data to examine the days recommended internationally. This conclusion is supported from a comparison of the very quiet days with the very quiet intervals given by Bartels and Veldkamp (1955). One day only at Resolute Bay was selected at a time not common to lower latitude observatories; this day was not selected at Baker Lake.

HARMONIC ANALYSIS OF SELECTED DAYS

Methods

The material for the analysis of daily variation consisted of 24-h mean values in three components, X, Y, Z at Resolute Bay and H, D, Z at Baker Lake. These mean values were plotted on graph paper with suitable abscissa (400 mm. ≡24 hrs) and ordinate scales (1 mm. ≡1 gamma on quiet days, and 1 mm. ≡2 gammas on disturbed days). The hourly means are centred on the hour; twenty-five points are shown for each Greenwich day, the first being the mean of the first hourly value for the day and the last hourly value of the previous day, and similarly at the end of the day. The curves were analysed on a Coradi Harmonic Analyser, and in general 4 sets of harmonic coefficients (a_1, b_1, ... a_4, b_4) determined for each day.

Scaling, drawing, tracking and instrumental errors influence the coefficients. Drawing errors do not exceed about $\frac{1}{2}$ mm. with the scales adopted and experiments with the analyser showed that results were reproducible using average care to an accuracy of about $1\frac{1}{2}$ mm. in 100 mm. amplitudes, and the absolute scale error of the machine was less than 0.5 per cent. It was concluded that errors in the coefficients determined by the machine, i.e. in a_1, b_1, $2a_2$, ... $4b_4$ do not exceed 2 per cent of large amplitudes or 2 mm., whichever is larger. Scaling errors are difficult to estimate, but are unlikely to produce systematic errors, unless e.g. the scale constants of the magnetograms are in error. It seems reasonable to assume from the observatory records that this source of error cannot exceed 5 per cent, and probably doesn't exceed 3 per cent. In practice this means that the uncertainties in the determination of na_n, nb_n do not exceed 5 per cent, or 2 gammas, whichever is larger. The accidental errors in any means are of course much smaller.

Non-cyclic corrections were applied; this procedure seemed best on quiet days in view of the existence of the post-perturbation effect which can be approximated by a linear function. It is however, arguable whether a non-cyclic correction is best applied to the results on disturbed days, since there seems little doubt that the disturbance daily variation (S_D) at times of definite storm commencement is best described as a disturbance local time inequality (D_S) and changes amplitude regularly during the development and decay of the storm (Chapman, 1952). However, the analysis on disturbed days generally corresponds to the determination of the solar daily variation during weak magnetic

disturbance where no storm-time can be assigned, and the average cyclic conception has meaning. Consequently non-cyclic corrections were applied to all the results, after the machine analysis using the form

$$n \Delta b_n = \frac{d_{24} - d_0}{\pi}$$

where d_{24} = value in magnetic element of 25th point on graph;

d_0 = value in magnetic element of 1st point on graph;

and nb_n (corrected) = nb_n (measured) + $n\Delta b_n$.

RESOLUTE BAY

HARMONIC		1							2							3							4						
DISTURBED DAYS		N	C γ	ε L.T. hrs	S_a^2 γ²	S_b^2 γ²	r	θ	R	C γ	ε L.T. hrs.	S_a^2 γ²	S_b^2 γ²	r	θ	R	C γ	ε L.T. hrs.	S_a^2 γ²	S_b^2 γ²	r	θ	R	C γ	ε L.T. hrs.	S_a^2 γ²	S_b^2 γ²	r	θ	R
SUMMER	-X	15	52·8	14·2	436	360	0·22	19·9	1·3	10·9	1·7	136	227	0·10	8·3	1·3														
	-Y	15	77·0	19·7	225	325	0·00	23·7	1·1	2·1	7·2	296	419	0·17	7·9	1·3	3·2	5·7	175	141	0·17	2·1	1·2	4·6	2·7	92	150	0·07	1·1	1·3
	Z	15	27·8	3·7	144	420	-0·39	0·2	3·6	3·4	2·8	208	264	0·74	7·4	1·6														
EQUINOX	-X	21	83·0	13·9	192	560	0·07	23·4	1·7	5·4	2·7	115	117	-0·35	10·2	1·4	4·4	5·0	100	156	-0·27	4·3	1·4	3·3	5·9	125	93	-0·03	2·6	1·2
	-Y	21	73·5	20·0	300	450	0·27	21·9	1·4	9·0	6·4	150	119	-0·05	11·3	1·1	3·0	6·7	161	144	0·30	2·6	1·4	3·8	2·2	77	84	-0·08	0·2	1·0
	Z	21	18·3	6·0	112	588	-0·37	0·4	2·7	10·6	1·1	77	138	0·00	8·7	1·3	2·7	4·2	72	120	0·05	3·5	1·1	2·6	2·6	42	63	-0·17	1·5	1·3
WINTER	-X	42	50·4	13·5	100	292	0·01	23·7	1·3	4·8	10·5	111	150	-0·14	9·4	1·2														
	-Y	43	61·5	19·7	400	525	0·38	21·4	1·5	8·0	1·2	250	212	0·30	6·9	1·3	2·3	6·0	119	175	0·33	4·4	2·7	0·1	1·9	144	56	0·04	5·7	1·6
	Z	42	24·0	5·3	256	264	0·12	21·0	1·1	1·3	8·6	96	104	0·12	7·5	1·1														
QUIET DAYS																														
SUMMER	-X	12	39·9	14·2	91	159	-0·30	1·3	1·6	6·8	0·9	31	78	0·72	7·8	2·8														
	-Y	12	41·6	19·8	34	152	-0·35	0·2	2·3	7·2	3·7	89	75	0·39	6·0	1·5	4·3	6·2	32	44	-0·52	2·5	1·2	2·8	1·2	14	40	0·65	2·3	2·5
	Z	12	6·9	2·7	179	328	-0·33	1·2	1·6	4·4	4·0	139	65	0·14	6·0	2·0														
EQUINOX	-X	25	30·3	13·8	132	246	0·48	1·6	1·8	2·6	9·7	74	54	0·22	10·8	1·3	4·2	5·8	55	30	0·10	5·5	1·4	2·7	5·8	15	19	0·06	1·0	1·1
	-Y	24	30·8	19·2	180	101	0·46	19·6	1·8	2·4	1·7	30	71	-0·07	8·8	1·6	0·9	7·8	28	29	0·00	5·6	1·0	2·5	1·2	26	13	-0·05	2·3	1·4
	Z	25	14·2	2·6	153	99	-0·22	4·2	1·4	3·7	4·7	39	45	0·06	8·0	1·1	0·5	3·1	14	26	0·14	3·4	1·4	0·9	2·4	11	11	0·18	0·6	1·2
WINTER	-X	67	17·5	13·3	26	93	-0·37	0·6	2·4	2·8	10·1	22	30	0·24	7·7	2·4														
	-Y	68	15·8	19·2	63	39	0·38	19·6	1·4	3·8	1·5	24	18	-0·24	7·7	1·3	0·6	6·8	8	10	0·18	3·0	1·2	0·3	3·2	7	9	0·22	0·6	1·3
	Z	67	5·8	6·2	19	37	-0·15	0·5	1·4	0·2	11·7	13	15	0·12	8·1	1·2														
ALL DISTURBED DAYS	-X	78	59·4	13·8	283	499	-0·20	0·8	1·4	2·7	0·6	119	173	-0·16	9·4	1·3														
	-Y	79	67·8	19·9	354	509	0·35	21·6	1·5	1·9	2·3	269	242	0·29	7·0	1·3	2·5	6·2	141	161	-0·13	4·4	1·2	2·1	2·4	119	82	0·01	5·8	1·2
	Z	78	21·3	5·0	203	601	-0·14	0·2	1·4	2·8	1·1	125	156	0·36	7·5	1·5														
ALL QUIET DAYS	-X	104	23·2	13·6	95	167	-0·57	1·8	1·8	2·6	10·6	37	45	0·17	7·7	1·2														
	-Y	104	22·2	19·3	149	93	0·52	19·9	1·9	3·6	2·0	36	39	-0·06	9·6	1·1	1·0	6·7	17	19	-0·04	4·6	1·1	0·7	1·5	13	16	0·18	0·7	1·2
	Z	104	7·2	4·3	74	107	-0·29	1·6	1·4	1·3	4·4	36	29	0·04	6·1	1·1														
ALL VERY QUIET DAYS	-X	14	9·1	12·7	3	26	-0·45	0·4	12·2	2·1	9·9	13	52	0·38	8·1	5·3														
	-Y	15	8·5	19·1	11	22	0·06	23·4	1·4	2·7	1·8	37	17	0·00	0·0	1·5	0·6	5·7	32	33	-0·18	4·7	1·3	0·0	5·4	20	29	0·04	1·1	1·2
	Z	15	2·6	6·4	10	21	-0·21	0·6	1·6	1·3	3·3	18	28	-0·09	9·1	1·2														

BAKER LAKE

HARMONIC		1							2							3							4						
DISTURBED DAYS	H, Z D	N	C γ mins	ε L.T. hrs.	S_a^2 γ² mins²	S_b^2 γ² mins²	r	θ	R	C γ mins	ε L.T. hrs	S_a^2 γ² mins²	S_b^2 γ² mins²	r	θ	R	C γ mins	ε L.T. hrs	S_a^2 γ² mins²	S_b^2 γ² mins²	r	θ	R	C γ mins	ε L.T. hrs	S_a^2 γ² mins²	S_b^2 γ² mins²	r	θ	R
SUMMER	D	21	51·0	9·4	36	188	0·02	23·6	2·3	22·0	4·4	174	159	0·13	6·8	1·1	11·8	0·4	90	128	0·54	2·8	1·9	4·0	1·9	113	99	-0·36	1·9	1·5
	H	21	15·6	20·4	224	424	-0·16	0·5	1·4	40·9	3·5	237	129	0·46	6·5	1·8	16·0	6·4	161	234	0·24	3·0	1·4	4·0	0·4	90	165	-0·43	1·6	1·7
	Z	21	85·4	4·8	576	672	0·42	21·0	1·6	14·7	10·6	740	540	0·10	6·1	1·2	20·6	6·7	394	358	-0·07	4·6	1·1	9·3	0·4	137	442	0·24	0·8	1·9
EQUINOX	D	61	59·6	9·3	532	328	0·24	19·1	1·4	9·8	4·4	253	165	0·15	6·2	1·3	2·8	3·0	104	117	-0·08	4·2	1·1	4·9	2·4	88	118	-0·02	1·2	1·2
	H	59	20·5	21·1	456	1316	0·06	23·4	1·7	28·5	3·3	485	544	-0·14	9·7	1·2	7·0	5·6	206	361	0·09	3·4	1·3	3·6	1·0	288	307	-0·18	1·8	1·2
	Z	61	10·2	4·2	688	752	0·06	21·8	1·1	21·3	10·0	715	527	-0·03	10·8	1·3	12·0	0·2	433	420	0·04	2·4	1·0	2·9	0·8	189	176	-0·02	2·4	1·1
WINTER	D	89	33·6	9·4	164	280	0·60	21·4	2·1	11·9	5·8	105	129	0·18	7·6	1·2	2·4	4·5	84	76	0·00	3·6	1·1	3·2	2·6	68	42	-0·18	2·3	1·4
	H	91	21·8	19·2	432	720	0·24	22·2	1·4	32·4	3·0	325	419	0·16	7·8	1·2	6·7	5·0	305	360	0·24	2·9	1·3	4·5	0·9	165	258	-0·03	1·2	1·3
	Z	91	75·6	4·6	1036	772	-0·13	4·2	1·2	12·0	8·9	359	623	-0·05	8·8	1·3	6·1	0·0	285	337	0·17	2·9	1·2	4·0	0·7	188	240	0·10	0·8	1·2
QUIET DAYS																														
SUMMER	D	25	24·2	8·5	47	72	-0·14	0·7	1·3	9·5	5·3	41	51	0·05	7·9	1·2	5·7	0·2	45	29	-0·09	5·1	1·3	2·3	1·7	12	23	-0·14	1·3	1·4
	H	21	27·8	20·3	61	97	0·38	21·7	1·6	23·9	3·3	81	80	-0·54	10·1	1·8	2·8	6·2	51	26	-0·05	5·5	1·4	3·8	4·9	20	29	-0·15	1·4	1·3
	Z	25	37·3	5·2	173	246	0·07	22·9	1·2	8·4	1·9	173	124	0·53	6·8	1·4	14·2	6·4	115	45	0·24	1·9	1·7	3·2	0·6	39	68	-0·03	1·2	1·3
EQUINOX	D	21	16·1	8·9	20	60	0·29	22·7	1·9	6·0	4·9	24	21	-0·04	10·9	1·1	1·8	0·0	21	15	0·24	2·3	1·3	5·1	2·7	12	18	0·06	1·0	1·2
	H	21	18·0	20·1	102	223	0·71	21·6	2·7	24·3	3·3	106	142	-0·65	9·6	2·2	8·6	6·3	116	48	0·06	2·1	1·9	4·6	1·2	19	50	-0·09	1·2	1·6
	Z	21	37·0	4·8	351	143	0·26	18·6	1·7	5·3	11·6	85	323	0·03	8·5	2·0	3·2	5·4	81	84	-0·15	4·5	1·2	5·5	1·6	68	55	0·19	0·1	1·3
WINTER	D	21	3·4	7·7	8	11	0·64	21·1	2·2	5·5	6·1	5	9	-0·39	9·5	1·7	1·4	1·7	1	3	-0·23	3·9	1·7	1·5	2·8	1	2	0·01	1·1	1·4
	H	21	13·2	18·3	23	33	0·25	21·8	1·3	10·4	3·3	8	37	-0·17	8·8	2·1	1·9	6·3	6	13	0·15	3·4	1·5	1·0	4·3	8	5	-0·28	2·2	1·5
	Z	21	14·3	4·1	51	44	-0·21	5·1	1·3	4·3	2·4	14	19	0·35	7·5	1·7	3·5	6·8	9	7	0·33	2·3	1·1	1·8	1·8	9	8	-0·23	1·9	1·3
ALL DISTURBED DAYS	D	171	45·0	9·3	335	378	0·49	20·8	1·7	11·7	5·1	175	168	0·11	6·9	1·1	0·8	4·4	100	112	-0·04	2·0	1·1	3·8	2·5	82	77	0·13	0·2	1·2
	H	171	20·2	20·0	428	903	0·12	23·0	1·1	32·0	3·2	382	436	0·03	8·2	1·1	7·1	5·5	258	361	0·22	3·0	1·3	4·0	0·8	199	264	-0·13	0·0	1·2
	Z	173	85·6	4·4	975	822	-0·11	21·9	1·2	14·6	9·6	563	586	-0·09	6·9	1·1	8·8	7·8	388	380	0·11	2·5	1·1	4·1	0·6	211	217	0·09	0·4	1·1
ALL QUIET DAYS	D	67	15·2	8·6	64	87	0·51	21·2	1·8	6·9	5·4	28	31	-0·01	5·9	1·1	2·9	0·4	25	23	-0·12	2·8	1·1	2·6	2·5	12	16	0·05	1·0	1·2
	H	63	19·4	19·9	73	167	0·63	21·7	2·4	19·9	3·2	68	131	-0·56	6·6	2·1	5·2	6·3	64	31	0·30	2·0	1·6	1·3	1·9	19	37	0·03	1·1	1·4
	Z	67	29·3	4·9	307	152	0·12	18·2	1·4	5·1	1·4	99	165	0·23	7·9	1·4	7·2	6·4	89	57	0·24	2·1	1·4	3·0	1·3	42	47	0·03	0·9	1·1
ALL VERY QUIET DAYS	D	17	3·4	7·0	7	6	0·10	19·3	1·1	5·5	6·6	4	3	-0·32	10·5	1·4	1·4	1·7	1	2	0·20	3·2	1·4	1·8	3·2	1	1	-0·46	2·2	1·9
	H	17	13·5	18·7	22	21	0·35	8·4	1·4	9·3	10·7	6	4	-0·92	10·2	5·2	1·6	6·1	6	8	0·14	2·0	1·3	1·0	5·6	4	3	-0·08	2·3	1·2
	Z	17	10·4	4·3	24	17	-0·31	1·5	1·4	3·9	2·9	11	13	0·21	7·5	1·3	3·1	6·6	10	14	-0·09	4·0	1·2	1·7	1·7	4	5	0·09	0·8	1·2

TABLE III. Geometrical properties of the clouds of points for four harmonics and three selected classes of days at Resolute Bay and Baker Lake observatories.

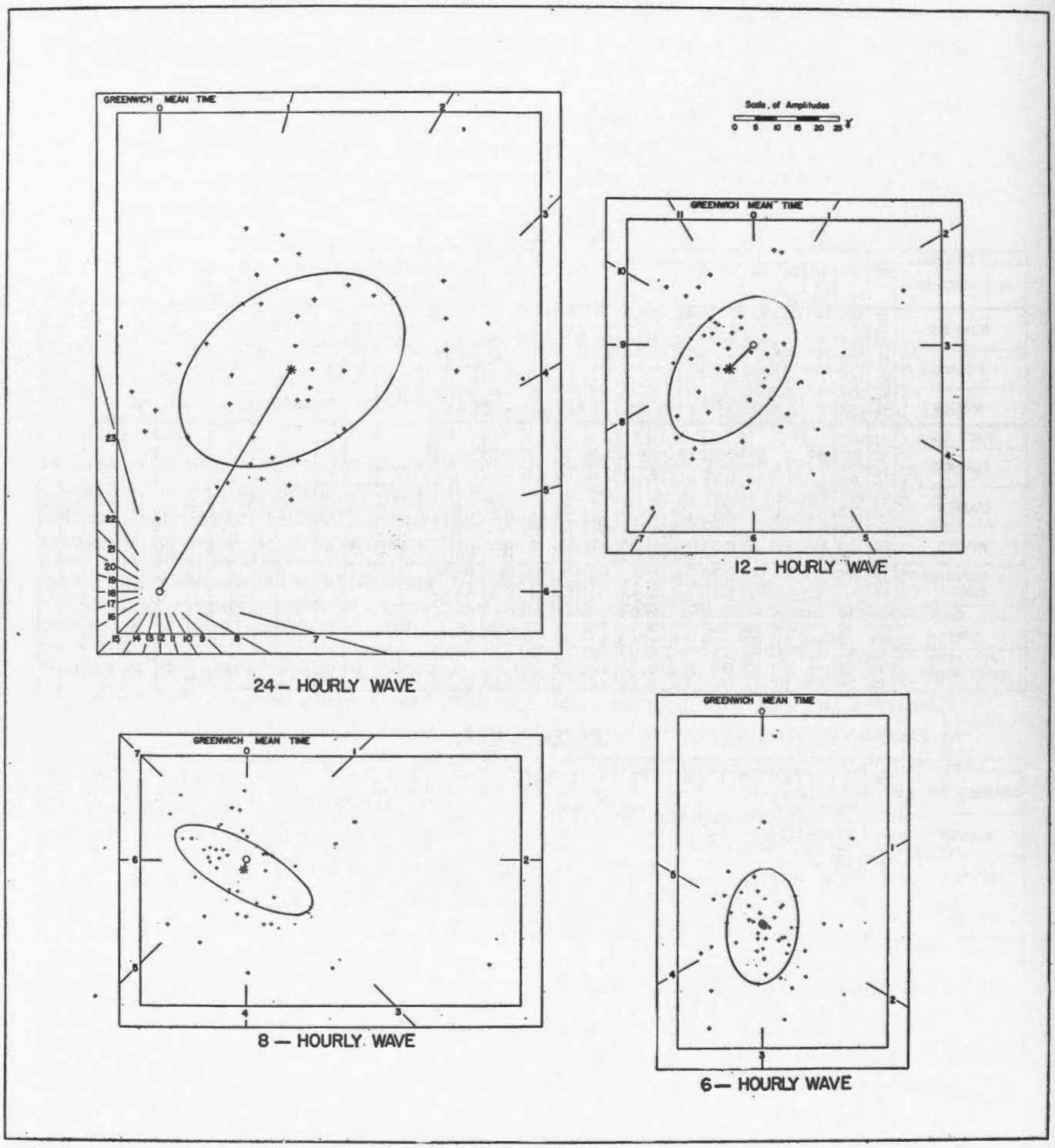


FIGURE 1. Harmonic dials for the 24-h, 12-h, 8-h, and 6-h waves in the diurnal variation of —Y at Resolute Bay, N.W.T. The 43 points refer to 43 disturbed days in the winters 1953-1955. The vector from the origin to the star on the dial indicates the amplitude and G.M.T. of the maximum of the sine wave. The average vectors and probable error ellipses are drawn.

The smoothing corrections were not applied since in the first and second harmonics they do not sensibly affect the results; in the fourth harmonic the correction is still less than 5 per cent.

Results for Resolute Bay and Baker Lake

Following Bartels (1935), harmonic dials for 24-h, 12-h, 8-h, and 6-h periods were constructed in which each point may be conceived as the end point of a clock hand which indicates the time of wave maximum and whose length indicates the amplitude of the wave. Analysis of the variability of the harmonics becomes an analysis of the geometrical properties of the clouds of points. Dials were constructed for each magnetic component in each season for quiet and disturbed days, and for all quiet, disturbed and very quiet days. Figure 1 is typical of the results for Resolute Bay showing the mean amplitudes and the probable error ellipses, and Table III is a summary of the results for both stations. Defining the variance as the quotient of the sum of the squares of the deviations from the average divided by the number in the sample, Table III shows the mean amplitude C, mean phase ϵ, the variance S_a^2, S_b^2 of the Fourier cosine and sine coefficients a and b, the coefficient of correlation r between a and b for the sample of N and the axis ratio R. The major and minor axes of the ellipse are equal to 0.83 S_1 and 0.83 S_2 respectively where S_1^2, S_2^2 are the variances found when the first coordinate axis lies along the major axis of the probable error ellipse, and the second coordinate axis along the minor.

Table IV shows the amplitude, phase and standard deviation of any sample. The expected amplitude for the average of N vectors having the same N amplitudes as the observed vectors but with phases random is equal to $\frac{1}{\sqrt{N}}$ times the expectancy $\sqrt{\left\{\frac{\Sigma_N(a^2 + b^2)}{N}\right\}}$ i.e. to $\sqrt{\left\{\frac{C^2 + M^2}{N}\right\}}$ where M is the standard deviation in the amplitude ($M^2 = S_a^2 + S_b^2$). The probability that the average vector C is K times as large as this expected amplitude is e^{-K^2} where $C = K\sqrt{\left\{\frac{C^2 + M^2}{N}\right\}}$ i.e. $K^2 = \frac{NC^2}{C^2 + M^2}$.
Thus assuming that the points for the selected days are independent, the probability that the mean amplitude C is accidental is e^{-K^2}. A small value for this probability shows that the directions of the N individual vectors are not random, but does not prove the presence of a purely periodic persistent wave in the data because quasi-persistent effects on successive days are known to exist in the solar variation, and this results in a serious reduction of the effective number of independent points in any dial. To examine the influence of quasi-persistence the data for Y west (—Y) at Resolute Bay in the winter solstice were examined, and the expectancies $E_h = \sqrt{\frac{C^2 + M^2}{N}}$ computed for the averages of h = 1, 2, 4, 8, 16, 32 and 64 successive vectors. The results are shown in curves of Figure 2. Quasi-persistence would be indicated by the ordinate increasing linearly with h for small h and becoming constant at large h; random waves by a constant ordinate value of unity and complete persistence by a slope of 45°. The curves obtained show that the third and fourth harmonic waves are random, whereas the first harmonic is noticeably persistent and the second harmonic semi-persistent. No striking evidence for quasi-persistence is obtained, and so the effective expectancy to be used in calculating probabilities in a dial should be $\frac{N}{\alpha}$ where α is a small number. The test described above together with the fact

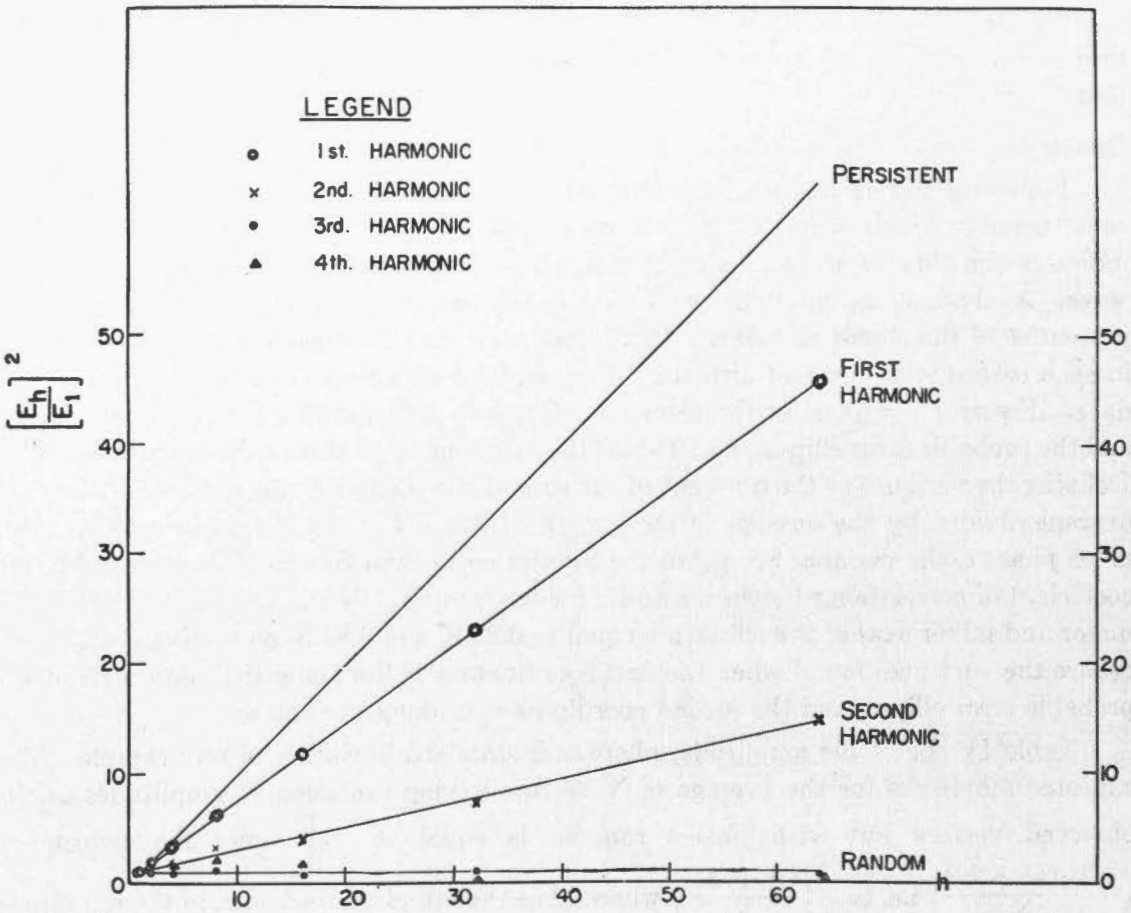


FIGURE 2. Persistence curves for —Y at Resolute Bay, N.W.T. on quiet days in the winters 1953-1955.

that quasi-persistence must be less important for the data where the number of selected days in any season is small suggests that if $\alpha = 2$ is adopted, no serious errors should arise. The column in Table IV showing $P_1 = e^{\frac{-C^2N}{(2C^2+M^2)}}$ should then be an over estimate, if anything, of the probability that the mean amplitude found was produced by accidental superposition of random waves. Table IV also shows the standard deviation in the mean amplitude calculated on the basis of N/2 independent points. This is $\pm\ \delta S = \pm \frac{M}{\sqrt{N/2}}$ where $M^2 = S_1^2 + S_2^2 = S_a^2 + S_b^2$. The standard deviation in the mean phase δ_ϵ is calculated using the concept of phase variance of the points of the cloud; the phase variance s^2 is defined $s^2 = \frac{1}{C^4}\left\{\bar{a}^2 S_b^2 + \bar{b}^2 S_a^2\right\}$ which result can be obtained by differentiation. Then by analogy $\delta\epsilon = s \Big/ \sqrt{\frac{N}{2}}$.

