Annual Variation of the Geomagnetic Field in Polar Regions

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極地域における地球磁場季節変化

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要旨：極地域においては，地球磁場が顕著な年周変化を示す．世界各地における 1957–1964 年の地磁気 H 成分と Z 成分観測値を用いて，この極地域独特の年周変化を研究し，中低緯度地域における地磁気年周変化との関連も併せて求めた．オーロラ帯以外の地域においては，地磁気年周変化の振幅・位相ともに磁気緯度に対してゆるやかに変化している．極地域の地磁気年周変化振幅には太陽活動周期との関係が見られるが，太陽黒点数よりは地磁気活動度に対して良い対応を示している．その際地磁気 H 成分と Z 成分とでは影響の受け方がやや異なっている．また，極地域における地磁気年周変化振幅は，惑星間空間磁場の南北成分 B_z に明らかに依存しており，B_z が南向きの時の方が，北向きの時に比べてより大きな年周変化振幅を示し，その傾向は地磁気 Z 成分よりも H 成分の方により大きくあらわれる．

Abstract: The annual variations of the geomagnetic field H and Z are studied by means of the data from worldwide stations during 1957–1964 The amplitudes and phases of the annual variations change smoothly with geomagnetic latitudes, except for the data within the auroral zones The amplitudes of the annual variations of H and Z in the polar regions show a clear dependence on the solar cycle. The solar-cycle modulation of the amplitudes is in approximate proportion to the geomagnetic activity rather than to the sunspot number. The modulation of H is different from that of Z in some years. The amplitudes of the annual variations of H and Z in polar regions depend clearly on the north-south component of interplanetary magnetic field, B_z When B_z is southward the amplitudes are larger in comparison with the cases of northward B_z The B_z-dependence of the annual variation amplitudes is greater for H than for Z.

1. Introduction

In recent years the annual variations of the geomagnetic field have been dis-

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cussed in connection with the configuration of the magnetosphere, the position of ring current in the magnetosphere, and the latitude of auroral electrojet in the ionosphere, all of which seem to depend on the incident angle of solar wind with respect to the geomagnetic axis.

A remarkable depression of the vertical component Z of the geomagnetic field is observed in summer in the polar region, as was first pointed out by VESTINE *et al.* (1947), and later by NISHIDA *et al.* (1966). The latter authors suggested that the geomagnetic field lines from the polar regions might be most effectively tilted in summer towards the night-side of the earth under the seasonal (annual) variation in the incident angle of the solar wind to the geomagnetic dipole axis. Recent studies by MANSUROV and MANSUROVA (1971) and SVALGAARD (1973) pointed out the modulation of the annual variations in the polar cap by the B_y-component of interplanetary magnetic field (IMF).

For middle and low latitudes, the horizontal component H of the geomagnetic field on disturbed days was demonstrated first by CYNK (1939) to be asymmetric with respect to the geomagnetic equator in the solstitial seasons, and this asymmetry seems to be interpreted by the annual variation in the position of the ring current in the magnetosphere on the night-side (FUKUSHIMA and NAGATA, 1968). MALIN and ISIKARA (1976) studied the all-day mean values of the geomagnetic field at stations in a wide range of latitudes, and they reached a similar conclusion concerning the annual variation in the magnetospheric configuration. They suggested also the annual variation in the latitude of auroral electrojet in the ionosphere.

Our present knowledge of the annual variation of the geomagnetic field is still too poor to interpret it in connection with the earth's environmental space. In order to contribute to the morphological study of the annual variation, the following characteristics are studied in this paper; *i.e.*

1) Annual variations for H and Z at each latitude,

2) Annual variations at some stations over a sunspot cycle,

3) Dependence of the annual variations of the geomagnetic field in the polar cap on the B_z-component of the interplanetary magnetic field.

2. Data Analysis

In the present study the monthly-mean midnight values for the data at the magnetic observatories summarized in Table 1 are analyzed. Throughout this paper the coordinates of observatories are the corrected geomagnetic latitudes and longi-

Table 1. Magnetic observatories, their corrected geomagnetic coordinates, their local midnight, and the year for data analysis

Station	Lat.	Long.	Local midnight	Year	
Thule	87.7	39.6	5 U.T.	*Z* 57-64	*H* 57-61
Resolute Bay	84.3	306.0	6	*Z* 57-64	*H* 57-64
Godhavn	77.7	43.3	4	*Z* 57-64	*H* 57-62
Baker Lake	75.1	320.4	6	*Z* 57-64	*H* 57-64
Tikhaya Bay	74.3	140.7	20	*Z* 59.6-64	
Cape Chelyuskin	71.3	173.9	17	*Z* 57-64	
Dixon	68.0	154.9	19	*Z* 60-64	
Leirvogur	66.6	71.2	2	*Z* 57.9-64	
Tromso	66.3	105.4	23	*Z* 57-64	*H* 57-64
Tixie Bay	65.6	194.9	16	*Z* 57-64	
College	64.9	260.3	10	*Z* 59-63	
Sodankyla	63.4	109.2	23		*