In Table IV a probability P_2 computed from the ellipticity statistic L_e, discussed by Mauchly (1940), is given. L_e is defined as $\frac{2R}{1+R^2}$ where R is the axis ratio of the probable error ellipse. The parameter L_e is used to discuss whether the cloud is significantly elliptical or not. $P_2(L_e)$ is the probability that an ellipticity statistic as small or smaller

RESOLUTE BAY

HARMONIC		1							2							3							4						
DISTURBED DAYS		C γ	±δC γ	M γ	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ	±δC γ	M γ	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ	±δC γ	M γ	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ	±δC γ	M γ	P_1	ε LT. hrs.	±δε hrs.	P_2
SUMMER	-X	52·8	10·3	28·2	3×10^{-5}	14·2	0·6	0·85	10·9	7·0	19·0	0·16	1·7		0·97														
	-Y	7·0	8·6	23·5	1×10^{-5}	19·7	0·3	0·99	2·1	9·8	26·7	0·96	7·2		0·97	3·2	6·6	17 9	0·80	5·7		0·90	4·6	5·7	15·5	0·55	2·7		0·65
	Z	27·8	14 5	39·6	0·08	3·7	1·7	0·03	3·4	8·0	21·7	0·83	2·8		0·56														
EQUINOX	-X	83·0	8·5	27·4	1×10^{-4}	13·9	0·3	0·33	5·4	4·7	15·2	0·30	2·7		0·59	4·4	5·0	16·1	0·78	5·0		0·59	3·3	4·6	14·8	0·61	5·9		0·64
	-Y	73·5	8·5	27·5	1×10^{-4}	20·0	0·3	0·61	9·0	5·1	16·5	0·09	6·4		0·98	3·0	5·4	17 5	0·74	6·7		0·59	3·8	4·0	12·8	0·44	2·2		0·98
	Z	18·3	8·2	26·6	0·03	6·0	1·6	0·02	10·6	4·6	14·7	0·03	1·1	0·6	0·78	2·7	4·2	13·7	0·68	4·2		0·98	2·6	3·2	10·3	0·52	2·6		0·78
WINTER	-X	50·4	4·3	19·8	2×10^{-4}	13·5	0·1	0·57	4·8	3·7	16·2	0·18	10·5	1·0	0·68														
	-Y	61·5	6·6	30·5	3×10^{-6}	19·7	0·3	0·23	8·0	4·9	21·5	0·07	1·2	0·7	0·56	2·3	3·9	17·2	0·70	6·0		2×10^{-4}	0·1	3·2	14·1	1·00	1·9		0·13
	Z	24·0	5·0	22·8	2×10^{-3}	5·3	0·6	0·95	1·3	3·2	14·1	0·84	8·6		0·94														
QUIET DAYS																													
SUMMER	-X	39·9	6·4	15·8	5×10^{-5}	14·2	0·4	0·66	6·8	4·3	10·5	0·17	0·9		0·16														
	-Y	41·6	6·8	16·6	5×10^{-5}	19·8	0·4	0·28	7·2	5·2	12·8	0·25	3·7		0·75	4·3	3·6	8.7	0·33	6·2		0·92	2·8	4·8	11·8	0·41	1·2		0·23
	Z	6·9	9·1	22·3	0·59	2·7	3·7	0·66	4·4	5·8	14·2	0·59	4·0		0·41														
EQUINOX	-X	30·3	5·5	19·4	1×10^{-4}	13·8	0·4	0·19	2·6	3·2	11·3	0·53	9·7		0·73	4·2	3·6	9·2	0·11	5·8		0·52	2·7	1·6	5·8	0·12	5·8		0·97
	-Y	30·8	4·7	16·8	1×10^{-4}	19·2	0·4	0·19	2·4	2·8	10·0	0·51	1·7		0·33	0·9	2·2	7·6	0·82	7·8		1·00	2·5	1·8	6·2	0·20	1·2		0·52
	Z	14·2	4·6	15·9	3×10^{-3}	2·6	0·8	0·56	3·7	2·6	9·2	0·17	4 7	1·0	0·97	0·5	1·8	6·3	0·93	3·1		0·52	0·9	1·3	4·7	0·61	2·4		0·81
WINTER	-X	17·5	1·9	10·9	3×10^{-11}	13·3	0·3	2×10^{-5}	2·8	1·2	7,2	0·01	10·1	0·6	2×10^{-5}														
	-Y	15·8	1·7	10·1	3×10^{-11}	19 2	0·3	0·16	3·8	1·1	6·5	2×10^{-6}	1·5	0·4	0·38	0·6	0·7	4·3	0·51	6·8		0·53	0·3	0·6	3·7	0·80	3·2		0·38
	Z	5·8	1·3	7·5	3×10^{-6}	6·2	0·7	0·16	0·2	0·9	5·1	0·95	11·7		0·53														
ALL DISTURBED DAYS	-X	59·4	4,5	28·0	1×10^{-14}	13·8	0·2	0·12	2·7	2·7	17·1	0·40	0·6	1·5	0·31														
	-Y	67·8	4·7	29·5	1×10^{-14}	19·9	0·2	0·06	1·9	3·6	22·6	0·75	2·3	2·5	0·20	2·5	2·8	17,4	0·46	6·2	1·0	0·64	2·1	2·3	14·2	0·42	2·4	0·7	0·55
	Z	21·3	4·5	28·4	1×10^{-6}	5·0	0·7	0·12	2·8	2·3	16·5	0·35	1·1	1·4	0·06														
ALL QUIET DAYS	-X	23·2	2·2	16·0	1×10^{-15}	13·6	0·2	2×10^{-5}	2·6	1·3	9·1	0·02	10·6	0·7	0·39														
	-Y	22·2	2·2	15·9	1×10^{-15}	19·3	0·2	8×10^{-5}	3·6	1·2	8·6	5×10^{-5}	2·0	0·4	0·82	1·0	0·8	6·0	0·25	6·7	0·8	0·82	0·7	0·8	5·1	0·37	1·5	0·7	0·39
	Z	7·2	1·9	13·4	1×10^{-15}	4·3	0·8	6×10^{-2}	1·3	1·1	8·0	0·28	4·4	1·2	0·55														
ALL VERY QUIET DAYS	-X	9·1	2·0	5·4	5×10^{-3}	12·7	0·3	1×10^{-4}	2·1	1·5	4·0	0·22	9·9	0·9	7×10^{-3}														
	-Y	8·5	2·1	5·7	5×10^{-3}	19·1	0·7	0·71	2·7	1·4	3·7	0·07	1·8	0·7	0·63	0·6	1·0	2·7	0,70	5·7	1·6	0·89	0·0	0·7	1·8	1·00	5·4	1·6	0·89
	Z	2·6	2·0	5·6	0·27	6·4	2·3	0·17	1·3	1·2	3·4	0·38	3·3	1·2	0·89														

BAKER LAKE

HARMONIC		1							2							3							4						
DISTURBED DAYS. H,Z	D	C γ mins	±δC γ mins	M γ mins	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ mins	±δC γ mins	M γ mins	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ mins	±δC γ mins	M γ mins	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ mins	±δC γ mins	M γ mins	P_1	ε LT. hrs.	±δε hrs.	P_2
SUMMER	D	51·0	4·6	15·0	8×10^{-5}	9·4	0·2	0·07	22·0	5·6	18·2	2×10^{-3}	4·4	0·3	0·97	11·8	4·5	14·7	0·02	0·4	0·3	0·20	4·0	4·5	14·6	0·48	1·9	0·8	0·51
	H	15·6	7·8	25·4	0·06	20·4	1·4	0·62	40·9	5·9	19·1	2×10^{-4}	3·5	0·2	0·25	16·0	6·1	19·9	0·02	6·4	0·4	0·62	4·0	4·9	16·0	0·55	0·1	0·9	0·32
	Z	85·4	11	35·4	1×10^{-4}	4·8	0·4	0·41	14·7	11·	35·8	0·22	10·6	1·1	0·87	20·6	8·6	27·8	0·02	6·7	0·3	0·97	9·3	7·4	24·1	0·25	0·4	0·6	0·20
EQUINOX	D	59·6	5·3	29·4	1×10^{-6}	9·3	0·3	0·21	9·8	3·7	20·4	3×10^{-3}	4·4	0·5	0·38	2·8	2·7	14·9	0·35	3·0	0·9	0·90	4·9	2·6	14·4	0·04	2·4	0·4	0·63
	H	20·5	7·7	42·0	3×10^{-3}	21·1	0·9	0·03	28·5	5·9	32·1	2×10^{-6}	3·3	0·3	0·64	7·0	4·4	23·8	0·09	5 6	0·7	0·40	3·6	4·5	24·4	0·55	1·0	0·3	0·64
	Z	102	6·9	38·0	1×10^{-12}	4·2	0·2	0·90	21·3	6·4	35·2	3×10^{-4}	10·0	0·4	0·38	12·0	5·3	29·2	0·01	0·2	0·4	0·97	2·9	3·5	19·1	0·52	0·8	0·8	0·90
WINTER	D	33·6	3·1	21·0	1×10^{-10}	9·4	0·2	2×10^{-3}	11,9	2·3	15·3	3×10^{-6}	5·8	0·3	0·50	2·4	1·9	12·7	0·20	4·5	0·7	0·85	3·2	1·6	10·5	0·02	2·6	0·3	0·10
	H	21·8	5·0	34·0	1×10^{-6}	19·2	0·7	0·09	32·4	4·0	27·3	1×10^{-12}	3·0	0·2	0·50	6·7	3·9	26·2	0·06	5·0	0·5	0·23	4·5	3·0	20·5	0·12	0·9	0·4	0·23
	Z	75,6	6·3	42·6	1×10^{-15}	4·6	0·2	0·60	12·0	4·6	31·4	3×10^{-3}	8·9	0·5	0·23	6·1	3·7	24·9	0·07	0·0	0·6	0·50	4·0	3·1	20·7	0·20	0·7	0·5	0·50
QUIET DAYS																													
SUMMER	D	24·2	3·1	10·9	3×10^{-5}	8·5	0·3	0·70	9·5	2·7	9·6	2×10^{-3}	5·3	0·4	0·88	5·7	2·4	8·6	0·02	0·2	0·4	0.76	2·3	1·7	5·9	0·20	1·7	0·5	0·52
	H	27·8	3·9	12·6	3×10^{-5}	20·3	0·4	0·42	23·9	3·9	12·7	5×10^{-5}	3·3	0·2	0·22	2·8	2·7	8·8	0·30	6,2	0·5	0.63	3·8	2·2	7·1	0·07	4·9	0·3	0·79
	Z	37·3	5·8	20·5	7×10^{-5}	5·2	0·4	0·81	8·4	4·9	17·2	0·09	1·9	0·8	0·60	14·2	3·6	12·6	9×10^{-4}	6·4	0·2	0·25	3·2	2·9	10·4	0·33	0·6	0·6	0·68
EQUINOX	D	16·1	2·7	8·9	5×10^{-4}	8·9	0·4	0·18	6·0	2·1	6·7	0·01	4·9	0·5	0·98	1·8	1·9	6·0	0·44	0·0	1·0	0·71	5·1	1·7	5·5	7×10^{-3}	2·7	0·2	0·84
	H	18·0	5·6	18·0	5×10^{-3}	20·1	0·9	0·03	24·3	4·9	15·8	6×10^{-4}	3·3	0·3	0·09	8·6	4·0	12·8	0·04	6·3	0·4	0·20	4·6	2·6	8·3	0·08	1·2	0·3	0·37
	Z	37·0	6·8	22·2	5×10^{-4}	4·8	0·4	0·33	5·3	6·2	20·2	0·51	11·6	2·1	0·17	3·2	4·0	12·9	0·55	5·4	1·1	0·93	5·5	3·4	11·1	0·13	1·6	0·4	0·83
WINTER	D	3·4	1·4	4·4	0·02	7·7	1·1	0·10	5·5	1·1	3·7	1×10^{-3}	6·1	0·3	0·34	1·4	0·7	2·1	0·03	1·7	0·5	0·34	1·5	0·6	1·8	0·02	2·8	0·3	0·61
	H	13·2	2·3	7·5	5×10^{-4}	18·3	0·5	0·70	10·4	2·1	6·7	6×10^{-4}	3·3	0·2	0·11	1·9	1·4	4·4	0·18	6·3	1·0	0·54	1·0	1·1	3·5	0·45	4·3	0·7	0·50
	Z	14·3	3·0	9·8	1×10^{-3}	4·1	0·6	0·80	4·3	1·8	5·8	0·03	2·4	0·5	0·32	3·5	1·2	4·0	0·01	6·8	0·3	0·93	1·8	1·3	4·1	0·20	1·8	0·5	0·77
ALL DISTURBED DAYS	D	45·0	2·9	26·7	3×10^{-20}	9·3	0·2	1×10^{-5}	11·7	2·0	18·5	2×10^{-11}	5·1	0·2	0·72	0·8	1·6	14·5	0·67	4·4	1·8	0·78	3·8	1·4	12·6	1×10^{-3}	2·5	0·2	0·56
	H	20·2	3·9	36·5	2×10^{-19}	20·0	0·5	0·78	32·0	3·1	28·6	2×10^{-21}	3·2	0·4	0·78	7·1	2·7	25·1	2×10^{-3}	5·5	0·4	0·05	4·0	2·3	21·5	0·06	0·8	0·4	0·24
	Z	85·6	4·6	42·5	7×10^{-31}	4·4	0·1	0·56	14·6	3·7	33·9	1×10^{-6}	9·6	0·3	0·72	8·8	3·0	27·7	4×10^{-4}	7·8	0·3	0·72	4·1	2·2	20·7	0·04	0·6	0·4	0·72
ALL QUIET DAYS	D	15·2	2·1	12·2	1×10^{-19}	8·6	0·4	4×10^{-3}	6·9	1·3	7·7	3×10^{-7}	5·4	1·5	0·94	2·9	1·2	6·8	6×10^{-3}	0·4	0·4	0·88	2·6	0·9	5·3	2×10^{-3}	2·5	0·3	0·58
	H	19·4	2·5	13·9	4×10^{-10}	19·9	0·4	5×10^{-3}	19·9	2·5	14·1	8×10^{-10}	3·2	0·2	9×10^{-4}	5·2	1·4	9·7	9×10^{-4}	6·3	0·3	0·04	1·3	1·3	7·5	0·15	1·9	0·4	0·20
	Z	29·3	3·7	21·7	4×10^{-10}	4·9	0·3	0·13	5·1	2·8	16·3	0·05	1·4	0·7	0·15	7·2	2·1	12·1	2×10^{-4}	6.4	0·3	0·18	3·0	1·6	9·4	0·05	1·3	0·4	0·91
ALL VERY QUIET DAYS	D	3·4	1·3	3·7	4×10^{-4}	7·0	0·6	0·98	5·5	0·8	2·6	1×10^{-3}	6,6	0·2	0·67	1·4	0·6	1·5	0·02	1·7	0·3	0·71	1·8	0·4	1·3	4×10^{-3}	3·2	0·1	0·27
	H	13·5	2·3	6·5	1×10^{-3}	18·7	0·3	0·67	9·3	1·1	3·3	5×10^{-3}	10·7	0·1	2×10^{-3}	1·6	1·3	3·7	0·26	6·1	0·5	0·84	1·0	1·0	2·7	0·36	5·6	0·4	0·93
	Z	10·4	2·3	6·4	2×10^{-3}	4·3	0·4	0·66	3·9	1·7	5·0	0·04	2·9	0·4	0·86	3·1	1·7	4 8	0·08	6·6	0·3	0·90	1·7	1·0	3·0	0·13	1·7	0·3	0·90

TABLE IV. Statistical properties of the harmonic waves for four harmonics and three selected classes of days at Resolute Bay and Baker Lake observatories.

than the value found for the cloud might be obtained in a random sample of N/2 points drawn from a circular population. $P_2 = L_e^{(N/2-2)}$ after Mauchly (1940).

Discussion of Seasonal Results for Resolute Bay

Using the probabilities P_1 it is apparent that whereas the 24-h waves in the horizontal components are very persistent, the Z wave is much more variable and in the summer on quiet days cannot be well described as a persistent wave. This is not a result of the number of quiet days in the summer season being small. The 12-h waves are very ill

defined by comparison with the 24-h waves, and the higher harmonics completely random. For this reason it was considered worthwhile completing the analysis in 4 harmonics for the Y component only at Resolute Bay. In Figure 1 probable error ellipses are shown, but the values P_2 in Table IV show that with the exception of the winter quiet day data in the X component only, the clouds are not significantly elliptical. This trend is true for both the 24- and 12-h waves, and so in general the direction θ shown for the major axis is not significant: there is also little evidence for real correlation between a and b in the sets.

Table V summarises the seasonal trends at Resolute Bay: no statistically significant differences appear in the phases of the waves for the quiet and disturbed days in all seasons, and no very significant shifts occur seasonally in phase. There is a suggestion that the average phase of the horizontal component waves is advanced from summer to winter by one half hour. The greater variability in Z and the correspondingly larger uncertainties mask any real seasonal shift. These suggest that quiet day effects at Resolute Bay represent a residual disturbance daily variation, and that the development of additional disturbance field in polar regions remains approximately constant independent of the intensity of disturbance. The quiet day mean horizontal amplitudes vary seasonally as would be expected, with amplitudes in summer, equinox and winter in the ratios 1 : 0.75: 0.41 respectively. (The average K sum from Table I goes as 13.4 : 11.0 : 7.2 or 1 : 0.82: 0.54.) The disturbed day means are less systematic but the equinoctial and summer amplitudes exceed those in the winter as would be expected. The mean Z amplitude data is too uncertain to be of much use.

RESOLUTE BAY		PERSISTENT 24 hr. WAVES			
		DISTURBED DAYS		QUIET DAYS	
		AMPLITUDE γ	L.T. of MAX. hrs.	AMPLITUDE γ	L.T. of MAX. hrs.
−X	SUMMER	52.8 ± 10.3	14.2 ± 0.6	39.9 ± 6.4	14.2 ± 0.4
	EQUINOX	83.0 ± 8.5	13.9 ± 0.3	30.3 ± 5.5	13.8 ± 0.4
	WINTER	50.4 ± 4.3	13.5 ± 0.1	17.5 ± 1.9	13.3 ± 0.3
−Y	SUMMER	77.0 ± 8.6	19.7 ± 0.3	41.6 ± 6.8	19.8 ± 0.4
	EQUINOX	73.5 ± 8.5	20.0 ± 0.3	30.8 ± 4.7	19.2 ± 0.4
	WINTER	61.5 ± 6.6	19.7 ± 0.3	15.8 ± 1.7	19.2 ± 0.3
Z	SUMMER	27.8 ± 14.5	3.7 ± 1.7	6.9 ± 9.1	2.7 ± 3.7
	EQUINOX	18.3 ± 8.2	6.0 ± 1.6	14.2 ± 4.6	2.6 ± 0.8
	WINTER	24.0 ± 5.0	5.3 ± 0.6	5.8 ± 1.3	6.2 ± 0.7
		PARTIALLY PERSISTENT 12 hr. WAVES			
−X	WINTER	4.8 ± 3.7	10.5 ± 1.0	2.8 ± 1.2	10.1 ± 0.6
−Y	WINTER	8.0 ± 4.9	1.2 ± 0.7	3.8 ± 1.1	1.5 ± 0.4
Z	EQUINOX	10.6 ± 4.6	1.1 ± 0.6	3.7 ± 2.6	4.7 ± 1.0

TABLE V. Summary of persistent seasonal waves at Resolute Bay.

It thus appears that disturbance at Resolute Bay merely enhances the quiet day daily variation, or alternatively the latter can be regarded as representing the residual effect of disturbance daily variation. The exact amplitude relationships depend on the criterion used in selecting the days, but the conclusion does not. Figure 3 illustrates this conclusion graphically showing the seasonal variation in the mean amplitude and phase and the probable error ellipse (circles might have been drawn) for the two classes of days.

The results for any 12-h waves which show partial persistence (one $P_1 < 0.05$) are shown in Table V, and no real differences are apparent. Once again the almost random Z wave shows poorest agreement.

Very Quiet Day Results at Resolute Bay

The question naturally arises whether there is a real quiet day field distinctly different in form from the disturbance variation and which can be detected at a polar cap station. To answer this question the selection described earlier of very quiet days was made. The last third of both Tables III and IV summarises the features found for the three classes of days over the period of 17 months investigated around sunspot minimum. The notation is that discussed earlier.

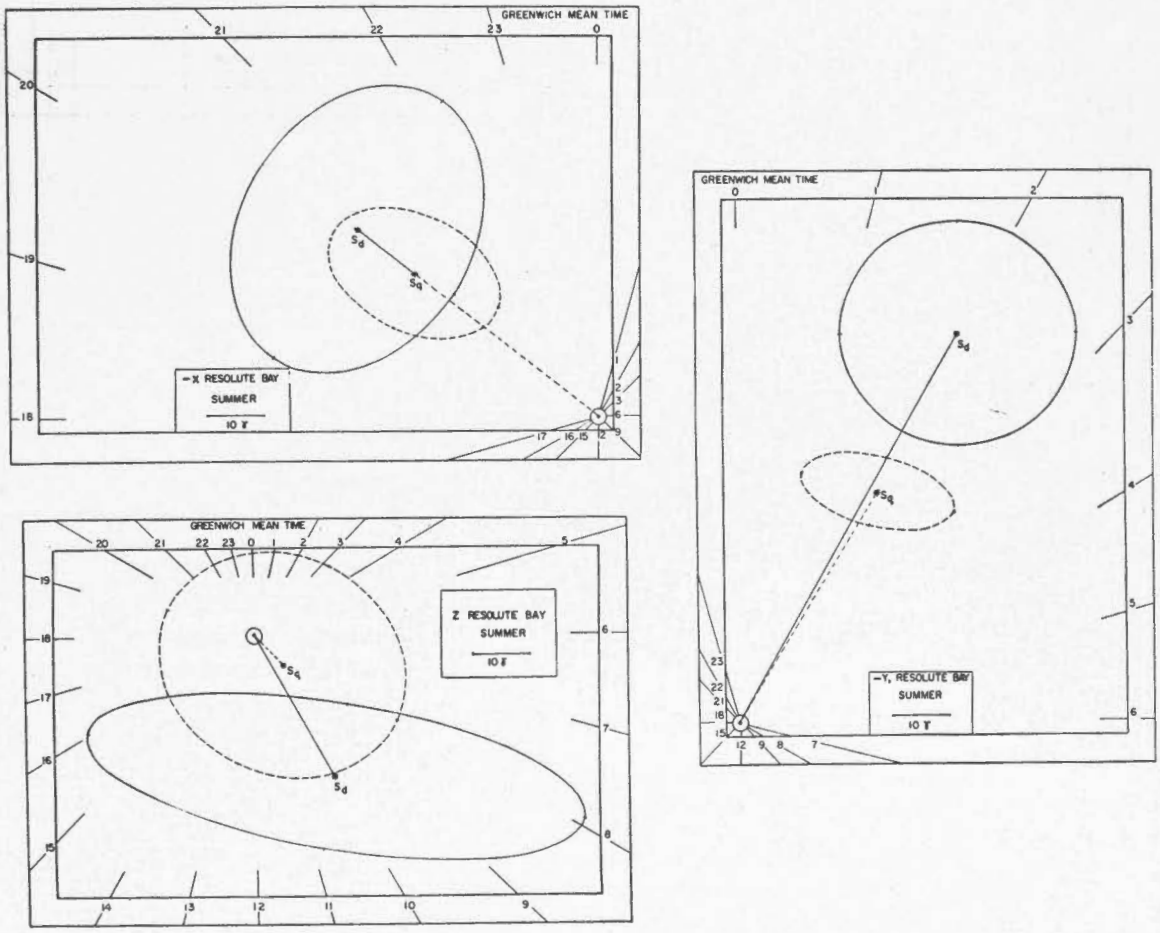
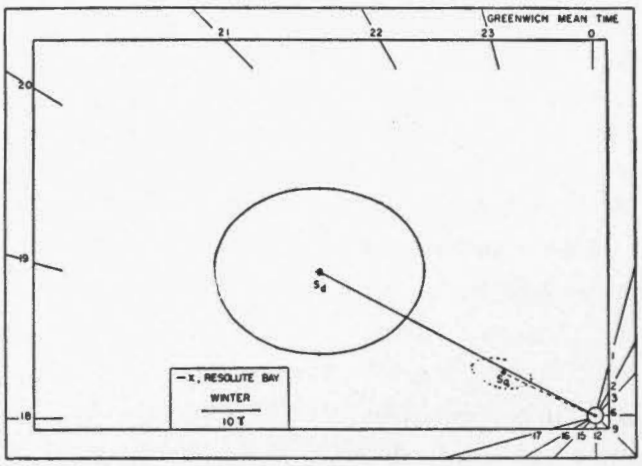
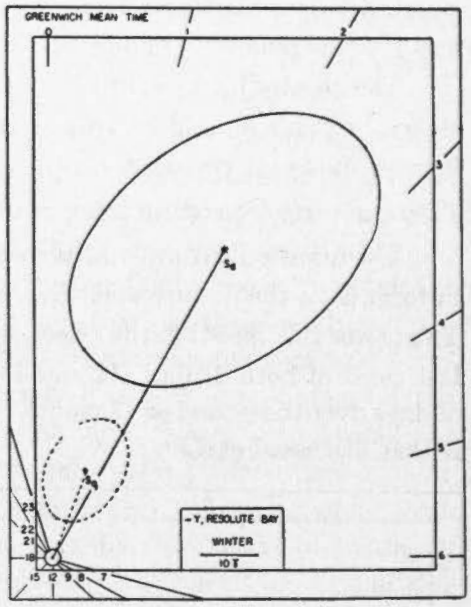


Figure 3a.

FIGURES 3a, (*and overleaf*) b, and c. Harmonic dials for the 24-h waves in —X, —Y, Z at Resolute Bay, N.W.T. for quiet and disturbed days in the summer and winter solstices and the equinoxes respectively.


GREENWICH MEAN TIME
-X, RESOLUTE BAY
WINTER
10 γ


GREENWICH MEAN TIME
-Y, RESOLUTE BAY
WINTER
10 γ

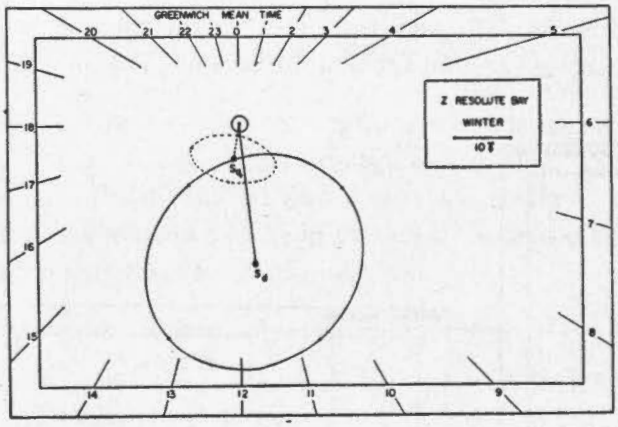
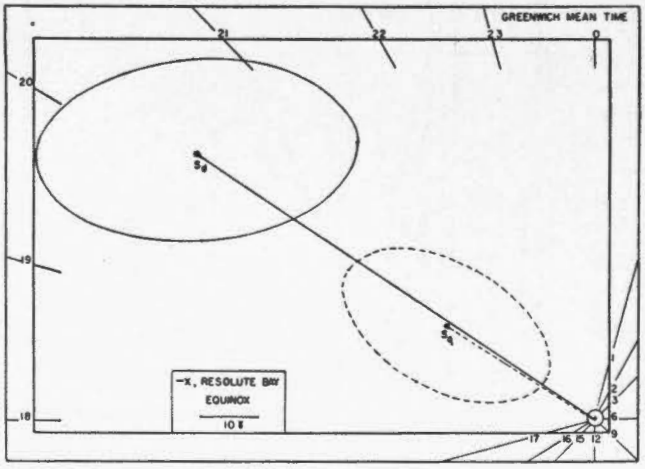
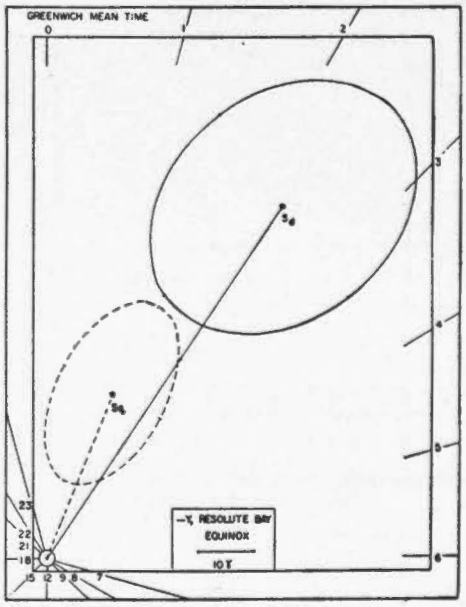
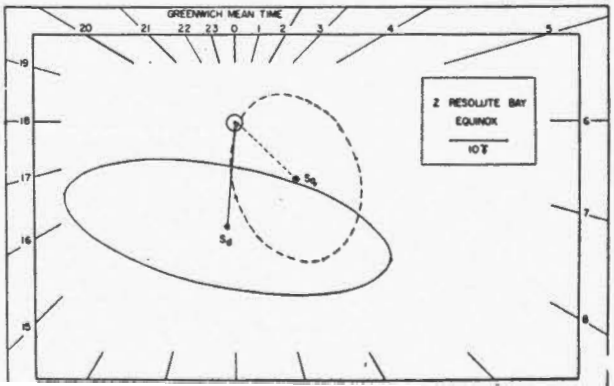

GREENWICH MEAN TIME
Z RESOLUTE BAY
WINTER
10 γ

Figure 3b


GREENWICH MEAN TIME
-X, RESOLUTE BAY
EQUINOX
10 γ


GREENWICH MEAN TIME
-Y, RESOLUTE BAY
EQUINOX
10 γ


GREENWICH MEAN TIME
Z RESOLUTE BAY
EQUINOX
10 γ

The probabilities P_1 indicate that the 24-h waves are not random, although once again the Z variability on very quiet days is pronounced. The clouds appear significantly elliptical except for very quiet days. The correlation coefficient r is real and pronounced for the quiet days only in the horizontal components; however, it is significant that the signs in r and the directions found for the major axes agree in the three classes very well. The harmonic dials of Figure 4 illustrate the three classes of days, and show there are no real differences in the form of the field.

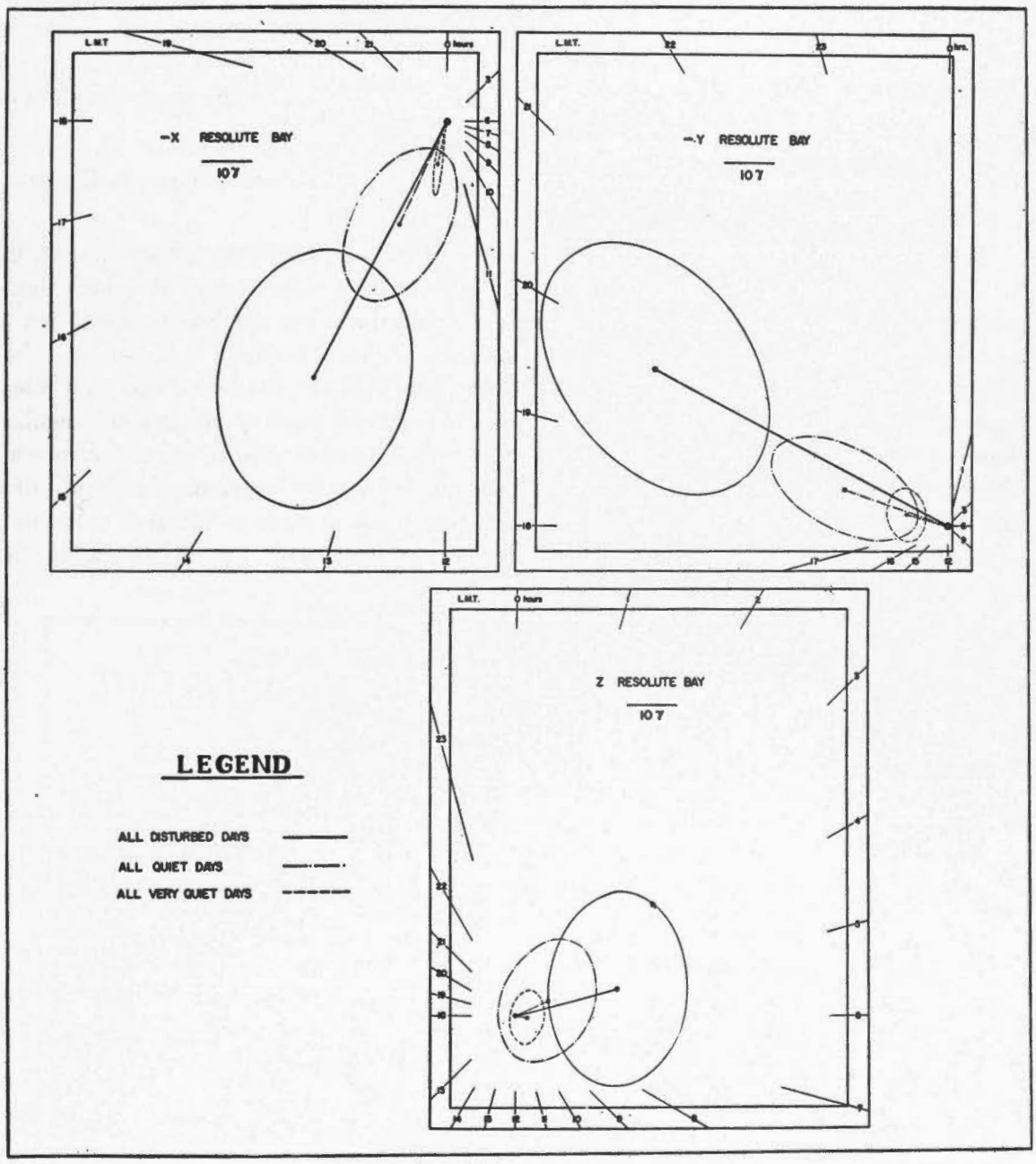


FIGURE 4. Harmonic dials for the 24-h waves in —X, —Y, Z at Resolute Bay, N.W.T., for very quiet, quiet and disturbed days during November 1953 to March 1955.

The tabular data indicate that the third and fourth harmonics are random, and partial persistence can be seen only in the horizontal components on quiet days. It should be noted that the 24-h wave amplitudes form much the largest part of the range observed in practice, and a theoretical explanation of these terms only would account for more than 90 per cent of the disturbance field on disturbed days, more than 80 per cent on quiet days and 60 per cent on very quiet days.

The ratio of amplitudes weighted according to their uncertainties in the usual manner on quiet and disturbed days is 0.35 ± 0.07 with no significant differences in this ratio for the three components. The ratio of very quiet day amplitudes to disturbed day amplitudes is 0.14 ± 0.04 for all components. It is of interest to note that the average K sums on the days adopted, shown in Table I, have corresponding ratios of 0.34 and 0.12. Consequently it follows that the K sum is a very good linear predictor of the diurnal variation amplitude, or smoothed range.

Day to Day Changes at Resolute Bay in the Amplitudes of the Disturbance Waves in Different Components

The analysis so far does not indicate how the relationship between the amplitudes in X, Y and Z varies from day to day. The 24-h wave amplitude in each of the three components was obtained for each day of the winter months using the Fourier coefficients a_1, b_1, and the day to day correlations computed. Table VI shows the results. The correlations are significantly high, even for the small diurnal amplitudes on the very quiet days: the correlations are highest for the class of quiet days, possibly because of irregular disturbance and bays influencing the results somewhat on disturbed days, and errors in determination of the Fourier coefficients being proportionately larger on the very quiet days. In all cases the correlation between the horizontal components is higher than that between a horizontal component and the vertical component. This agrees with the

	CORRELATION COEFFICIENTS	
	$r_{x,y}$	$r_{x,z}$
DISTURBED DAYS	0.45 ± 0.08	0.35 ± 0.09
QUIET DAYS	0.70 ± 0.04	0.48 ± 0.06
VERY QUIET DAYS	0.54 ± 0.14	0.30 ± 0.18

TABLE VI. Correlation coefficients between the first harmonic wave amplitudes at Resolute Bay for very quiet, quiet and disturbed days in the winters 1953-1955.

experience of Chapman and Stagg (1931), but it is not certain that at Resolute Bay the result is not a consequence of the small Z amplitudes found and the larger uncertainties in the determination of any one. In any case the systematic nature of the cyclic field changes at Resolute Bay is clear.

Discussion of Seasonal Results for Baker Lake

Table VII summarises the seasonal characteristics for the persistent waves at Baker Lake. Because of the greater complexity of disturbance at Baker Lake, it was considered best to complete the analysis in all seasons for quiet and disturbed days in four harmonics. Most of the 24-h and 12-h waves, though highly variable, do show persistence in each season, whereas the 8-h and 6-h waves are almost random. Without a fuller examination of the influence of quasi-persistence at Baker Lake it is doubtful if the probabilities P_1 in Table IV really demonstrate the existence of persistent 8-h and 6-h waves. The 12-h wave in Z and the 24-h wave in D are only developed on disturbed days.

BAKER LAKE		24 hr. WAVES			
		DISTURBED DAYS		QUIET DAYS	
	H, Z / D	AMPLITUDE γ mins.	L.T. of MAX hrs. "	AMPLITUDE γ mins.	L.T. of MAX. hrs. "
H	SUMMER	15.6 ± 7.8	20.4 ± 1.4	27.8 ± 3.9	20.3 ± 0.4
	EQUINOX	20.5 ± 7.7	21.1 ± 0.9	18.0 ± 5.6	20.1 ± 0.9
	WINTER	21.8 ± 5.0	19.2 ± 0.7	13.2 ± 2.3	18.3 ± 0.5
D	SUMMER	51.0 ± 4.6	9.4 ± 0.2	24.2 ± 3.1	8.5 ± 0.3
	EQUINOX	59.6 ± 5.3	9.3 ± 0.3	16.1 ± 2.7	8.9 ± 0.4
	WINTER	33.6 ± 3.1	9.4 ± 0.4	3.4 ± 1.4	7.7 ± 1.1
Z	SUMMER	85.4 ± 11.	4.8 ± 0.4	37.3 ± 5.8	5.2 ± 0.4
	EQUINOX	102. ± 6.9	4.2 ± 0.2	37.0 ± 6.8	4.8 ± 0.4
	WINTER	75.6 ± 6.3	4.6 ± 0.2	14.3 ± 3.0	4.1 ± 0.6
		12 hr. WAVES			
H	SUMMER	40.9 ± 5.9	3.5 ± 0.2	23.9 ± 3.9	3.3 ± 0.2
	EQUINOX	28.5 ± 5.9	3.3 ± 0.3	24.3 ± 4.9	3.3 ± 0.3
	WINTER	32.4 ± 4.0	3.0 ± 0.2	10.4 ± 2.1	3.3 ± 0.2
D	SUMMER	22.0 ± 5.6	4.4 ± 0.3	9.5 ± 2.7	5.3 ± 0.4
	EQUINOX	9.8 ± 3.7	4.4 ± 0.5	6.0 ± 2.1	4.9 ± 0.5
	WINTER	11.9 ± 2.3	5.8 ± 0.3	5.5 ± 1.1	6.1 ± 0.3
Z	SUMMER	14.7 ± 11.	10.6 ± 1.1	8.4 ± 4.9	1.9 ± 0.8
	EQUINOX	21.3 ± 6.4	10.0 ± 0.4	5.3 ± 6.2	11.6 ± 2.1
	WINTER	12.0 ± 4.6	8.9 ± 0.5	4.3 ± 1.8	2.4 ± 0.5

TABLE VII. Summary of persistent seasonal waves at Baker Lake.

The distribution of the cloud of points is usually not significantly elliptical, although the necessary parameters required to define the probable error ellipse are given in every case. The exceptions usually occur on quiet days.

Table VII summarises the seasonal changes for the significant first and second harmonics. Any significant vertical differences in L.T. of maximum in the eighteen rows occurs for the 12-h Z wave where the phase is advanced by more than 90° on disturbed days. The physical consequences of this are discussed later. The amplitudes of the first harmonics show a seasonal variation compatible with the average sum of K for the selected classes (*see* Table I) at different seasons. The 12-h disturbed day amplitude in H is somewhat smaller in the equinoctial months than might be expected; the interpretation advanced later requires that the concentrated currents of the auroral zone be further from the station on these equinoctial days.

Very Quiet Day Results at Baker Lake

If the above results are interpreted in terms of a considerable change of type in the disturbance daily variation as the intensity of disturbances changes (the change of type being formally represented in terms of the different relative magnitudes of the first and second harmonic waves with less important phase changes), it is of interest to examine the results for the very quiet days, the selection of which was described earlier. The features for the three classes of days, disturbed, quiet and very quiet days, are shown in Tables III and IV.

The very quiet day disturbance shows persistent first and second harmonic waves only; the populations are circular and the other harmonics random. Reasons are advanced later for estimating that approximately 50 per cent of the disturbance amplitudes on very quiet days is produced by residual disturbance: thus no pure solar daily variation on quiet days, such as can be derived at low latitude observatories, can be isolated from the Baker Lake data.

However, if corrections for the solar daily variation on quiet days are to be made to Baker Lake results, the formal representation of the very quiet day results in terms of the first and second harmonic waves is the best approximation.

Day to Day Changes at Baker Lake in the Amplitudes of the Disturbance Waves in Different Field Components

The procedure used was similar to that described on page 304. The correlations between the 24-h waves and 12-h waves in H and Z were computed for the winter months on disturbed days for comparison with the systematic results shown in Table VI. The coefficients found were $+ 0.23 \pm 0.07$ and $+ 0.21 \pm 0.07$ respectively for the first and second harmonics indicating very poor correlation, in contrast with the results obtained at Resolute Bay. Hence the field changes from day to day in different components do not change proportionally, although they do increase together. This is considered further later.

DYNAMO THEORIES

Dynamo Theory Applied to Polar Cap Disturbance

The harmonic analysis of Resolute Bay cyclic field changes has demonstrated the existence of a unitary phenomenon, expanding from very quiet to quiet to disturbed days

with no significant change of form. It is suggested therefore that an atmospheric dynamo might have this property, and the conductivity, or the amplitude of the driving motion, or both, must change for different levels of disturbance.

Chapman and Bartels (1940, Ch. 23) and Fukushima (1953) have discussed dynamo theories and derived the dynamo equation: the derivation given below is added only to clarify the concept of conductivity in high magnetic latitudes. Using Martyn's (1948) expression for the conductivity in the ionosphere in a region where the magnetic dip can be considered 90°, and letting Ox be an axis to the south, Oy to the west and Oz vertically downwards, then the current density j has components along the axes

$$j_x = \sigma_1 E_x - \sigma_2 E_y,\ j_y = \sigma_2 E_x + \sigma_1 E_y,\ j_z = \sigma_0 E_z$$

$$\text{where } \sigma_0 = e^2 \left\{ \frac{n_e}{m_e \nu_e} + \frac{n_-}{m_- \nu_-} + \frac{n_+}{m_+ \nu_+} \right\}$$

$$\sigma_1 = e^2 \left\{ \frac{n_e}{m_e} \frac{\nu_e}{\nu_e^2 + \omega_e^2} + \frac{n_-}{m_-} \frac{\nu_-}{\nu_-^2 + \omega_-^2} + \frac{n_+}{m_+} \frac{\nu_+}{\nu_+^2 + \omega_+^2} \right\}$$

$$\sigma_2 = \frac{e}{F} \left\{ \frac{n_e \omega_e^2}{\nu_e^2 + \omega_e^2} + \frac{n_- \omega_-^2}{\nu_-^2 + \omega_-^2} - \frac{n_+ \omega_+^2}{\nu_+^2 + \omega_+^2} \right\}$$

$$\text{with } \omega_e = \frac{eF}{m_e},\ \omega_- = \frac{eF}{m_-},\ \omega_+ = \frac{eF}{m_+},$$

and suffices refer to electrons, negative ions and positive ions respectively. Then $\sigma_3 E_x = j_x + (\sigma_2/\sigma_1)\, j_y$, $\sigma_3 E_y = -(\sigma_2/\sigma_1)\, j_x + j_y$ where $\sigma_3 = \sigma_1 + \sigma_2^2/\sigma_1$. Denoting the height integrated conductivity by Σ and current density by I

$$\Sigma_3 E_x = I_x + \Sigma_2 I_y/\Sigma_1,\ \Sigma_3 E_y = -\Sigma_2 I_x/\Sigma_1 + I_y$$

If the motion of the layer is considered horizontal and irrotational, it is associated with a velocity potential ψ such that if u, v, are velocity components along axes Ox, Oy respectively $u = \frac{-\partial\psi}{\partial x}$, $v = \frac{-\partial\psi}{\partial y}$. If θ is the colatitude, ϕ the east longitude measured from the Greenwich meridian and a the radius of the shell $u = \frac{-\partial\psi}{a\partial\theta}$, $v = \frac{\partial\psi}{a \sin\theta \partial\phi}$.

With the usual notation the vertical magnetic field

$$Z = \frac{2\,M \cos\theta}{a^3} = 2\,G \cos\theta. \quad \text{Then } E_x = vZ = \frac{2G}{a}\left(\cot\theta \frac{\partial\psi}{\partial\phi}\right)$$

$$\text{and } E_y = -uZ = \frac{2G}{a}\left(\cos\theta \frac{\partial\psi}{\partial\theta}\right)$$

The existence of a steady current system implies that I_x, I_y, are derivable from a current function J such that

$$I_x = \frac{1}{a \sin\theta} \frac{\partial J}{\partial\phi},\ I_y = \frac{1}{a} \frac{\partial J}{\partial\theta}.$$

$$\text{Therefore } 2\,G\,\Sigma_3 \left(\cot\theta \frac{\partial\psi}{\partial\phi}\right) = \frac{1}{\sin\theta} \frac{\partial J}{\partial\phi} + \frac{\Sigma_2}{\Sigma_1} \frac{\partial J}{\partial\theta}$$

$$\text{and } 2\,G\,\Sigma_3 \left(\cos\theta \frac{\partial\psi}{\partial\theta}\right) = \frac{-\Sigma_2}{\Sigma_1} \frac{1}{\sin\theta} \frac{\partial J}{\partial\phi} + \frac{\partial J}{\partial\theta}$$

From these equations it is simple to derive the well known dynamo equation assuming uniform conductivity in the region of interest

$$2\,G\,\Sigma_3 \left\{ \cot\theta \frac{\partial^2\psi}{\partial\phi^2} + \frac{\partial}{\partial\theta}(\sin\theta\cos\theta\frac{\partial\psi}{\partial\theta}) \right\} = \frac{1}{\sin\theta}\frac{\partial^2 J}{\partial\phi^2} + \frac{\partial}{\partial\theta}(\sin\theta\frac{\partial J}{\partial\theta})$$

showing the enhanced conductivity Σ_3 is applicable to the polar cap.

Assuming no obliquity of the earth's axis, if $\psi = k_1^1 P_1^1 \sin(t + \alpha_1^1)$ where t = L.T. in degrees i.e. $t = \phi + t^1$, t^1 being the time of the Greenwich meridian, and P_1^1 is the normalized Schmidt spherical harmonic function, then the solution of the dynamo equation is

$$J = 2\,G\,\Sigma_3 \frac{\sqrt{3}}{2.3} k_1^1 P_2^1 \sin(t + \alpha_1^1)$$

The magnetic potential

$$= -4\pi\frac{3}{5}\left(\frac{r}{a}\right)^2 2\,G\,\Sigma_3 \frac{\sqrt{3}}{2.3} k_1^1 P_2^1 \sin(t + \alpha_1^1)$$

where r is the radius of the earth and it is simple to derive the field components ΔX^1 southerly, ΔY^1 westerly and ΔZ^1 downwards. For small θ,

$$\Delta X^1 = C\cos(t + \alpha_1^1 - 90°),\ \Delta Y^1 = C\cos(t + \alpha_1^1 - 180°),$$
$$\Delta Z^1 = C.\,2\,\theta\cos(t + \alpha_1^1 + 90°) \text{ where } C = 4\pi.\frac{3}{5}\frac{r}{a^2}G\,\Sigma_3 k_1^1.$$

If the angle between the geographic meridian and a great circle through Resolute Bay and the effective pole of the dynamo is β, then

$$\Delta X_s = C\cos(t + \alpha_1^1 - 90° + \beta)$$
$$\Delta Y_w = C\cos(t + \alpha_1^1 - 180° + \beta)$$
$$\Delta Z = C.\,2\,\theta\cos(t + \alpha_1^1 + 90°).$$

It would appear best to compare these predictions with the results for the quiet class of days: the disturbed class then requires an expansion of 2.9 times and the very quiet days a contraction of 2.5 times.

Using the ratio of vertical to horizontal component amplitudes, $\theta = 9 \pm 3$ degrees.

Using the phase of the Z wave, $\alpha_1^1 = 206 \pm 12°$, and then the phase of $-X$ wave requires $\beta = 40 \pm 12°$, and the phase of $-Y$ wave requires $\beta = 44 \pm 12°$.

Assuming the pole of the dynamo coincides with the geomagnetic pole at 78.5°N, 291°E, the geomagnetic colatitude of Resolute Bay is 7° and the angle $\beta = 45.6°$, in remarkably good agreement with the predictions above. It should be noted that in a more rigorous treatment with a transformation of the effective pole of the system, geomagnetic rather than local time should be used: geomagnetic local noon is 3.0 hrs. behind local noon at Resolute Bay at the equinoxes and varies by about one-half hour from the winter to summer solstices.

The partially persistent 12-h waves at Resolute Bay are consistent with a P_2^2 term in the velocity potential, but the uncertainties in the mean data are such as to make the determination of θ and β not possible: however it can be shown that $\frac{k_1^1}{k_2^2} = 2.0 \pm 1.0$ so the amplitude ratio of the first harmonic to the second harmonic motions is 19:1. The phase of the semi-diurnal wind referred to these axes is $139 \pm 36°$.

We note that if $2G \approx 0.6$ e.m.u., we require

$$3.5 \times 10^{-9}\,\Sigma_3 k_1^1 = 8.8 \pm 2.0 \times 10^{-5} \text{ on very quiet days}$$
$$= 23 \pm 2 \times 10^{-5} \text{ on quiet days}$$
$$= 64 \pm 5 \times 10^{-5} \text{ on disturbed days.}$$

Comparison with Earlier Analyses

The phase angle $\alpha_1^1 = 206 \pm 12°$ deduced at Resolute Bay corresponds to a current sheet across the polar cap directed towards the 10.3 hrs. local time meridian. This is in approximate agreement with the idealised current system for the disturbance field of Chapman (1935), and in close agreement with the results of Hasegawa (1940). However this phase angle does not agree with that deduced by Chapman (1919) in his analysis of the S_q field for sunspot minimum: referred to the same axes his result was 305°, with a change to 294° at sunspot maximum. This discrepancy is not explained by assuming that the very quiet day amplitudes at Resolute Bay correspond to a masking of the true quiet day effect by residual disturbance. Using Chapman's velocity potential it was estimated that C = 13 gammas, whereas the amplitudes of the 24-h waves in horizontal components at the sunspot minimum 1954 were 9 ± 2 gammas. The phase of the driving motion is thus about 90° different from that predicted by the lower latitude Chapman analyses in the dynamo theory of solar daily variation on quiet days.

Fukushima (1953) has considered the complementary functions

$$J = C_1^1 \tan \frac{\theta}{2} \sin (t + \alpha_1^1)$$

and considered this current system responsible for the disturbance field. Inside the polar cap $\tan\frac{\theta}{2}$ is very nearly equal to $\frac{1}{2}P_1^1(\theta)$ (error less than 3 per cent at $\theta = 20°$) so the expected vertical to horizontal component ratio should be θ instead of the 2θ found above. We note that

$$\frac{\text{Z amplitude}}{\text{X or Y amplitude}} = 0.30 \pm 0.30 \text{ on very quiet days,}$$
$$= 0.32 \pm 0.11 \text{ on quiet days,}$$
$$= 0.33 \pm 0.09 \text{ on disturbed days,}$$
$$\text{and } = 0.34 \pm 0.12 \text{ for (disturbed-very quiet) days.}$$

There is no obvious change by a factor of 2 in this ratio between the disturbance field and the quiet or very quiet day field, although the uncertainties are such that definite rejection of Fukushima's solution is not possible. There is also the possibility that internal field contributions might modify these ratios in different ways.

The Polar Cap Conductivity and the Velocity Amplitude

In the absence of appreciable ionisation by incoming charged particles it seems reasonable to assume $\Sigma_1 = 1.2 \times 10^{-10}$ e.m.u. and $\Sigma_2 = 1.8 \times 10^{-9}$ e.m.u. for a 20 km. thick layer at 100 km. height. These correspond to 3.4×10^4 electrons and ions/cc. at 100 km. as a yearly average around sunspot minimum. Then $\Sigma_3 = 2.7 \times 10^{-8}$ e.m.u., and since on very quiet days $\Sigma_3 k_1^1 \times 10^{-4} = 8.8/3.5$,

$$k_1^1 = 9 \text{ m/sec.} = 34 \text{ km./hr.}$$

The phase corresponds to an air flow from the p.m. hemisphere to the a.m. hemisphere (to the N at 16.3 hrs.). The way in which these very quiet day currents complete their circuit is obscure.

Since there are no important seasonal shifts in phase, which in itself does not suggest a heat driven air circulation, but rather a tidal motion, it is possible that the different

amplitudes on different days reflect changes in conductivity rather than changes in the amplitude of the circulation. This is supported by the relationship suggested earlier between the average amplitude and the average K sum, which can be roughly regarded as an index of solar particle precipitation.

The class of disturbed days would require a conductivity of about 2×10^{-7} e.m.u., which could be produced by (say) a positive ion and electron density of 2×10^5/cc. in a twenty km. thick layer. It has been shown by Fukushima (1953) that a proton stream of 1/cc. moving with an initial velocity of 10^9 cms./sec. (500 keV.) produces about 2×10^7 ion pairs/c.c. near the bottom of its penetration range, a little above 100 km. from the ground. It seems likely therefore that the direct entry of weak corpuscular streams into the polar cap during disturbed conditions could easily produce the conductivity required. Then statistical variations in the wind and in the distribution of ionization produce the large uncertainties described analytically earlier in the day to day features of disturbance. The large scale circulation of air from the p.m. to the a.m. hemispheres approximately is the only statistically persistent feature in the problem.

Extension of Dynamo Theory

In view of the successful numerical aspects of the elementary dynamo outlined above, it seemed worthwhile to consider the implications of more refined models, and in particular to consider the effects produced by the difference between the positions of the geomagnetic pole and the geographic pole and the effects produced by a diurnally varying conductivity on very quiet days. Both these problems have been considered before at different latitudes.

(1) Using geographic axes, if the geomagnetic pole has coordinates (θ_0, ϕ_0), then $Z = 2\,G\,\{\cos\theta + \tan\theta_0 \sin\theta \cos(\phi - \phi_0)\}$. Assuming $\psi = k_1^1 P_1^1 \sin(t + \alpha_1^1)$ an exact solution of the dyanmo equation is of the form

$$\begin{aligned} J = {} & 2\,G\,\Sigma_3 \frac{\sqrt{3}}{2\cdot 3} k_1^1 P_2^1 \sin(t + \alpha_1^1) \\ & - 2\,G\,\Sigma_3 \tan\theta_0 \frac{1}{6} k_1^1 P_2^\circ \sin(\alpha_1^1 + \theta_0) \\ & + R(\theta) \sin(2t + \alpha_1^1 - \phi_0) \end{aligned}$$

where R satisfies the equation $\dfrac{-4R}{\sin\theta} + \dfrac{\partial}{\partial\theta}\left(\sin\theta \dfrac{\partial R}{\partial\theta}\right) = -2\sin\theta\tan\theta_0$.

This suggests that the X and Z first harmonic waves should be in phase which is not true. The zonal terms are largest in Z, and are $2\frac{1}{2}$ times larger in Z than in X. Their magnitude is too small to relate to the phenomena discussed in Part II of this paper. In practice the second harmonic amplitudes are known to be unimportant.

(2) In view of the complexity of the actual field distribution over the polar cap region, which corresponds to a complex Z distribution in the lower part of the ionosphere, it is of interest to examine the simple case when $Z = 2\,G$ is assumed. In northern Canada this is not at all a bad approximation particularly near the auroral zone. Then the solution leads to a magnetic potential

$$= -4\pi \frac{2}{3}\left(\frac{r}{a}\right)^2 2\,G\,\Sigma_3 k_1^1 \sin\theta \sin(t + \alpha_1^1)$$

and the situation is the same as before except that $\frac{Z}{X \text{ or } Y} \approx \theta$ instead of $2\,\theta$. Once again an effective centre for the motion not at the north geographic pole is required to explain the observed phases.

(3) It has been found that the horizontal movements in the ionosphere in moderate northern latitudes show a pronounced 12-h period with a mean velocity of about 30 m/sec. (Briggs and Spencer, 1954). This suggests that the 24-h periods found in magnetic variation may be produced by the semi-diurnal wind movements when allowance is made for the diurnally varying conductivity of the layer. Chapman (1913) has examined this question using a certain conductivity expression, and recently his work has been extended by Chakrabarty and Pratap (1954) who give reasons for using a diurnally varying conductivity of the form $\Sigma \propto 1 + 2.45 \cos \chi + 2.25 \cos^2 \chi$ where χ is the zenith distance of the sun. Using this expression the field produced by a semi-diurnal motion has been calculated with the aid of the current function coefficients found by Chakrabarty and Pratap (1954): at the summer and winter solstices the semi-diurnal component amplitudes predicted are 70 per cent of the diurnal ones, and a phase change occurs unless $\alpha_2 = 0$. At the equinoxes a negligible (2 per cent) semi-diurnal amplitude is predicted. Furthermore the predicted phase relationships between the components, and the measured amplitude relationships between the diurnal terms do not agree with experience. It is therefore considered doubtful whether a semi-diurnal oscillation could be responsible for the fields found inside the polar cap, and with the present state of knowledge of atmospheric motions, it is considered that detailed calculations are not justified.

Furthermore using the selected quiet days, the equinox: summer amplitude ratio is 0.75 whereas examination of vertical incidence ionospheric records for Resolute Bay for the year 1954 gives a $n_{max.}$ ratio of 0.22; the seasonal average of the radio data gives 0.50. Thus $n_{max.}$ of the E layer above the station is an unsatisfactory parameter for the determination of the conductivity in the dynamo layer; this might be expected since the field variations are influenced by the integrated effect of conductivity over a wide area and height. During the summer months, the average value of $n_{max.}$ is not appreciably different on the selected disturbed and quiet days.

At Resolute Bay the expression $1 + 2.45 \cos \chi + 2.25 \cos^2 \chi$ represents the seasonal variation in $n_{max.}$ of the E layer no better than Chapman's expression $(1 + 1.5 \cos \chi)^2$. At the summer solstice when the sun is above the horizon for 24 hrs., then $\frac{n_{min}}{n_{max}}$ in 1954 = 0.43. Chapman's expression predicts 0.39 and the former 0.40.

Corrections for Internal Contributions Inside the Polar Cap

The internal contributions to the observed daily variation have been neglected; it would however appear reasonable for very quiet day phenomena to reduce the observed horizontal components by multiplication by 0.71 and increase the observed vertical components by multiplication by 2.5 to obtain the external contribution only. These figures correspond to an external: internal amplitude ratio of 2.5, $n = 2$, $m = 1$ and neglecting the small phase difference in the internal and external contributions. The effective pole of the dynamo becomes east of Greenland and agreement with the geomagnetic pole disappears.

This suggests that inside the polar cap, internal contributions to very quiet day variations are not so large as the analysis of quiet day variations at low and moderate latitudes suggests. When the results from a greater number of stations are published this point should be pursued further. Other authors (Vestine *et al.* 1947) have used corrections of 10 per cent inside the polar cap for the disturbance field; since all three classes above reflect the same phenomenon this figure might also be applicable to the very quiet day variation.

Application of Dynamo Theory to Very Quiet Day Results at Baker Lake

Since the very quiet days selected at Baker Lake and Resolute Bay are much the same, it is important to compare the Baker Lake data with predictions based on the velocity potential described above which fits the Resolute Bay data. We then find that

(i) the predicted 24-h wave in D is more than four times the observed amplitude,

(ii) the predicted ratio of $\frac{Z}{H}$ corresponds to an angle of 16.3°, and the observed ratio corresponds to an angle of 22 ± 9°,

(iii) the angle α_1^1 required at Baker Lake referred to axes as before is 206 ± 6°,

(iv) the difference in phase between the two horizontal components is 177 ± 10° instead of 90°,

(v) the angle β required at Baker Lake = 144°, whilst the actual angle between the magnetic meridian and the geomagnetic meridian is 17°, and

(vi) similarly unsatisfactory conclusions can be drawn from the second harmonic.

Generally the results are not compatible with functions of the form$P_n^{1,2}$ unless n is not small. Presumably this means that there is an appreciable residual disturbance field (n known to be large) on very quiet days at Baker Lake. Assuming on these days equal Σ K products at the two stations, the horizontal components expected at Baker Lake should be ~ 9 and 6 gammas respectively in 24-h and 12-h components and ~ 6 and 3 gammas respectively in the vertical components. These estimates suggest that approximately 50 per cent of the disturbance on very quiet days is produced by residual disturbance (n large), and hence predictions based on the elementary model described above are worthless.

THE DISTURBANCE FIELD AT BAKER LAKE

We have shown that the application of dynamo theory to Baker Lake observations fails for very quiet day phenomena and that the disturbance field present on quiet days is different in intensity and form from that present on disturbed days. The implications of the formal results presented earlier are best seen in the form of vector diagrams.

The Magnetic Auroral Zone near Longitude 60°W Geomagnetic

Harang (1946) has given a graphical representation of the disturbance field determined as a function of geomagnetic latitude and local time using observatories situated near geomagnetic longitude 120°E. No corresponding line of observatories is in operation in the western hemisphere, but if the results from Resolute Bay and Baker Lake are combined with those from Second Polar Year and other stations (note that both 1954 and

1932-33 were years of minimum solar activity) approximate polar plots are possible which can be continued beyond geomagnetic latitude 75°. The stations used at different times include Thule, Resolute Bay, Baker Lake, Chesterfield Inlet, Fort Rae, Meanook, Agincourt and Tucson. Although geomagnetic position coordinates are used it is simpler to consider the plots as local time plots: the refinements in correcting to geomagnetic local time are probably not important for the purpose of the diagrams shown. At Baker Lake, at the equinoxes the difference between local noon and local geomagnetic noon is 1.2 hrs. Figure 5 is typical of many plots, and shows the diurnal variation for all days in June of the disturbance field in Z across the geomagnetic meridian $\Lambda = 60°W$. The heavy line indicates the horizontal position of any assumed line current system. The similarity with Harang's (1944) results is striking, but the latitude range covered is much larger. Figure 6 shows approximate estimates of the positions of the lines of zero ΔZ and the maximum ΔH, and a mean between these. This mean line is regarded as the best approximation to the auroral zone. The dotted lines at lower latitudes in the afternoon and evening hours

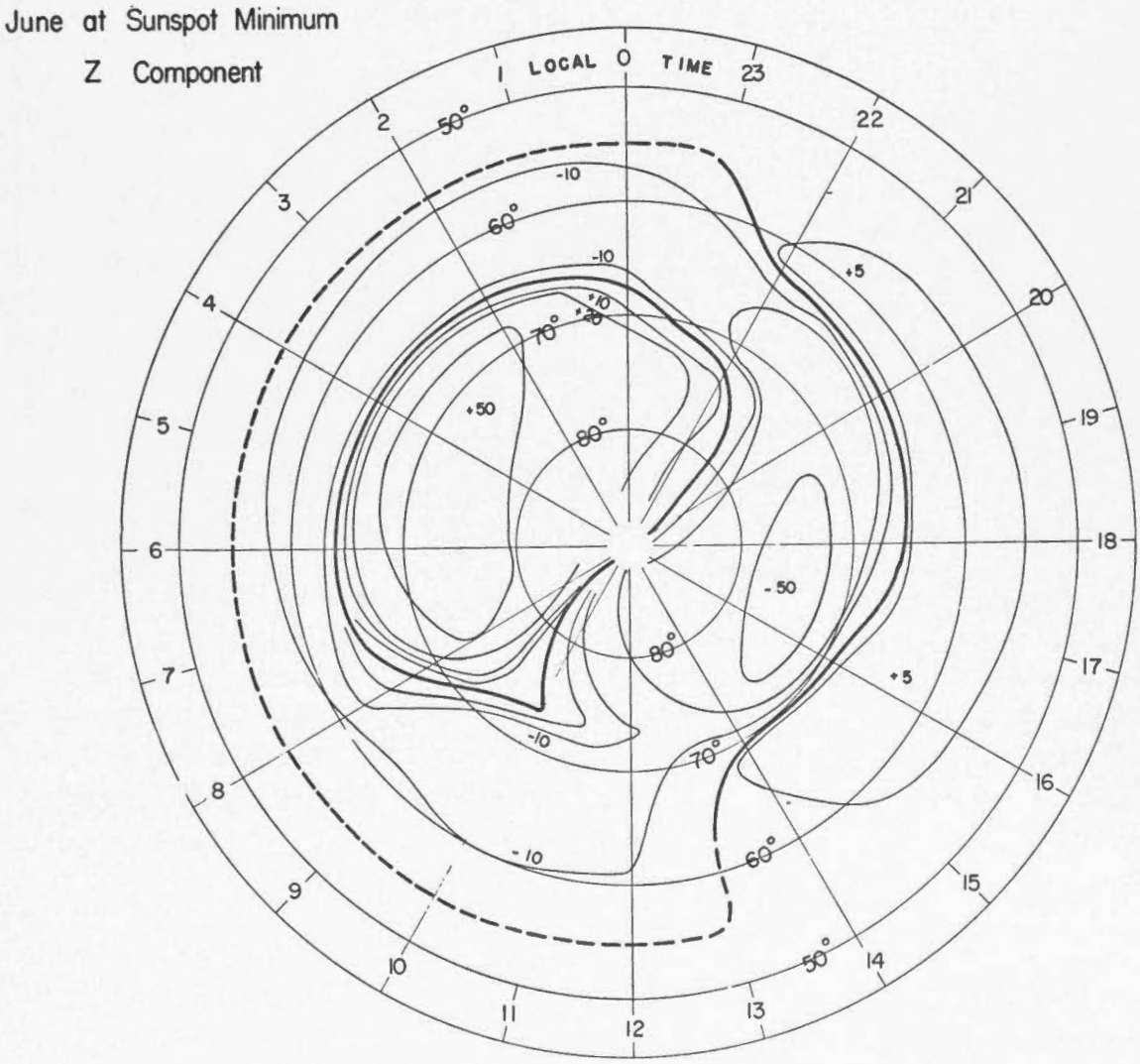


FIGURE 5. Diurnal variation of the disturbance field in Z (all days) across geomagnetic meridian $\Lambda = 300°$. The heavy line indicates the horizontal position of any assumed line current.

correspond to a minor maximum in Δ H and an ill defined line Δ Z = 0. The auroral zone is much more clearly defined on the morning side. In Figure 6 the maximum Δ H and zero Δ Z curves intersect at about 16-h and 24-h L.T. in approximate agreement with Harang (1946) and suggesting that the systematic change in phase of the amplitude of the disturbance field with longitude, which can approach 4 hours, is not obvious on two lines 180° apart. The material is not yet sufficient for a closer examination of the pattern.

Vector Diagrams at Baker Lake

The analysis of Baker Lake disturbance field characteristics can contribute to the study of the morphology of auroral zone disturbance. Figure 7 shows mean horizontal vector diagrams for the three classes, correcting the quiet and disturbed days using the

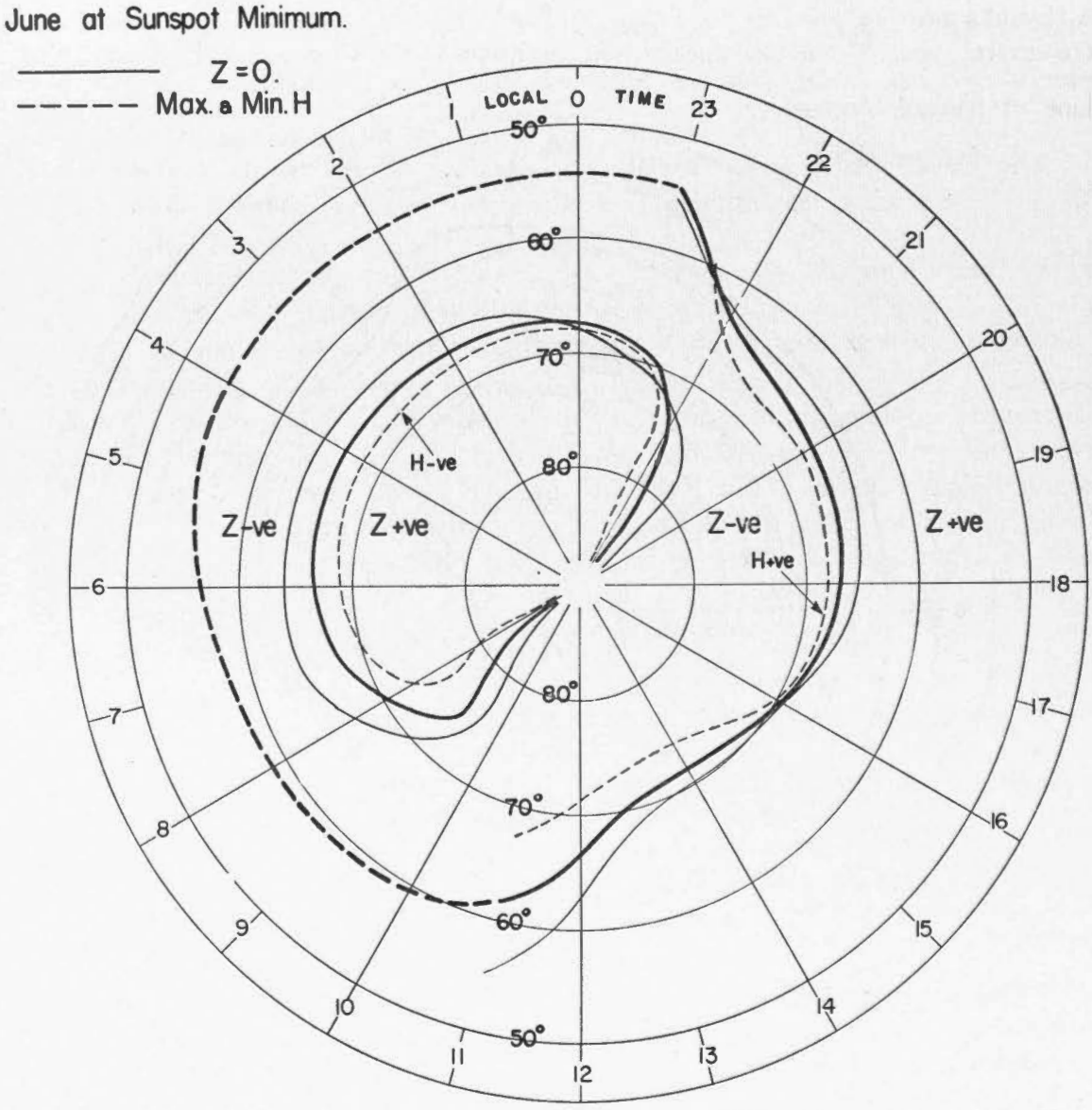


FIGURE 6. Polar plot of the position of the lines of zero Δ Z, maximum | Δ H | and the auroral zone, deduced from the diurnal variations of the disturbance field in H and Z across geomagnetic meridian Λ = 300°.

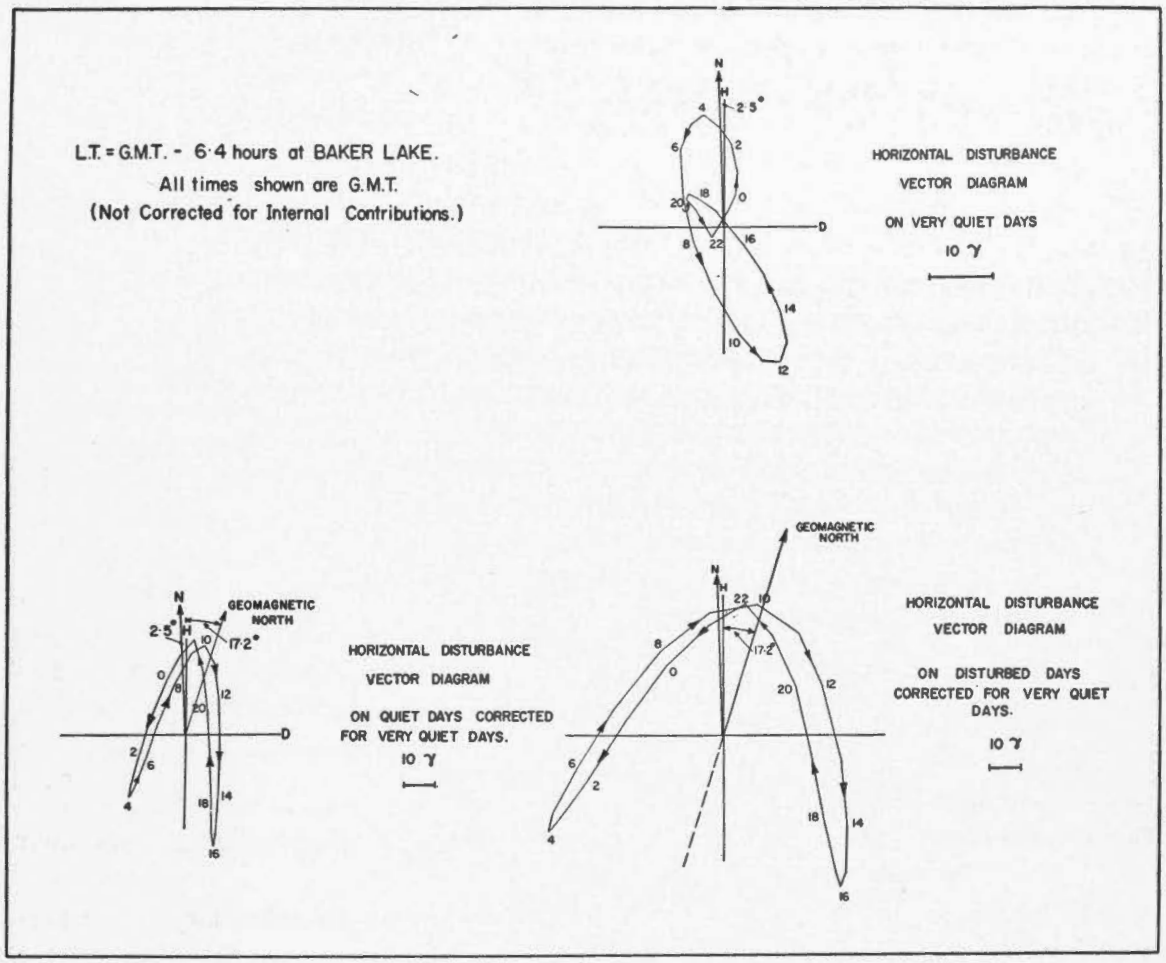


FIGURE 7. Horizontal vector diagrams for the three classes of selected days at Baker Lake, N.W.T.

very quiet day disturbance as an approximation to the true unperturbed solar daily variation. The similarity between the quiet and disturbed classes is striking, and the distinction from very quiet day phenomena clear. In Figure 7 the persistent features of disturbance only are shown: the inclusion of the higher harmonic terms, however, changes nothing significantly. Figure 8 shows the diurnal variation for the three classes in Z. No attempt has been made to combine Figures 7 and 8 in the form of total perturbing vector diagrams, vertical plane vector diagrams and so on, because it is not clear what corrections are required for internal contributions to the observed cyclic field variations.

However, it does seem likely that the average night-time perturbing vector is larger than the average daytime perturbing vector on very quiet days, but smaller by 10 to 20 per cent (depending on the corrections adopted) for the quiet and disturbed days: this again suggests a difference. The perturbations are stronger over the p.m. than over the a.m. hemisphere, a result in agreement with those found in the belt between zones.

Table VIII summarises certain numerical results deduced from Figures 7 and 8. The horizontal vector diagrams suggest symmetry about an axis between true and geomagnetic north, and tending towards the latter with increasing disturbance. At local times 04 hrs.

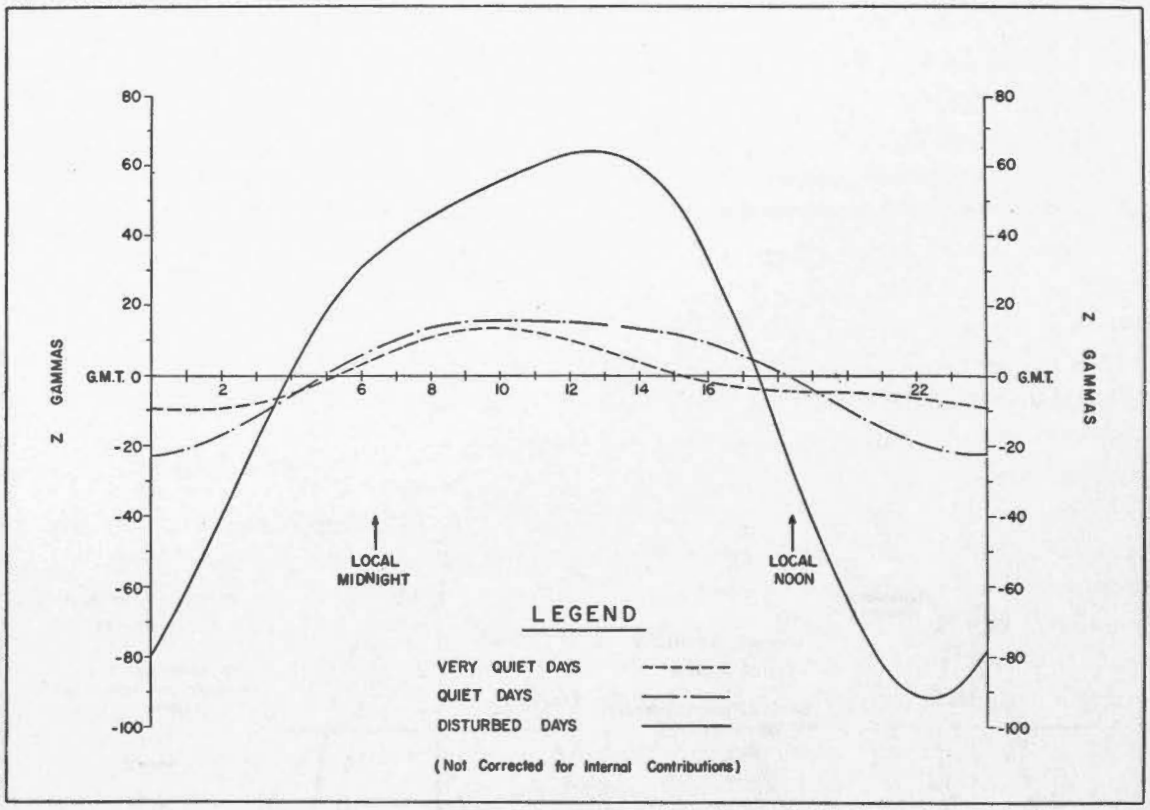


FIGURE 8. The diurnal variation of the disturbance field in Z for three classes of selected days at Baker Lake, N.W.T.

and 15 hrs. approximately, corresponding closely to the second subsidiary set of horizontal vector maximum, the auroral zone currents are along geomagnetic parallels of latitude. The afternoon maximum corresponds to easterly flowing current in the auroral zone to the south of Baker Lake, and in Table VIII the current in this branch is calculated assuming a line current (or sheet of small lateral extent), and its position south of the station estimated assuming a height of 100 km. The estimates are made using a number of different corrections: it appears that corrections of 30 per cent to 40 per cent are necessary to obtain general agreement with the synoptic plots and place the concentrated current at geomagnetic latitude 69°. This agrees well with Vestine's (1947) estimate but not with that of Harang (1946).

The morning flow is more surprising. The equivalent line current is flowing easterly N of the station. Either this implies that Baker Lake is so far north of the main westerly auroral zone currents in the morning that the direction of the resultant horizontal force is influenced more by the return path currents north of the station, which seems unlikely, or the westward flowing currents south of Baker Lake in the morning branch are more diffuse laterally than the eastward currents to the north of Baker Lake. In any case, because of the effective Z enhancement in the centre of even a diffuse ring, calculations of current or position based on one station assuming a line current north of the station are not very reliable, though corresponding estimates are shown in Table VIII. A more dense network of observations in this transitional region might therefore show a maximum

in Δ H corresponding to Δ Z = 0 at geomagnetic latitudes around 76° at the time of the minimum in Δ H corresponding to Δ Z = 0 known to exist around this local time about geomagnetic latitude 68° (*see* Figure 6).

Table VIII demonstrates that the effect of increasing disturbance is to increase the latitude separation of the branches considered above by about 4-5°: as might be expected the movement to the south of the stronger p.m. branch is the larger.

It is of interest to consider the closure paths of the auroral zone currents. Much of the p.m. branch is closed in the form of a sheet flowing parallel to the 10-h meridian in the centre of the cap. However, the Baker Lake results show that by geomagnetic latitude 74° this sheet is so distorted that Δ Z = 0 about one hour later in the morning: this distortion can also be seen in that the second set of horizontal vector maxima near 10-h and 22-h L.T. for the two classes do not coincide exactly with the times when Δ Z = 0. Furthermore it can be seen from the magnitude of the horizontal vector when Δ Z = 0 that closure must correspond to some sheet and cannot be well represented by a concentrated current on the average. Chapman and Bartels (1940, Ch. 9) suggested that more than 80 per cent of the current in the auroral zone returns over the polar cap, whereas Harang (1946) considered that the available material was insufficient to support the view that the perturbing currents as a whole are closed over the polar cap. Combining the data in Table VIII with the horizontal amplitudes at Resolute Bay found on quiet and disturbed

	NO CORRECTIONS	10% CORRECTIONS	30% CORRECTIONS	40% CORRECTIONS
i_{pm}				
DISTURBED DAYS	0.6×10^5 a	1.6×10^5 a	3.1×10^5 a	4.7×10^5 a
QUIET DAYS	0.2×10^5 a	0.2×10^5 a	0.3×10^5 a	0.4×10^5 a
i_{am}				
DISTURBED DAYS	0.6×10^5 a	0.7×10^5 a	1.2×10^5 a	1.8×10^5 a
QUIET DAYS	0.2×10^5 a	0.2×10^5 a	0.2×10^5 a	0.3×10^5 a
d_s°				
DISTURBED DAYS	2.0	2.4	4.1	5.4
QUIET DAYS	0.6	0.7	1.2	1.6
d_N°				
DISTURBED DAYS	1.2	1.4	2.5	3.3
QUIET DAYS	0.5	0.6	1.0	1.4
i_{pm}/i_{am}				
DISTURBED DAYS	2.1	2.3	2.6	2.6
QUIET DAYS	1.1	1.1	1.2	1.3

ASSUMED HEIGHT = 100 km

TABLE VIII. Summary of strength of perturbing currents, with and without corrections for internal contributions, assuming auroral zone characteristics at Baker Lake, N.W.T.

days, it was estimated that about 40 per cent of the auroral zone currents return over the polar cap on disturbed days, and all the current returns over the polar cap on quiet days. This estimate suggests therefore that a rückstrom for lower latitudes is only significantly developed on the selected disturbed days, and on the quiet days (or days of moderate disturbance) this rückstrom is not appreciable.

The correlation between the 24-h wave amplitudes in Z at Baker Lake and Z and X at Resolute Bay were computed for the common disturbed days in the winter months. The results were $r_{Z,Z} = 0.75 \pm 0.05$ and $r_{Z,X} = 0.45 \pm 0.08$. These coefficients are higher than the internal ones found in the polar cap (*see* page 304) and contrast strikingly with the results for Baker Lake (*see* page 306). The coefficients found suggest partial or complete closure on disturbed days: however it is not clear why the correlation between the Z amplitudes exceeds that between Z Baker Lake and a horizontal component at Resolute Bay. Whitham and Loomer (1956) have found that disturbance generally is as highly correlated between the two stations as the 24-h wave amplitudes in Z.

Comparison of Observations with Auroral Zone Theories

Meek (1955) has re-examined the Polar Year data 1932-33 in a discussion of the location and shape of the auroral zone, and gives reasons for doubting the existence of an equatorial ring current. The stream of particles from the sun is supposed to separate under the influence of the earth's magnetic field, and the charged particles of opposite sign are precipitated into the atmosphere in the form of Størmer-like spirals: the spiral produced by positive particle precipitation expands in an anticlockwise direction and that due to negative particle precipitation in a clockwise direction. The positions of these spirals are deduced from the local geomagnetic time of the diurnal increase and decrease in H respectively, and the cross over points are near 10 a.m. and 10 p.m. L.G.M.T. Since the basic data used was much the same as that used in deriving Figures 5 and 6, it is obvious that the existence of spirals is open to considerable doubt. Furthermore it is not clear how spiral precipitation could account for the observed minimum in geomagnetic north component at about 22 hrs. L.T., and maximum at about 16 hrs. L.T., or the results at Resolute Bay. However, the large declination changes observed during disturbance at Baker Lake do not support the idealised concept of concentrated current flow westwards on the a.m. side and eastwards on the p.m. side advanced by Chapman (1935) or the drift currents advanced by Martyn (1951).

At the present time it would appear that the proposals of charge leaking down the lines of force of the earth's magnetic field advanced by Chapman-Ferraro-Martyn (1951) and Alfven (1950) form a satisfactory basis for the explanation of auroral zone magnetic disturbance. However, idealized concepts of concentrated current flow are not very valid even in the average data discussed above. The authors consider it premature to discuss the detailed form of precipitation unless the morphology of the disturbance field is much more carefully determined from observatory records. However, a number of the magnetic field changes discussed in Part II of this paper suggest that none of the theories presently advanced is fully satisfactory.

Nikolski (1947) has discussed in detail magnetic disturbance at Calm Bay (Tikhaya) ($\Phi = 71.5°$N, $\Lambda = 153.3°$E) in an important paper. He concludes that "the changes of

magnetic disturbance during the night and morning hours depend on different laws and that the mean regular variations S_D and D_{st} in the disturbed field do not correspond to any real prolonged phenomena in the field of magnetic storms and are fictitious i.e. merely statistical results". Since Baker Lake and Calm Bay are both north of the auroral zone and show similar diurnal variation in K index when plotted against L.G.M.T., it is important to consider how applicable Nikolski's conclusions are to the analysis described in this paper. The similarities of the horizontal vector diagrams shown in Figure 7 suggest that there is correlation between the two disturbance maxima (the wing tips in Figure 7), and that there is no shift in the times of the maximum disturbance on the more disturbed days. Moreover in Part II of this paper clear evidence is presented for the existence of regular non-cyclic field changes at times of disturbance at both Baker Lake and Resolute Bay. Hence since the harmonic analysis has given a formal representation of persistent features of the disturbance field, it is difficult to agree with Nikolski's conclusions that "the mean regular peculiarities in the field of disturbance of magnetic storms in high latitudes . . . represent fictitious, quite statistical results, and have nothing to do with any real long-period physical phenomena".

Fukushima (1953) and Vestine (1954) have discussed dynamo theories of auroral zone disturbance, assuming that the conductivity in the auroral zone is much greater than in other atmospheric regions, and have pointed out the difficulties. The current systems calculated on certain two-layer conductivity models show features similar to those of Chapman's (1935) idealized system but often more diffuse and to this extent may be thought to be in agreement with observation. It should, however, be noted that the low correlation coefficients described on page 306 do not in themselves support very strongly a dynamo model.

Variations in the Position of the Auroral Zone

The averaged persistent waves described earlier strongly suggest that the afternoon maximum at Baker Lake is the most pronounced auroral zone feature at Baker Lake. Table VIII discusses the average features associated with this maximum, but cannot indicate how stable its properties are from day to day. To consider this the correlation between the 12-h wave amplitude in H and the sum of the 24-h and 12-h wave amplitudes in Z was computed. These parameters can be seen to largely define the amplitudes of the field disturbance at the time of the afternoon maximum. The result was $+ 0.11 \pm 0.07$ for all disturbed days in the winter months. A similar calculation for the morning maximum gave $- 0.19 \pm 0.07$. Thus we conclude that though the waves show formal persistence properties their interdependence is random, and the mean position of the auroral zone deduced above is a statistical average: the position for any day can vary widely.

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PART II: TRANSIENT FIELD CHANGES

ABSTRACT

The analysis of magnetic disturbance at Resolute Bay and Baker Lake has been extended to include sudden commencements, sudden commencement storms, non-sudden commencement storms, and bay phenomena. The physical meaning of the mean disturbance field and non-cyclic changes is also discussed.

A number of new results are suggested by these analyses. There seems little doubt that Arctic sudden commencements are atmospheric in origin. They occur equally frequently throughout the day but appear to show systematic diurnal properties in preliminary impulse only.

The distinctions found at lower latitudes in the properties of sudden commencement and non-sudden commencement storms are not so evident. In particular both classes of storm evidence storm time effects in one of two regular patterns which are discussed. The expected differences in recurrence properties are not found. The equivalent current systems of different types of storm are discussed.

The frequency, amplitude and sign of bays occurring on the selected days have been analysed. It was found that Martyn's explanation of bays is not satisfactory, and that the idealized form of the elementary polar disturbance field shows properties systematically different from that of the idealized S_D field. The relation of bays to aurora and polar blackouts is discussed.

Inside the polar cap certain features of the bay field appear which may be related to the second class of storms found. The suggestion emerges of an inner pattern of zonal current and bay disturbance which predominates in the polar cap in the summer months, and shows certain features the reverse of those found in the auroral zone. It appears to develop instead of, rather than with, the usual pattern.

The mean disturbance field is shown to represent very largely the effect of the bay field, but unexplained terms remain.

INTRODUCTION

The analysis of Resolute Bay and Baker Lake magnetograms described in the previous paper has been extended to include a number of non-cyclic magnetic phenomena: these include storm sudden commencements, moderate magnetic storms of the sudden and non-sudden commencement type, bay phenomena, the mean disturbance field and non-cyclic changes. The records used cover the period from 1949 to 1955 with special attention being given the previously selected days. In each case an attempt has been made to relate the findings to recent ideas in the field and show what contribution, if any, it is possible for observatories in high latitudes to make. A number of properties of disturbance have been found which are very different from those generally accepted; these suggest that at the best, present day theory is inadequate.

It is the hope of the authors that some of the features of high latitude disturbance outlined below will be investigated at other observatories before or after the forthcoming International Geophysical Year, and that the unexplained differences in disturbance characteristics from those at lower latitudes will help in the development of more satisfactory theories, and act as a guide in deciding between them. The terminology used here follows Chapman (1951, 1952).

INVESTIGATIONS OF SUDDEN COMMENCEMENTS

Comparison with Occurrence at Lower Latitudes

Resolute Bay magnetograms from September 1949 to November 1955 and Baker Lake magnetograms from February 1951 to November 1955 were searched for sudden commencements. The S C listed in the I.U.G.G. (earlier in the I.A.T.M.E.) bulletins were used as a guide, but the magnetograms for each day were examined. During the

interval September 1949 to December 1954, 167 S S C and S C were listed (in 1949, the bulletin included S C only: in 1950 S S C and S C were listed and in the following years only S S C), whereas 70 only were definitely identified at Resolute Bay. From February 1951 to December 1954, 71 S S C were listed in the bulletins and 20 only were clearly identified at Baker Lake. In each case a number of those found were not included in the bulletins. It therefore appears that inside the polar cap, sudden commencements can be identified half as frequently as in low and moderate latitudes, and nearer the auroral zone less than one third as frequently. S C is however definitely not a localized equatorial phenomenon, as has been suggested by certain authors. A comparison with the selected planetary S C listed in the I.U.G.G. (earlier I.A.T.M.E.) bulletins of Bartels and Veldkamp (1949 to 1954) showed that 41 per cent of the planetary S C (53 out of a possible 128) were identified at Resolute Bay and 26 per cent (15 out of a possible 58) at Baker Lake. Approximately one in four of the identified S C at both stations during these intervals were not listed.

Comparison with Lower Latitude Times

Except for seven cases all times agree within 1 minute with the times found at lower latitudes: in one case the time difference was 4 minutes and in the remaining cases less than 2 minutes. It is doubtful if these differences are significant since it is not now possible to check the accuracy of the time marks. It seems likely that polar S C occur simultaneously (to within 1 minute) with those at lower latitudes.

Classification of Sudden Commencements

The S C were classified according to a scheme suggested by Jacobs and Obayishi (1956). S C with a preliminary reverse impulse, sometimes very quick and sometimes lasting for a few minutes, were most common, forming 78 per cent of the S C at Resolute Bay and 89 per cent at Baker Lake. The amplitudes of both the initial and main phases were measured, wherever possible. Sudden impulses (S I) were not recorded: in northern stations S I occur very frequently, and occasionally almost continuously, and it did not seem reasonable to discuss their statistics with the well marked events preceding clear and well defined disturbance. The data below does not include the sudden commencements corresponding to the leading edge of a clear bay-like disturbance: these are often pulsational and well marked in the horizontal force components at Baker Lake, where they occur frequently.

The Diurnal Frequency Distribution

Figure 1 shows the diurnal frequency distribution of all identified S C in three-hour intervals for the two observatories, for the cases where a reverse impulse does and does not occur; the total number in the latter case is however very small. Chi-squared tests for homogeneity indicate that the hypothesis of equal frequency of total S C in each interval is a satisfactory fit, and it is considered therefore that the deviations shown from a straight line are random. A Poisson distribution would then be expected and the numbers found at both stations are satisfactory on this hypothesis. For example, at Resolute Bay the maximum number in any interval is 15 and the chance of this appearing in any interval is nearly 30 per cent assuming a Poisson distribution, and a mean of 9. Thus there appears

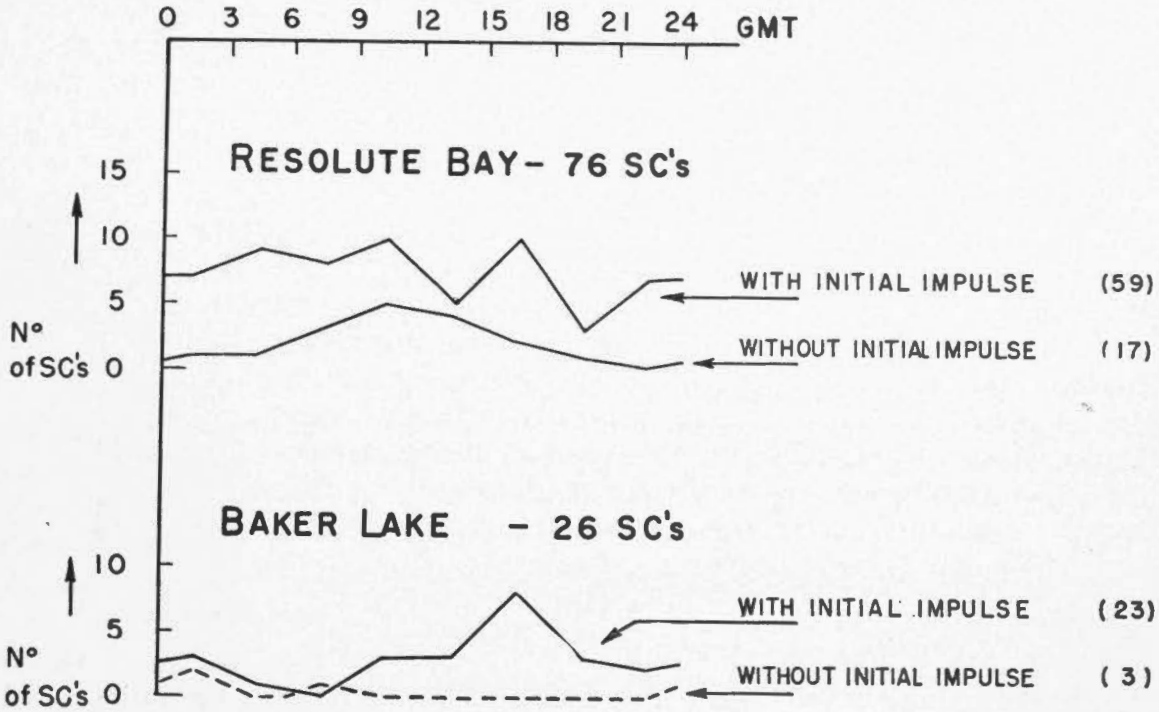


FIGURE 1. The diurnal frequency distribution of S C at Resolute Bay 1949-1955 and Baker Lake 1951-1955.

to be no evidence for a significant diurnal variation (D V) in the frequency of occurrence. Since most of the S C are of the type with a reverse preliminary impulse, this result does not confirm the suggestions of Ferraro *et al.* (1951) of a local time effect with an afternoon maximum. It is in agreement with the analysis of Forbush and Vestine (1955) of S C occurrence at Watheroo and Huancayo observatories. It may be that a significant diurnal variation (D V) in the frequency of occurrence can only be found when the form of the S C can change appreciably: since the above results largely refer to one type of S C, homogeneity may not be surprising. Many more years of records would be necessary to test this suggestion in polar regions.

The Diurnal Variation in Amplitude of the Initial Movement

At Resolute Bay three component records are available only after October 1953, and the determination of the mean azimuth and inclination of the perturbing vector is only possible for the morning hours. Although substantially constant values are found, it is believed that a real D V exists. Figure 2 shows the mean results for the nine cases where measurements are possible at Resolute Bay: Δ Z is always negative and the azimuth is never in the north quadrants. An examination of the longer sequence of La Cour declination records for the entire period of operation of the observatory showed that 14 out of 17 S C with no reverse impulse show northerly motions, whereas 41 out of 59 S C with an initial impulse show initial southerly motions: thus over 70 per cent of the main motions are to the north. It should be noted that this is the same direction as that generally accepted for a normal S C at low and moderate latitudes. Both the D and the three component records suggest that sudden commencements near noon are larger than ones occurring near midnight.

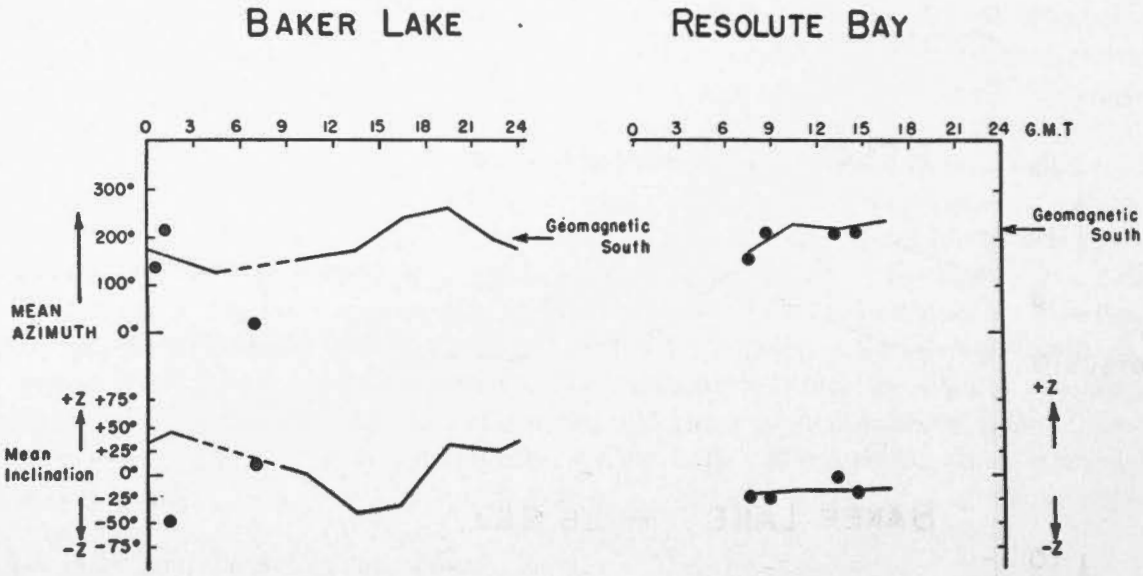


FIGURE 2. The diurnal variation in the azimuth and inclination of the perturbing vector producing the initial impulse of S C at Resolute Bay and Baker Lake.

At Baker Lake three component records are available covering the entire period searched, and Figure 2 shows the estimated D V in azimuth and inclination for the initial motion based on twenty-one cases. In 79 per cent of the cases the motion is southerly, whether a reverse impulse or the main phase of S C without reverse impulse. If an atmospheric current source is assumed, Figure 2 shows that during the initial impulse, the burst of current is westerly and north of both stations in the morning hours whereas in the afternoon hours the Baker Lake results indicate an equivalent current flow south of the station. The direction of the Z motion during the afternoon at Resolute Bay cannot yet be determined.

Analysis of the Main Impulse in Sudden Commencements

Measurement on the D records at Resolute Bay suggest that the main impulse is not appreciably different in size whether it appears with or without a preliminary impulse: an average of 35 gammas in Δ X was obtained for both classes. The main impulse movements do not appear to be at all systematic, and it was concluded that no persistent D V could be found. However, in Figure 2, the individual points shown refer to the main impulse for those few cases where records in three components are available and no initial impulse occurs. At Resolute Bay the points lie close to the partial curve derived for the systematic initial impulses, but this is not the case at Baker Lake. It is concluded that the initial impulse in S C is a physically distinct phenomenon.

The only systematic feature found in the main impulses of four S C which were identified at both observatories and for which three component records exist is that the main perturbing vector is about twice as intense at Baker Lake as at Resolute Bay, whereas the initial impulse perturbation is twice as intense at Resolute Bay as at Baker Lake. In the preliminary impulse these four S C have azimuths close to geomagnetic south at both observatories (all in 06-12 hr. L.T.), and an elementary calculation shows that the position

of an equivalent westerly line current source is about 3.5° of latitude N of Resolute Bay at a height of 1100 km.: the internal corrections are then about 10 per cent. It is of interest to note that this corresponds to the calculated latitude of the dip pole at this height, 5° north of its epochal position (Jacobs and Sachs, 1956). There are certain longitude uncertainties but there is a possibility that the two facts may be related. In any case, if charged particle precipitation north of Resolute Bay is assumed, within minutes of time the pattern of disturbance becomes much more complex and diffuse, and its maximum certainly moves south. Although the mean azimuths for the initial phase are often close to geomagnetic south, the initial phase data from Resolute Bay suggests that deviations from this occur, particularly around noon and midnight. This suggests the possibility of a dynamo-like generation of the initial impulse in S C, and it would be of interest to discover the world-wide pattern and its relations to auroral zone precipitation. Forbush and Vestine (1955) have shown that there is a major and immediate atmospheric source of field in S C and the initial phase of storms at low latitude stations, and suggested that electric currents in or near the E layer near the magnetic equator are driven by electrojets of polar regions.

The Size of Sudden Commencements at High Latitude Stations

Chree (1912) found that S C in the Antarctic average about 4.5 times the amplitudes found at Greenwich. Combining all the S C for which the total perturbing vector could be measured, the preliminary impulses were found to have equal amplitude (54 gammas) at both stations, whereas the main impulse amplitude was nearly twice as large at Baker Lake as at Resolute Bay (101 gammas compared with 54 gammas). Since the data is not homogeneous, and no internal contribution corrections are applied, the figures are not too reliable, but they confirm the trend discussed above for the few common S C. A comparison with the median size for Hucancayo determined by Forbush and Vestine (1955) shows the average Baker Lake amplitude to be only slightly larger, but a direct comparison using homogeneous data would be preferable.

A seasonal effect is suggested in that the average perturbing vector found in the summer at Baker Lake is larger than that in the equinoxes and about twice that found in the winter. Furthermore there is the suggestion of a daylight hours enhancement since the initial phases at Baker Lake are 80 per cent larger and the main phases 60 per cent larger during daylight hours than during night hours. The Resolute Bay results, with one main phase exception show a similar daylight enhancement. These results support an atmospheric origin.

It is suggested that the relations between polar and equatorial S C require further examination preferably with fast magnetographs and accurate timing.

Internal Corrections

The approximate calculation considered above suggested that perhaps about 10 per cent of an average observed movement is produced by field sources internal to the earth. It is the purpose of this paragraph to note that initial impulses followed by a main impulse can often be approximated by a sine wave with a period of a few minutes, and it is not

unreasonable that corrections of this order could occur. The neglect, for example, of the influence of the oceans on the size of the S C observed at certain observatories may be serious: it should be noted that the integrated conductivity of 10,000 ft. of sea water is $\sim 10^{-5}$ e.m.u. or one hundred to one thousand times that of the ionosphere. There might well be systematic differences in the amplitude of the S C field determined from island and coastal observatories and from those in the centres of land masses.

THE ANALYSIS OF SUDDEN COMMENCEMENT STORMS

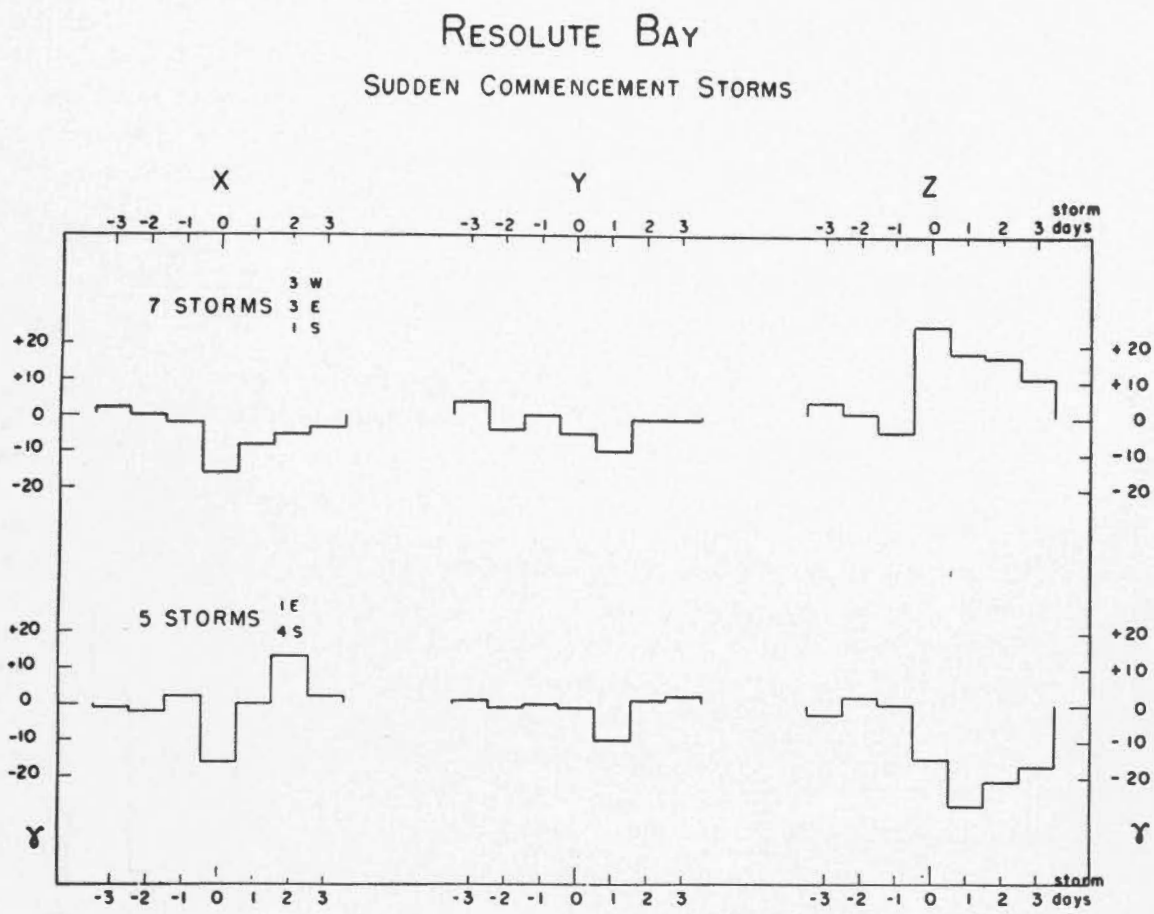
The Selection of Storms

A total of 12 storms at Resolute Bay and 23 storms at Baker Lake were examined in three components. The intervals searched and the storms selected correspond to the S C described above.

The Storm-Time Variation, D_{st}

In order to obtain the character of the storm-time variation in these high magnetic latitudes a number of procedures are possible. Derivations of storm-time variations have been described for lower latitude stations by Chapman (1927) using 40 storms, and for a wider range of latitude by Vestine (1947) using 11 storms of the Polar Year. The results of Vestine (1947) showed incomplete removal of the local time disturbance field S_d, or the disturbance local time inequality D_s as it appears at the time of moderate disturbance (Chapman, 1952).

An attempt to derive D_{st} for the first 48 hours of a storm was made, but the incomplete removal of D_s and irregular disturbance, and the small number of storms made the development in time of the storms at these high latitudes very difficult to follow. Local time corrections based on monthly means, or on the idealized S_d field, described in Part I of this paper, all failed to remove the disturbance local time inequality satisfactorily. Consequently the superposed epoch method was used to derive the storm-time effects averaged over daily intervals. This method of course, tells nothing about initial phases of storms. The daily means for the day of the storm (commencing at the time of the S C) and for the three 24-h periods previous to and after the first day of the storm were derived and averaged. Figure 3 shows the results at Resolute Bay and Figure 4 the results at Baker Lake, collecting the storms into two classes at Resolute Bay and three classes, at Baker Lake. The zero line for each plot is the average of days -3, -2, and -1. The figures also indicate the seasonal distribution among the classes and the mean storm changes. The latter in any component is arbitrarily defined by the mean change in the first seventy-two hours of the storm from the value in the seventy-two hours previous to the commencement of the storm. This definition seems a reasonable one since whenever storm-time changes are clearly defined in any component, the time constant of recovery seems to be about one day, so that the mean storm changes are effectively zero after about four days. In any case it seems a more reliable measure of magnitude than the change in amplitude on the first day of a storm, particularly for field components in which real storm-time effects are small. It should be noted that all the storms are moderate to small in intensity, and it is not certain if the time constant of recovery changes with more intense storms. No weighting procedures were used in deriving Figures 3 and 4.



Mean Storm Changes	X γ	Y γ	Z γ
7 + ΔZ storms	−10	−5	+20
5 − ΔZ storms	−1	−3	−21

FIGURE 3. Mean storm changes for sudden commencement storms at Resolute Bay, 1953-1955.

The two classes of storms at Resolute Bay, + Δ Z and − Δ Z storms, might well be called winter-type and summer-type storms respectively. The horizontal components for the summer-type storms are very small and southerly, and from Figure 3 obviously ill defined. Those for the winter type storms appear well defined in X only and are negative. The winter type storms therefore correspond to zonal current flow westwards south of the station.

At Baker Lake, 16 out of 23 of the storms correspond to westerly current flow south of the station. The azimuth of the mean perturbing vector is 190°, which agrees more closely with geomagnetic south, 197°, than geographic south, and is in very good agreement with the direction of the axis suggested in Part I of this paper, Figure 7, for the S_D field variation. However, in 7 storms real positive changes in Δ H occur, corresponding to a current reversal. Four were associated with large negative Δ Z values and 3 with large positive Δ Z values; i.e. concentrated current flow south and north of Baker

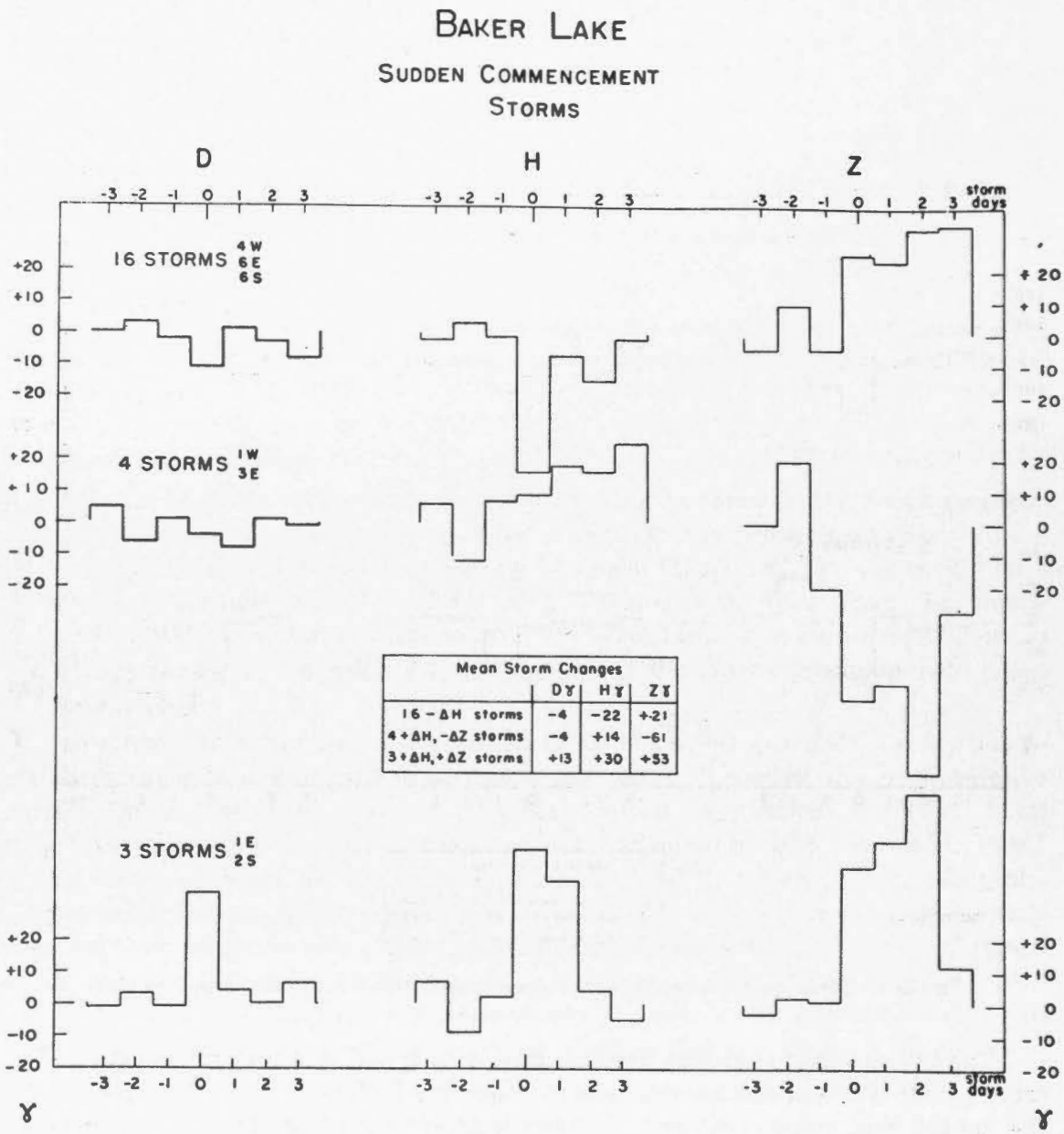


FIGURE 4. Mean storm changes for sudden commencement storms at Baker Lake, 1951-1955.

Lake, respectively. This type of storm occurs most frequently in the summer and equinoctial months. Neglecting the small and ill-defined horizontal components found at Resolute Bay for the summer type storms, it appears that these correspond to the + Δ H classes at Baker Lake. Two opposite systems of zonal current flow are required therefore to explain the character of averaged storm-time.

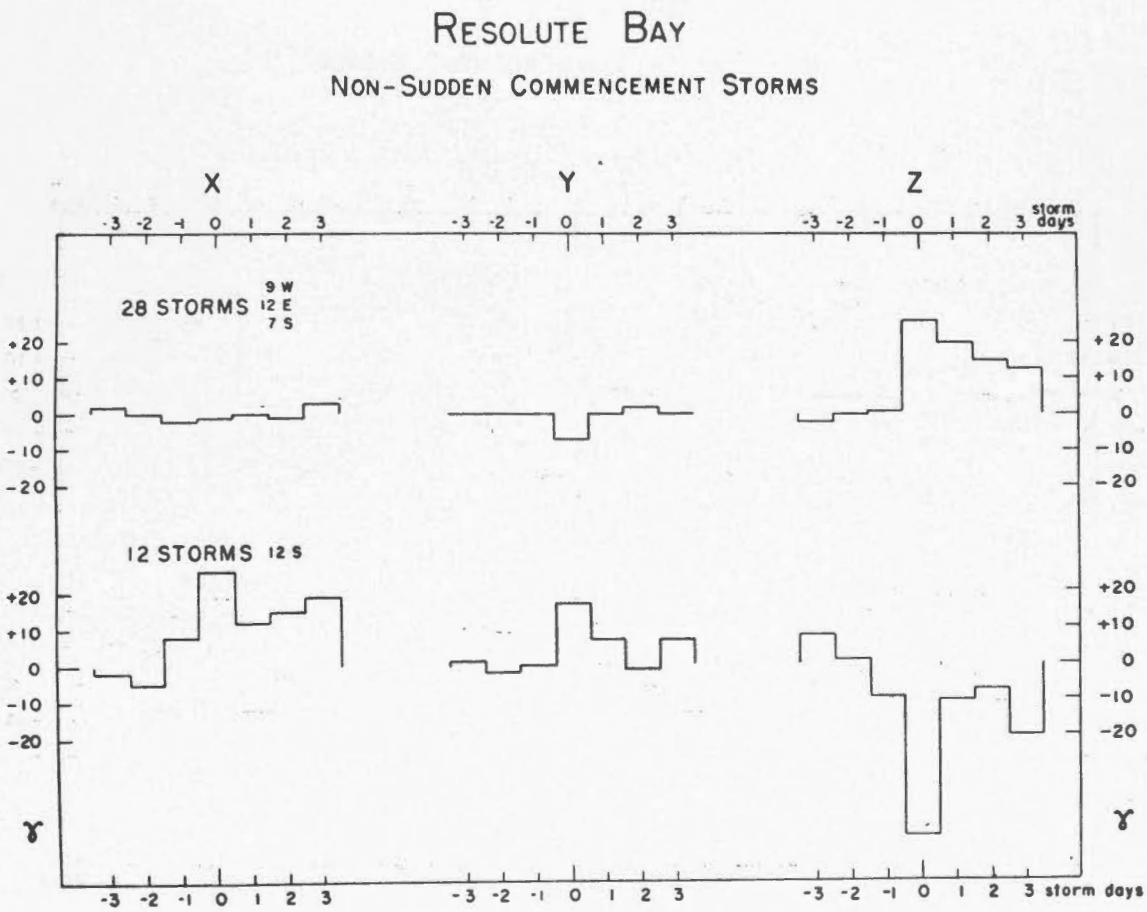
Since the number of S C storms measured which are common to both stations is only 4 and these belong to the different classes, it does not seem worthwhile examining their numerical implications. These are presumably the same as those discussed below in an account of the non-sudden commencement storms.

THE ANALYSIS OF NON-SUDDEN COMMENCEMENT STORMS

A total of 40 such storms were selected at Resolute Bay and 47 at Baker Lake in the intervals discussed. Many of these corresponded to stormy periods reported by the observers in the Journal of Geophysical Research, but in any case the magnetograms were searched individually. One only of the storms selected was reported elsewhere as a sudden commencement storm. In each case the onset was indefinite to the extent of about one hour as would be expected. It appears likely that the storms correspond to the polar equatorial storms of Birkeland (1908).

The Storm-Time Variation D_{st}

Newton and Milsom (1954) have discussed the characteristics of small storms of the non-S C type found in the Greenwich records, and compared them with S C type storms. Characteristic differences were noted, and it was suggested that the origin of these small



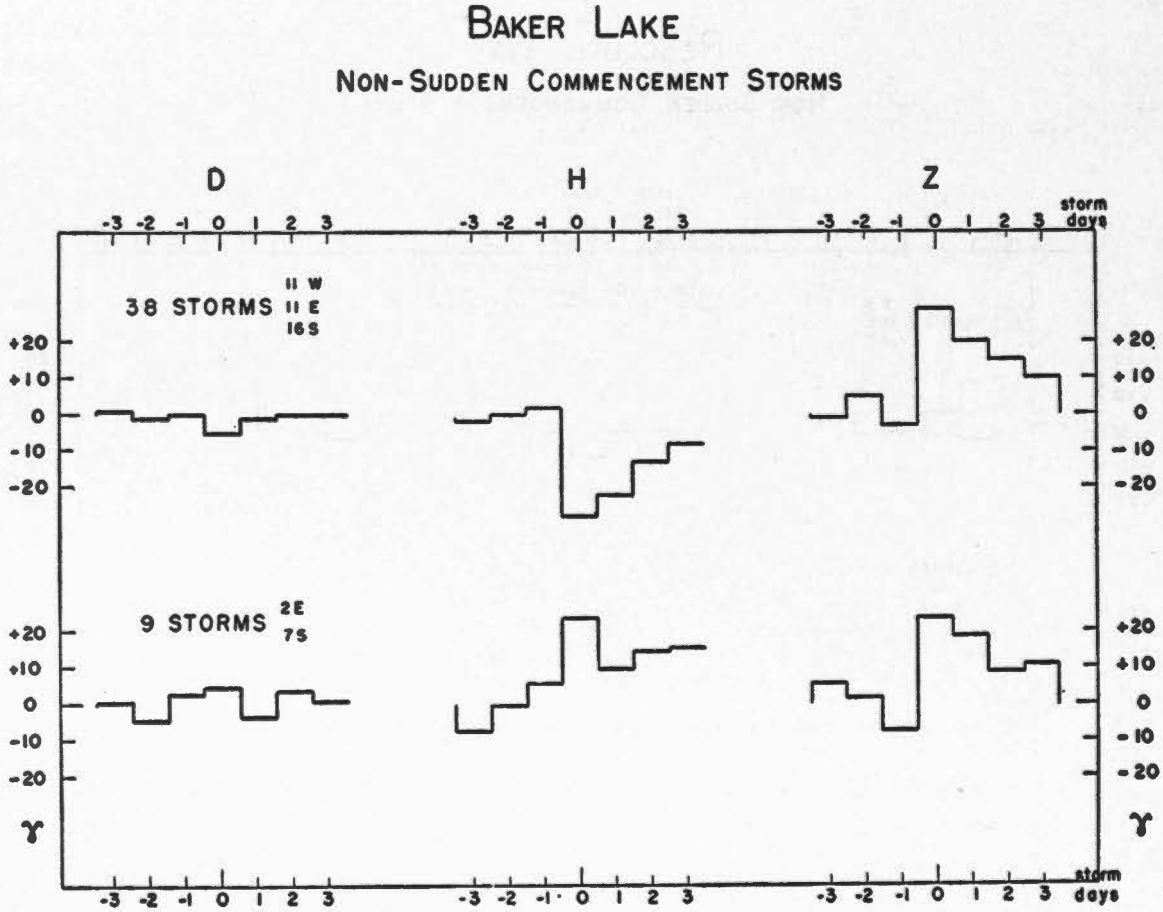
Mean Storm Changes	XT	YT	ZT
28 +ΔZ storms	-1	-2	+20
12 -ΔZ storms	+18	+8	-22

FIGURE 5. Mean storm changes for non-sudden commencement storms at Resolute Bay, 1953-1955.

storms might be in the corona. Non-S C storms at Greenwich also show 27 day recurrence characteristics, particularly near sunspot minimum, not shown by the S C storms, but do not show a storm-time variation.

The storms selected above were tested for storm-time effects using the superposed epoch method described above, and estimating the time of beginning of the storm day to the nearest hour. Such effects are very clear, and again two classes of winter type (+ Δ Z at Resolute Bay, − Δ H at Baker Lake) and summer type (− Δ Z at Resolute Bay, + Δ H at Baker Lake) storms are found. Figure 5 for Resolute Bay and Figure 6 for Baker Lake show the results, with the seasonal distribution and the mean storm changes defined as before, since no striking differences in the time constant of decay of the mean storm changes is apparent.

The mean azimuths determined from Baker Lake results are again between geographic and geomagnetic south for the − Δ H storms and north for the + Δ H storms.



Mean Storm Changes	Dγ	Hγ	Zγ
38 − ΔH storms	−2	−21	+21
9 + ΔH storms	+2	+16	+17

FIGURE 6. Mean storm changes for non-sudden commencement storms at Baker Lake, 1951-1955.

27-Day Recurrence Characteristics

The superposed epoch method has given results which suggest that there are no fundamental differences in storm-time between the S C and non-S C types of storm, although there do appear to be systematic differences in the ratio of horizontal to vertical field components and hence in the latitude of the effective atmospheric ring. The K-indices available from the two stations were used therefore to examine the recurrence characteristics of the two classes at both observatories. Since the K-indices are available until the end of March 1955 only, the results in Figures 7 and 8 do not apply to all the storms examined. The sum of K was subjected to a recurrence examination: it is considered that recurrence (a broad peak about 28 days after the onset of the storm) is shown for both classes of storms at Resolute Bay whereas the Baker Lake results are rather ambiguous. However irregular disturbance, bay-like events, pulsations, etc., which largely influence the K measure, persist several days longer for the S C storms than for the non-S C storms. It is concluded that residual disturbance does persist for a longer time in the case of S C storms, and this effect is believed to be real although it is the opposite to that previously accepted for moderate latitude stations (Newton and Milsom, 1954).

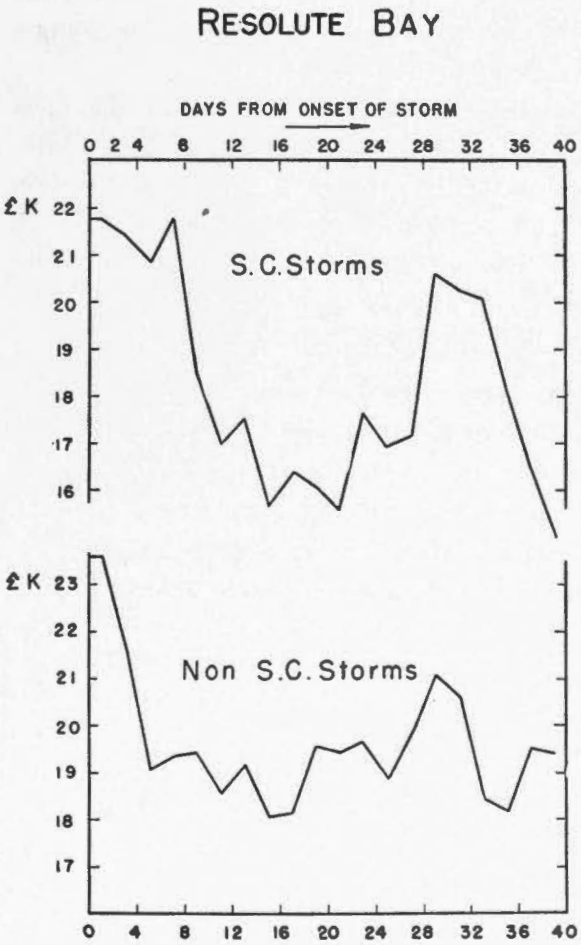


FIGURE 7. Recurrence of Σ K for non-sudden and sudden commencement storms at Resolute Bay.

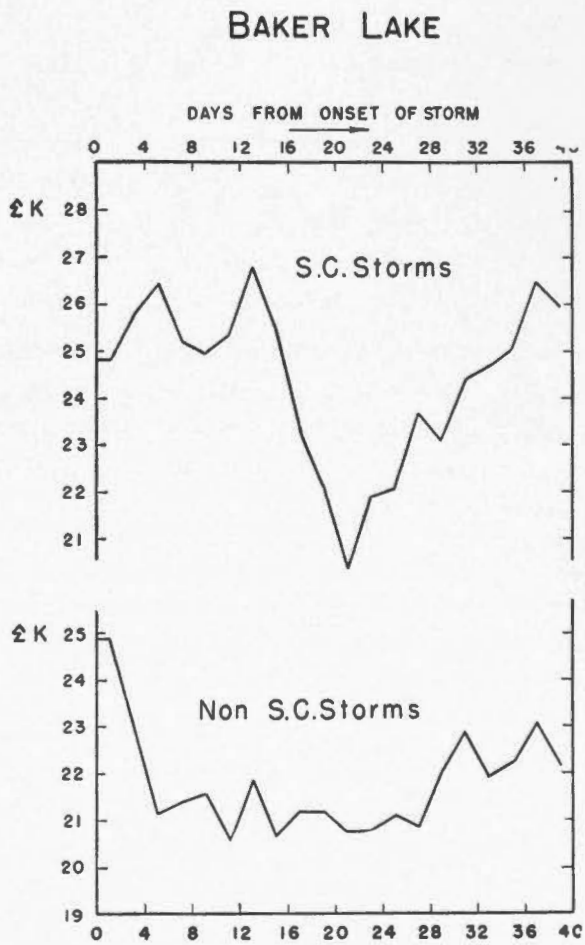


FIGURE 8. Recurrence of Σ K for non-sudden and sudden commencement storms at Baker Lake.

Since atmospheric current flow in high latitudes seems to provide the only reasonable explanation of highly differentiated storm-time patterns at high latitudes, and since such a current flow is commonly associated with an equatorial ring current, the suggestion follows that both S C and non-S C storms require the formation of an equatorial ring, but that the instabilities associated with the ring, producing bay-like and irregular disturbance, persist much longer than the zonal current flow, and possibly the ring itself in the case of the S C storms.

Alternatively if a completely atmospheric source is assumed for storms, and elementary polar disturbances are generated by wind action in the atmosphere (Vestine, 1954), the length of time that residual disturbance persists apparently requires entry of charged particles from the sun into the atmosphere at these latitudes for a longer period of time for S C type storms.

Non-Sudden Commencement Storms Common to Resolute Bay and Baker Lake

Eighteen storms were examined common to both observatories; 13 of these were of the winter type and the remaining 5, in the summer months, were of the opposite type. Table I shows the mean storm changes defined as before. The azimuths at both stations correspond closely to current flow along geomagnetic parallels of latitude. The changes were examined with the following results for the winter-type storms:

(1) if corrections for internal induction at both stations are made of the form $H_{obs.} = H_{ext.}(1 + \alpha)$ and $Z_{obs.} = Z_{ext.}(1 - \alpha)$ corresponding to a highly differentiated storm-time field at these latitudes and n in a P_n harmonic description assumed large, then a westerly current flow near geomagnetic latitude 71° is required at a height of 500 km. to obtain these results, and $\alpha = -0.5$ approximately. This sign would not be expected from the results at low latitude stations (Chapman and Price, 1930);

(2) alternatively, if a current at 100 km. in latitude 67° is assumed, then different corrections are required at the two stations: $\alpha = +0.68$ at Baker Lake and $\alpha = +0.87$ at Resolute Bay. However, an observed horizontal amplitude of more than twenty gammas would be expected at Resolute Bay and this is not observed. This model is therefore not very convincing.

STORM TYPE	Nº OF STORMS	RESOLUTE BAY			BAKER LAKE		
		X γ	Y γ	Z γ	D γ	H γ	Z γ
WINTER	13	-3	- 2	+26	- 1	-20	+28
SUMMER	5	+20	+19	-10	+ 5	+14	+26

TABLE I. Mean storm-time changes at Resolute Bay and Baker Lake for eighteen non-sudden commencement storms.

For the summer type storms the storm-time changes indicate an easterly current flow near latitude 81°N geomagnetic at a height of about 900 kms. with $\alpha = -0.3$ approximately.

It should be emphasized that there were no cases when a storm did not clearly fit into one of these two classes corresponding to westerly or reversed current flow, but occasionally storms do occur where the westerly flow at Baker Lake can move north of the station as the storm progresses.

Although it is obvious that the field of an equatorial ring current could not produce the $-\Delta Z$ changes found at Resolute Bay in the summer unless the ring is reversed, which is not reported at lower latitudes, it is instructive to compare the horizontal components found with those to be expected in the field of such a current ring for the winter type storms. The potential of a strictly linear circular current of radius R expressed in terms of spherical polar coordinates with respect to the earth's centre and axis is

$$2\pi i \sum_{n=0}^{n=\infty} (-1)^n \frac{1.3 \ldots\ldots (2n-1)}{2.4 \ldots\ldots 2n} \left(\frac{r}{R}\right)^{2n+1} P_{2n+1} (\cos \theta)$$

The principal term at low latitudes is that for $n = 0$, and the horizontal to vertical components ratio is $\frac{1+\beta}{1-2\beta} \cdot \tan \theta$, where the fraction β has its origin in sources internal to the earth and θ is the colatitude. We can immediately deduce that at Resolute Bay it is required that $\beta = 0.04$ and at Baker Lake $\beta = 0.24$, and the corrected perturbing vectors at the two stations are 24 gammas at Resolute Bay and 29 gammas at Baker Lake instead of being equal. Since Chapman and Price (1930) have shown that at low latitudes $\beta = 0.42$ effectively for $n = 0$ in the above expression, it is not very convincing evidence for an explanation of storm-time changes produced entirely by extra-atmospheric current flow, and more complex atmospheric zonal currents than those discussed above seem a more likely explanation.

Relation to Theories of Magnetic Storms

The relation of these findings to theories of magnetic storms is obscure. It appears at any rate that the incomplete corpuscular theory of Chapman and Ferraro (1931) and Martyn (1951) does not anticipate the summer-type storms. The possibility of a dynamo origin of magnetic disturbance generally, including the main phase and the D_{st} components of storms has been discussed in great detail by Vestine (1954) and Fukushima (1953). Vestine (1954) has discussed the difficulties regarding conductivity and the driving force of the wind systems. It seems worthwhile pointing out that in the summer months over the polar cap, appreciable changes in heat driven air circulation of the upper atmosphere might reasonably be expected though whether they would correspond to a reversal of the zonal and meridional flows deduced by Vestine (1954) for the main phase of what we would call a winter-type storm is not clear. Data from southern polar cap stations might provide an important check.

CHARACTERISTICS OF BAY DISTURBANCE

Bay occurrence is a very characteristic feature in the magnetograms from Resolute Bay and Baker Lake, being particularly evident nearer the auroral zone at Baker Lake.

It may be regarded as the elementary polar disturbances of Birkeland (1908) and shows a variety of pattern and form. Meek (1954) has examined the relationship between bays, visible aurora and ionospheric phenomena at Saskatoon and elsewhere, and other authors (Fukushima, 1953) have examined the form of the bay field during certain well defined bays using polar year data. A systematic study of the properties of bays north of the auroral zone has apparently not yet been made.

Selection and Measurement of Bays

The magnetograms on each of the days whose selection is described in the first part of this study were examined, and bay occurrence, duration and average amplitude noted. Since the change in time of particular appearances of the bay field has been previously studied (*see* for example, Fukushima 1953), this interesting aspect was not considered further. Instead the amplitude measured was an estimated mean for the entire duration of the bay.

Because of the complexity of the magnetic disturbance on the selected disturbed days and the high level of irregular disturbances at both observatories, it was found necessary to arbitrarily measure only those events with a duration exceeding one half hour and persisting less than two hours. Only those bay-like events were measured where the beginning and end of the disturbance could be determined: at times of irregular disturbance this condition becomes virtually the same as that of being definite in at least two components. Many bays are obviously double, but this complexity was ignored in the succeeding analysis. It is also possible to recognize certain differences in type of bays (e.g. those with a sharp and often pulsational beginning are common at Baker Lake) and seasonal differences in definition seem to be present, but a more complete classification must be deferred until a later publication. Occasionally bay-like events were noted in which rapid sign changes occur in the horizontal perturbing vector. These were particularly noticeable in certain polar cap records, and should be studied synoptically.

Characteristics of the Bays at Baker Lake

Since bays are much more evident nearer the auroral zone, it seems reasonable to discuss first the findings at Baker Lake. Figure 9 shows the diurnal distribution of bays for three seasons on the selected disturbed days and the diurnal variation during the year 1954 for all selected disturbed and quiet days in the year. The quiet day data represents the pattern expected from residual disturbance, and can therefore be neglected in this treatment. A pronounced peak at about 23:00 hrs. L.T. or 22:00 hrs. local geomagnetic time is apparent in all three seasons. This peak is not at all sharply defined, and has a half-width of between 4-h and 5-h in all seasons. Figure 9 also indicates the average number of bays per selected disturbed day, and a small equinoctial maximum is found. This requires that the total number of bays also reaches a maximum in the equinoxes. It is not clear if the minor peaks evident in Figure 9 are real.

Figure 10 shows the diurnal variation of the average bay amplitude in different seasons and in 1954 at Baker Lake, obtained by finding the average amplitude in each field component in three hourly intervals of the day. The curves are dashed where the

points are based on a total of fewer than five bays. From these curves it is simple to derive an equivalent line current which would produce such a D V in bay amplitude. This is discussed later.

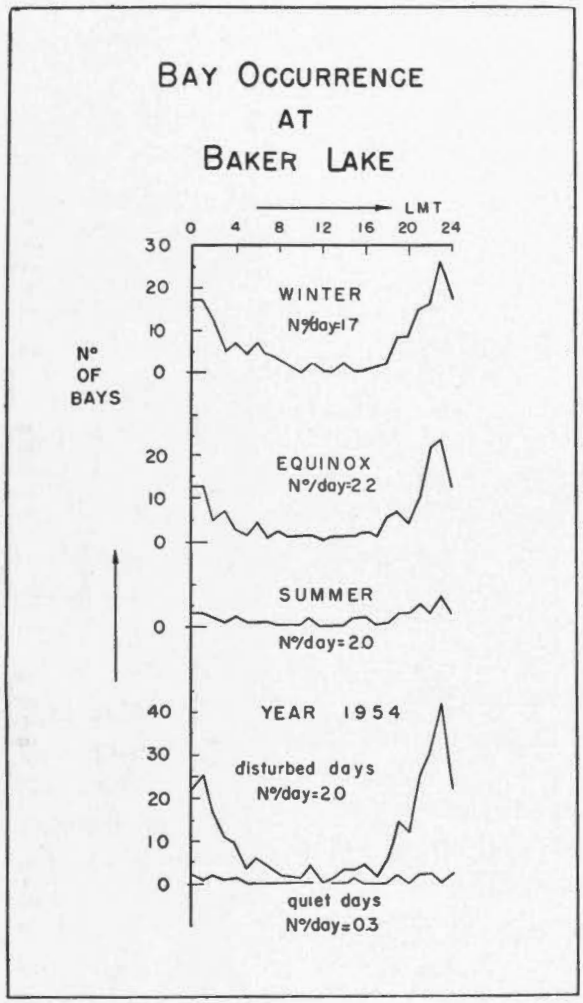


FIGURE 9. The diurnal frequency distribution of bays on local disturbed days at Baker Lake during three seasons.

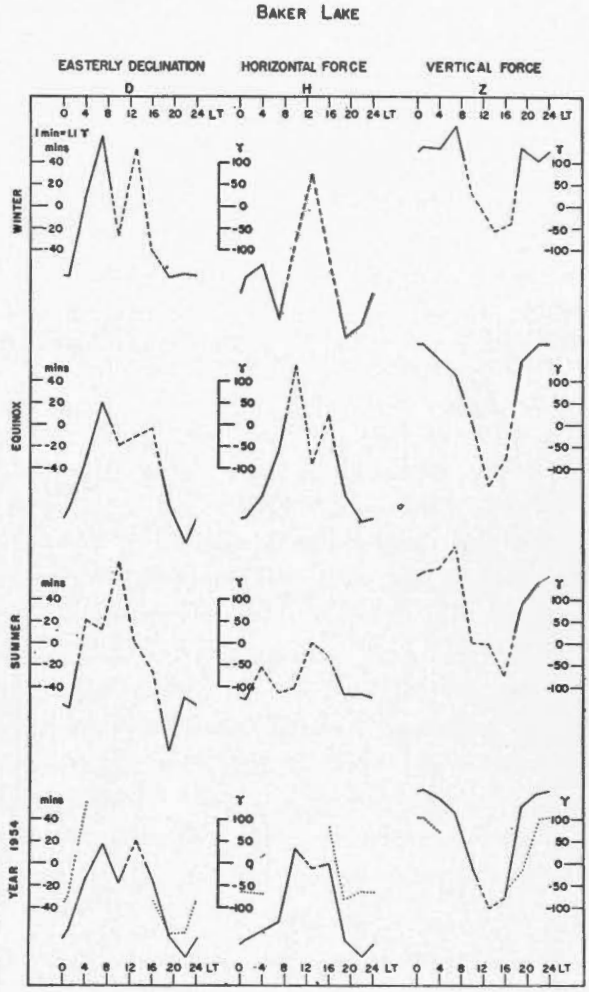


FIGURE 10. The diurnal variation in three force components of the average bay amplitude on the selected disturbed days during three seasons at Baker Lake. The dotted lines indicate the partially derived diurnal variation of the average bay amplitude on the selected quiet days during 1954.

Characteristics of the Bays at Resolute Bay

Figure 11 shows the D V in frequency of occurrence and Figure 12 the D V in the average bay amplitude at Resolute Bay. The data refers to the selected days at Resolute Bay described in Part I. The frequency of occurrence of well-defined bays on any day at Resolute Bay is almost one half that found at Baker Lake: this is true for all seasons, and on both the selected quiet and selected disturbed days. This suggests that half the bays identifiable to the north of the auroral zone can be seen over the polar cap. There are two peaks of occurrence, near 22:00 hrs. and 13:00 hrs. L.T. respectively; the night peak is predominant in the winter months and the midday one in the summer months, whilst they are about equal in the equinoxes. Both peaks are very broad

On the very quiet days discussed in Part I of this paper, only one very small bay at Baker Lake was found.

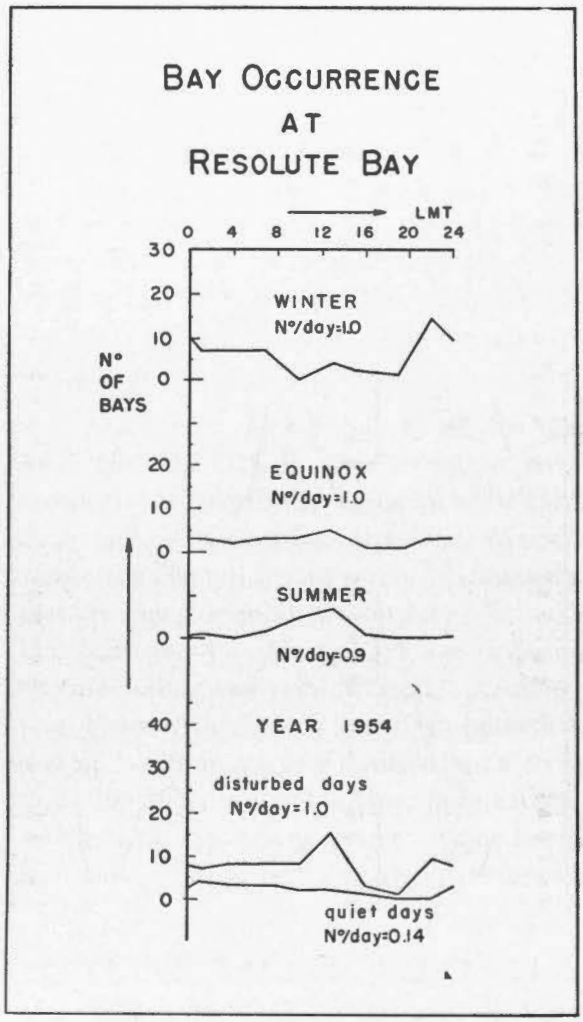


FIGURE 11. The diurnal frequency distribution of bays on local disturbed days at Resolute Bay during three seasons.

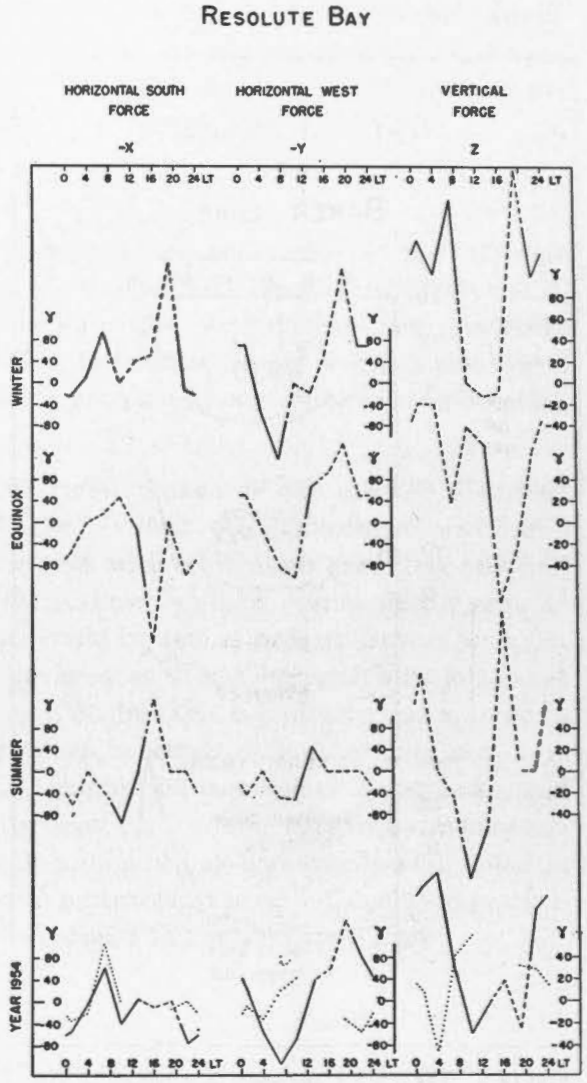


FIGURE 12. The diurnal variation in three force components of the average bay amplitude on the selected disturbed days during three seasons at Resolute Bay. The dotted lines indicate the partially derived diurnal variation of the average bay amplitude on the selected quiet days during 1954.

Duration of the Bays

At Resolute Bay the average duration of all bays on the selected disturbed days was 1.3 hours with insignificant seasonal differences: on the selected quiet days the average duration was 1.1 hours. It is not clear whether this difference is real and what its implication is in such a case, since the infrequent bays on quiet days have amplitudes comparable to the average amplitudes found on disturbed days for bays appearing at the same period of the day.

In deriving the bay field the approximation was made that all bays last equally long—about one and a quarter hours: this seems reasonable since no systematic DV in duration is apparent from the inspection of many magnetograms.

Relation to Irregular Disturbance

It is clear that a number of bays are not considered because of practical limitations and the background of low frequency magnetic noise on the magnetograms. At Baker Lake the very large amplitude pulsational noise frequently found on the magnetograms always appears in the interval local noon $\pm$ 6 hours, i.e. around the bay occurrence minimum. Because of the masking effect of this noise, it is possible that the evening peak in bay occurrence has been unintentionally emphasized. This is not, however, very likely since on days when no such masking noise is present, an evening peak in bay frequency is still pronounced. It seems possible that the noise bursts and bay activity are closely related, and can both be regarded as produced from peculiar instabilities in an equatorial ring. The relationship between them should be studied further. Irregular oscillations and noise bursts often begin abruptly and less frequently end abruptly. Relationship with daylight aurora is a possibility.

At Resolute Bay, well inside the polar cap, irregular oscillations occur less frequently and with smaller amplitudes: however they too appear in the interval local noon $\pm$ 6 hours. It should be emphasized that this aspect of disturbance is not a daylight zone phenomena. It occurs frequently in winter when both observatories are in darkness.

Large pulsations, usually very clear in vertical force, with amplitudes of a few tens of gammas and periods from 5 to 10 minutes were noted on occasion at both observatories. The regularity of these pulsations is pronounced in contrast to pulsational noise. It was noted that the abrupt start to well-defined pulsations can often be seen to take the form of a higher frequency pulsational burst, suggesting a possible local atmospheric resonant phenomenon. At Resolute Bay, during a great part of the total period under investigation the sensitivity of the Y variometer was several times larger than that of the X and Z variometers. It was then apparent that irregular pulsations of low amplitude are very commonly present. All periods from the shortest resolvable, 1 to 2 mins., up to a half hour or so are recorded at different times.

The 24-h Recurrence of Bays

This property of bays is very easily seen at even a casual inspection of Baker Lake magnetograms. At Resolute Bay it is less pronounced. Further detailed studies are required but a number of preliminary conclusions are possible:

(1) the recurrence interval can commonly vary by up to 2 hrs. from 24 hrs.,
(2) the average recurrence time of the bays is apparently nearer 23 hrs. than 24 hrs.,
(3) there is the suggestion at Baker Lake that bays occurring before local midnight have an average recurrence interval less than 24 hrs., whereas often, but not always, bays developing after local midnight recur later than 24 hrs.

This should be investigated further but suggests that if bay particles are ejected from equatorial ring instabilities, then an analysis of recurrence may throw some light on the drift motions of the instabilities. It should be emphasized that because of changes in form it is not always possible to measure the recurrence interval very exactly. At Resolute Bay where bay forms usually have less clear commencements, it is only possible to say that deviations from 24 hrs. occur and that the mean value is somewhat less than one day.

The Amplitude of Bays on the Selected Quiet Days

Although bays occur on the selected disturbed days about seven times more frequently than on the quiet days, it appears that the rather inaccurately determined D V in bay amplitude at Baker Lake is much the same on both types of days, see the dotted lines in Figure 10. At Resolute Bay (*see* Figure 12) the results are much more ambiguous, but so are the bays. It is suggested therefore that at least near the auroral zone, the average amplitude of a bay appearing at a given local time is much the same on local quiet and disturbed days. This result would perhaps not be expected, since most theories require a close relationship between bay amplitude and the disturbance daily variation. However, it is hoped to investigate this further at some later date.

The Relationship between Bays and Auroral Activity

Davies (1950) has discussed the diurnal occurrence of aurora across the auroral zone in Canada and concluded that auroral activity reaches a maximum about one hour before local midnight at the centre of the auroral zone, and appears to become progressively later with respect to local midnight south and north from the centre of the auroral zone. Towards the northern limit of the effective auroral zone, a diurnal maximum appears in both morning and evening hours: thus winter observations at Clyde (Φ = 81.5°N) showed maxima about 19:00 and 06:00 L.T. This morning maximum at 06:00 L.T. was observed at Chesterfield Inlet during the polar year 1932-33. The frequency of occurrence of radiation 3578 Å of the second positive system of nitrogen corresponds to that of bright and active auroral bands and rays and was found to have a maximum at about 23:00 L.T at Chesterfield Inlet. No secondary morning maximum of occurrence of this line was found by Currie and Edwards (1936). This maximum close to local midnight corresponds closely to the peak in bay occurrence shown in Figure 9. Visual observations at Baker Lake also confirm the presence of bright active aurora often covering a great part of the sky during bay occurrence, and so it seems quite possible that magnetic disturbance during bays is produced by the moving charged particles in the auroral forms.

The relationships of the changes observed in Figure 11 to auroral frequency at Resolute Bay is unknown. Daytime measurements on aurora by radio means during the summer months to discover the significance of the midday peak should be undertaken, if possible.

Positive and Negative Bay Occurrence at Baker Lake

The averaged data show that positive bays in Δ H are infrequent at Baker Lake. The diurnal frequency of occurrence of negative bays is therefore much the same as that shown in Figure 9, but positive bays occur throughout the day with a diffuse maximum near 16:00 L.T. which may not be significant. It should be noted that these results are different from those reported by Meek (1954) at Saskatoon. Figure 13 summarises the findings for more than 300 positive and negative bays examined in this analysis.

Comparison with Martyn's Theory of the Auroral Zone

Martyn's (1951) theory of aurora predicts an auroral zone of $\sim$5° latitude in width with auroral effects produced by precipitation, along magnetic lines of force, of positively and negatively charged particles from an equatorial ring about five earth's radii away.

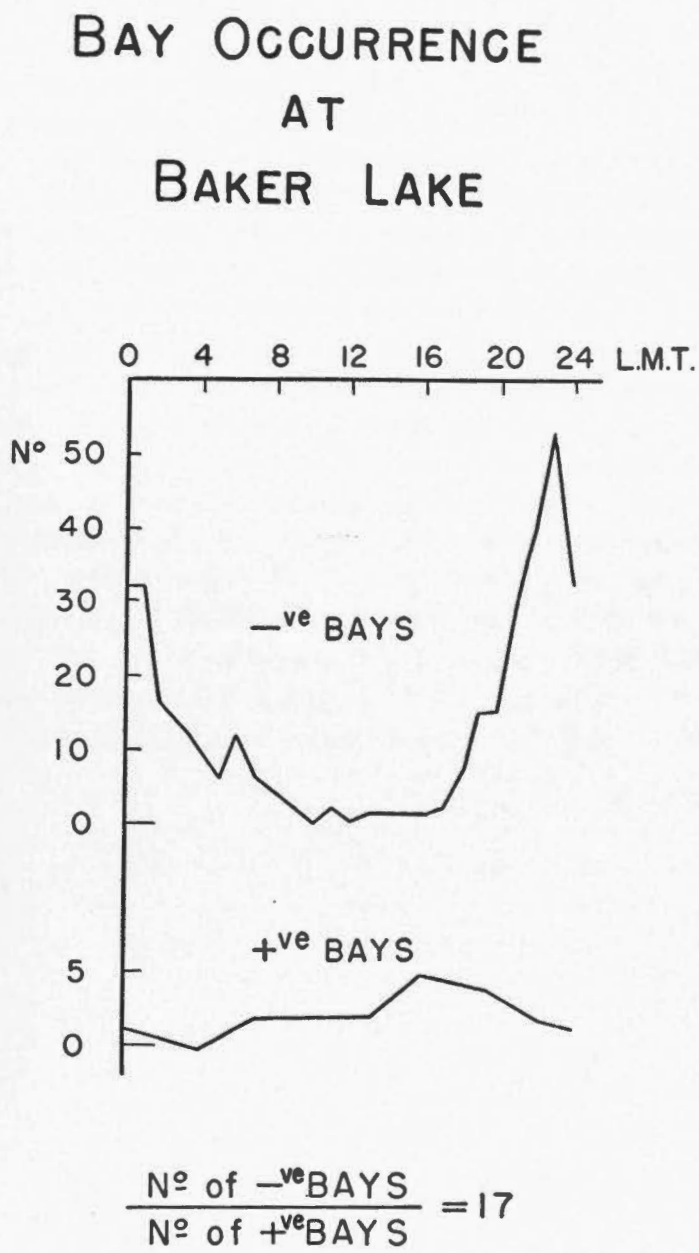


FIGURE 13. The diurnal frequency distribution of all positive and negative bays measured at Baker Lake.

In the early stages of disturbance during the afternoon and early evening, precipitation of positively charged particles occurs at the northern edge of the auroral zone and negatively charged particles at the southern. After midnight this situation is reversed, and in the final stages of disturbance the latter condition is thought to exist in both the morning and evening. Drift currents in which the positive ions drift faster than the negative are set up, and are thought to explain certain ionospheric and magnetic phenomena. The current system of bay disturbances is regarded as similar to that for the diurnal disturbance variation but advanced in phase 6 hours.

Thus it would be expected that during the early phase of a storm at a station like Baker Lake, negative bays ($-\Delta H$, $+\Delta Z$) would occur in the period from 6 p.m. to 6 a.m. and the positive bays ($+\Delta H$, $-\Delta Z$) in the period from 6 a.m. to 6 p.m. In the later main stages of a storm, negative bays should occur over 24 hrs. Figure 13 shows that during disturbed days no clear cross-over times are found, although positive bays are found mainly in the hours around noon and negative bays in the hours around midnight. The presence of negative bays at all hours, since they occur throughout the day in the main phase of disturbance, might be expected. It should also be noted that the total number of positive bays found at times not predicted above is small.

It is difficult to determine at a station like Baker Lake if positive bays develop during the early phase of a disturbance since disturbance is more or less continuous. Thus examination of the magnetograms at the times of positive bay occurrence suggests that such is not the case, but an examination of the international character figures for the days of positive bay occurrence show that most of them correspond to a local maximum in the C_i figure. Bay occurrence on quiet days, which it might be thought could be regarded as definitely referring to the very early stage of disturbance, revealed 21 negative bays (between 19:00 and 05:00 L.T.) and 1 positive bay (15:00 L.T.): these do not contradict the expectations of theory.

It was noted that the tendency of the small number of positive bays to appear in the equinoxes is striking, during the 17 months data used around sunspot minimum.

At the northern edge of the zone, negative changes in ΔZ should occur in the period 6 a.m. to 6 p.m. in the early phase of disturbance and should be associated with $+\Delta H$ changes. 29 cases only out of more than 300 bays have $-\Delta Z$ movements at Baker Lake; 17 of these occur in the predicted time interval but only 12 are associated with $+\Delta H$ changes. It is concluded that bay phenomena at Baker Lake are not very perfectly explained in terms of Martyn's theory.

At Resolute Bay the situation is more complex and the summer midday peak is associated with $-\Delta Z$ changes whilst before noon ΔX and ΔY are positive and after noon largely negative. This corresponds to current flowing easterly on the a.m. side and westerly on the p.m. side which is the reverse of idealized concepts of current flow producing the disturbance daily variation near the auroral zone. Furthermore the current system of the bay disturbances is effectively south of the station before noon and north in the afternoon hours. The data from the winter months which show a peak in frequency of occurrence before midnight correspond largely to $+\Delta Z$ changes and changes in the geomagnetic horizontal component to the south. This is what would be expected in the main phase of disturbance. The Resolute Bay bays occurring near noon in the summer months appear different in character from, and more diffuse than, the evening bays in the Baker Lake magnetograms, suggesting again that a different origin and explanation is required.

The suggestion of occurrence of a bay current system of limited size appearing inside the polar cap during the summer seasons is an important one. Its morphology appears in certain respects to be the opposite of that associated with the auroral zone, which suggests a relation with the reversed summer type of storm discussed above. The relation to the

inner zone of high magnetic disturbance suggested by Russian Arctic research is not clear (Anon., 1954), and it may be a reflection of an outer equatorial ring with reversed properties from the Martyn (1951) ring. Alfvén (1955) in a recent discussion of his electric field theory of magnetic storms and aurora has shown that if the inertia of the storm-producing beam is considered, a second ring current is produced which flows anticlockwise at about 30 earth radii and he assumes this to be an extra-atmospheric source of the initial phase (I P) of storms, associated with an inner auroral zone with a polar distance of 5°-10°. The theoretical duration of this I P is a few minutes only. Whitham and Loomer (1956) have shown that disturbance at Resolute Bay and Baker Lake is highly correlated in general and the results in Part I of this paper make it clear that there are no cyclic field changes at Resolute Bay analogous to those found at Baker Lake; these results suggest little support for the existence of an inner auroral zone magnetically. However, the anti-clockwise ring in Alfvén's theory exists together with the usual clockwise ring in the main phase of storms, and it is interesting to wonder if its properties are associated with the probably atmospheric zonal currents discussed above for summer-type storms. If this is the case, it should be possible to show that at lower latitudes the usual pattern is present and there might be interesting time differences apparent in the development of the two, and interesting relations between the magnitude of the two systems. It is hoped to pursue this point in a later publication. The seasonal nature of the reversed ring is difficult to understand on this hypothesis. Considering all the results in these papers it seems difficult to support the contention that observational data require the existence of an inner auroral zone, but obviously much more work is required.

Another possibility is that a real change occurs in the heat driven air circulation of the upper atmosphere as discussed earlier. This is required if a dynamo origin for the main phase of storms and bays is accepted. It is then reasonable that partial appearance in the equinoxes is possible, but not at all clear why two apparently reversed modes of zonal and meridional air circulation can exist with different frequency in different seasons.

The unusual features at Resolute Bay may be a consequence of the pronounced non-dipole properties of the earth's magnetic field in Canada. Thus the vertical force map of Canada suggests the presence of a large regional pole over the barren lands, and Resolute Bay is only about 100 miles from the dip pole of the earth's field. It seems likely that theories involving the interaction of the field with single incoming charged particles, or leakage down lines of force to the lower atmosphere, would produce unique observational aspects at the Canadian Arctic observatories. Against this viewpoint is the experimental result of surprisingly good geomagnetic control in much of the data discussed. One obvious need is a similar discussion for the Antarctic.

Relation of the Bay Field to the Disturbance Daily Variation

Figures 10 and 12 show the diurnal variation in bay amplitude, independent of the probability of appearance of a bay in any interval. These curves show striking similarities with the disturbance daily variation curves discussed in the previous paper: however, agreement in form is not very good for the horizontal component at Baker Lake and the vertical component at Resolute Bay. Fukushima (1953) in an examination of the equivalent current systems of the field of elementary polar disturbances has arrived at two

groups, one of which corresponds to the equivalent current system of the average disturbance daily variation field, or of the average bay field, and one in which marked differences occur because of a predominant westward auroral zone flow. The simplest pattern is thought to be similar to the electric current system on a conducting spherical surface caused by an electric doublet situated on the auroral zone and directed westward. Bays are thus considered to be a temporary appearance of a polar magnetic storm within a short duration of time.

The analysis considered here supports the idea that the bay field represents a temporary appearance of a systematic disturbance field, similar to, but not identical with, that of the disturbance daily variation. It would also suggest that the presence of a current ring is a necessary condition for the appearance of bays. To search for the presence of D_{st} in the field for a few hours before a bay occurs is very difficult at Baker Lake since the reference value for the month in any component is so uncertain. It is thought that at the present time such a determination is not possible. However, at Resolute Bay where the magnetic conditions are less disturbed, a test of this sort using the Z component was attempted with inconclusive results. Once again the correct reference values to use are difficult to determine.

Relation to Polar Blackouts

Wells (1947) has discussed the relation between individual bays and radio blackouts at College, Alaska, and explained the latter by the development of intense ionization in the ionosphere below the normal E layer, produced directly or indirectly by the incoming charged particles. Cox and Davies (1954) have published statistical studies on blackouts recorded at ionosphere stations in Canada, including Baker Lake and Resolute Bay, over the period 1949-1952. The DV in frequency shows a well-defined maximum near 11:00 L.T. at Baker Lake and two maxima near 06:00 hrs. and 13:00 hrs. L.T. at Resolute Bay. More blackouts are observed at Resolute Bay (500/year) than at Baker Lake (250/year). Considering their evidence with the bay analysis presented above, it is by no means clear that the direct relationship reported by Wells (1947) can be said to be evident, and a direct examination of the radio data might be of help in considering the classification of bays.

It should be noted that the times of maximum K index at the two stations are 09-12 hrs. 90°W meridian time at Baker Lake and 12-15 hrs. at Resolute Bay in agreement with the times of maxima found by Cox and Davies (1954). However by the geomagnetic latitude of Meanook ($\Phi = 61.8°$) even this agreement disappears.

THE GEOMAGNETIC POST-PERTURBATION

The monthly mean values of the geomagnetic field undergo changes due to the variation of average disturbance with season and the effect of disturbance on the daily means. One convenient measure of this effect is provided by the average D_m field defined by the mean daily values for disturbed days minus those for quiet days. Second order errors produced by secular change and base-line errors are unimportant. The annual variation can then be regarded as produced by this averaged field appearing in different months

with different frequency and intensity. The seasonal variation in disturbance at Baker Lake and Resolute Bay is discussed in Part I of this paper.

The annual variation in 1954 is shown in Figure 14 together with estimates of the secular change rate in that year. Figure 14 also shows the monthly variation in the D_m field derived for each month using the selected quiet days and disturbed days discussed in Part I. It is clear that partial appearance of this field in different months can explain the main features observed in the annual variation. The Z component shows the largest annual variation and also the greatest variation from month to month in the D_m field.

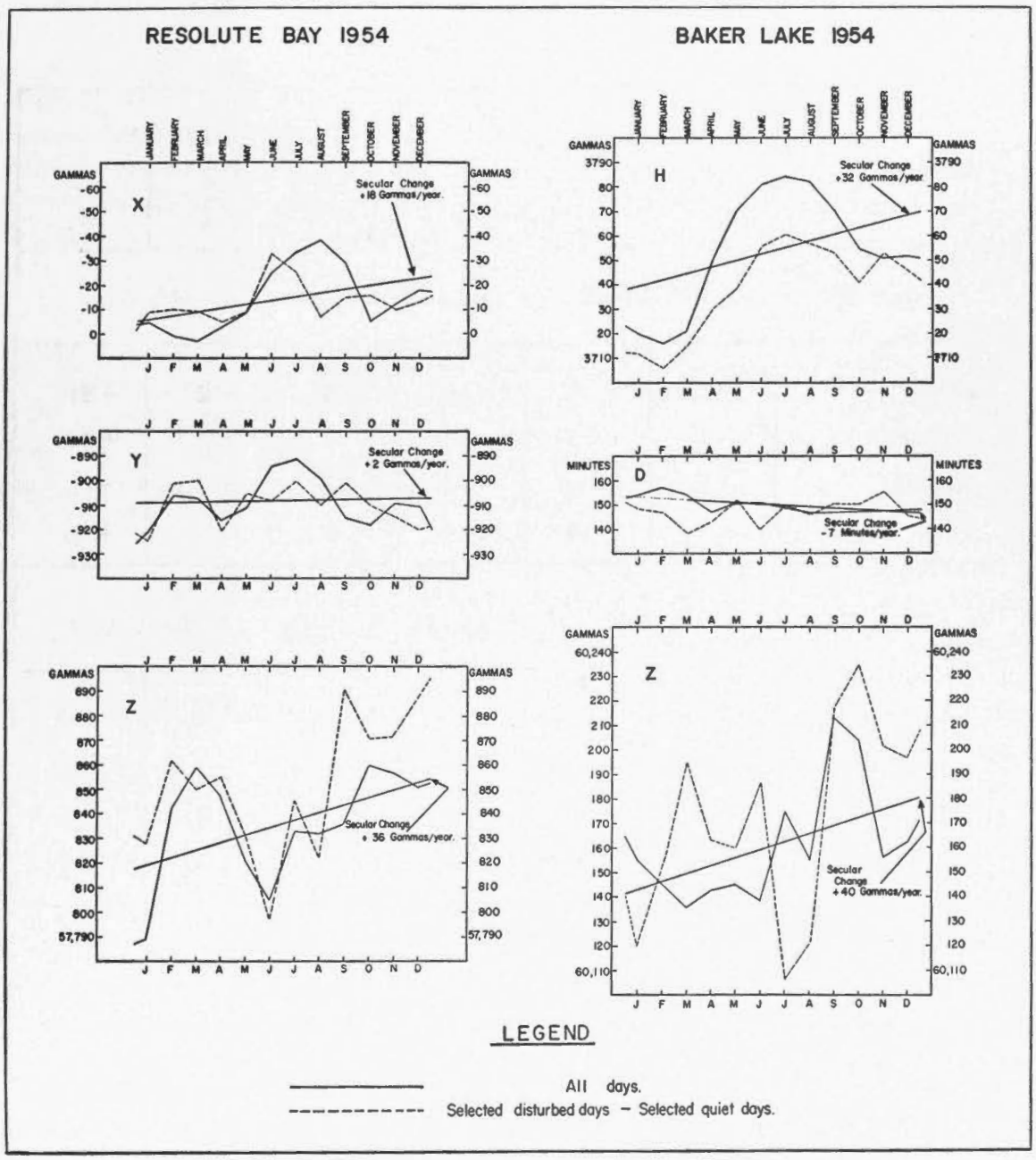


FIGURE 14. The annual variation in 1954 at Resolute Bay and Baker Lake: all day means and selected disturbed minus selected quiet means are shown. The ordinates of X Resolute Bay are shown reversed in the figure in error.

In view of the studies which have been made using the relatively easily computed D_m field values, it is of interest to consider the contributions of the different phenomena described previously to the measured D_m values. Table II shows the seasonal value of the D_m field to the nearest gamma, over 17 months in 1953-55, and the value for the year 1954; since the number of disturbed days/month varies in the selection made in Part I the monthly values were weighted according to the number of selected days/month in this determination of field components. This is thought to give the purest form of D_m variation but the results were not substantially different with each month assigned equal weight. Also shown is an estimate of the influence of the bays measured and defined as described earlier.

SEASON	BAKER LAKE			RESOLUTE BAY		
	D γ	H γ	Z γ	X γ	Y γ	Z γ
D_m = SELECTED DISTURBED − SELECTED QUIET DAY MEANS						
WINTER	−2	−28	+18	−6	−2	+31
EQUINOX	−5	−23	+46	−3	+3	+31
SUMMER	−3	+1	−40	+2	+3	−1
YEAR 1954	−3	−18	+14	0	0	+21
ESTIMATED CONTRIBUTION OF SELECTED BAY DISTURBANCE						
WINTER	−4	−20	+11	−1	0	+5
EQUINOX	−10	−21	+18	+1	−1	+3
SUMMER	−5	−11	+12	+2	0	−2
YEAR 1954	−7	−18	+14	+1	0	+2

TABLE II. Seasonal values of D_m field and estimated contributions from the bay field at Resolute Bay and Baker Lake.

At both observatories it is clear from Table II that this measure represents largely the average effect of bays; the residual part of the D_m components must correspond to the averaged effect of storm-time and irregular variations. The only serious discrepancy occurs in Z Baker Lake where the influence of bays is of opposite sign to the D_m field recorded; when zonal terms corresponding to the average pattern of summer-type storms (*see* Figure 6) are added, the discrepancy is increased. This may mean that the residual

effects of the summer-type storms on average disturbed days correspond to easterly flow south of Baker Lake (whereas the concentration is usually to the north during the first few days of a storm). This seems unlikely both numerically and in view of the time constant of decay of the order of one day discussed earlier. Alternatively it appears that the average effect of irregular disturbance during the summer months is largely to depress the Z field component, a surprising result. At Resolute Bay, the influence of measurable bays is much smaller and we conclude that the D_m field is effectively a description of the averaged zonal terms described earlier.

In any case the magnitude of the difficulties in reducing field observations to a satisfactory epochal value is clear, and the authors suggest that the only reliable secular variation data is that obtained from observatories operating continuously, and programs of repeat observations at infrequent intervals over short durations are of doubtful use. The magnitude of the seasonal changes is such that the determination of 11-year cycles in secular variation near the auroral zone should be quite feasible. There are certain suggestions of this (Barta, 1956).

NON-CYCLIC CHANGES

In the harmonic analysis of the selected groups of days described in Part I, the non-cyclic changes were removed mathematically, assuming a linear variation with time to be a good physical approximation. Because of irregular disturbance, not completely removed in the use of hourly mean values, it is not certain how regular such changes are. For the three classes of selected days at Baker Lake, Table III shows the results of an analysis of non-cyclic changes in the Z component for three seasons. The storm-time analysis showed that the main phase of storms usually results in a Z enhancement at Baker Lake: therefore on disturbed days on the average one might expect a positive or zero non-cyclic variation and on quiet days a negative variation on the average. Such simple results are not found in the selection made, except in so far as the non-cyclic change on disturbed days is always smaller than on quiet days, and the equinoctial results do show the predicted pattern.

SEASON	DISTURBED DAYS	QUIET DAYS	VERY QUIET DAYS
WINTER	−0.2 γ	+6.8 γ	+5.6 γ
EQUINOX	+2.7 γ	−5.6 γ	−8.0 γ
SUMMER	−1.9 γ	+5.6 γ	(NO DAYS)

TABLE III. Non-Cyclic changes in Z, Baker Lake 1954, for three selected classes of days.

There is a suggestion therefore that because of the influence of bays and irregular variation, the corrections introduced in Part I are not always physically plausible. However, it is apparent from Table III that the corrections introduced to the sine components do not exceed 2 to 3 gammas on the average in even the first harmonic, and the final statistical uncertainties exceed this. This investigation suggests that the practice of publishing calculated non-cyclic changes may be worthless for high latitude stations.

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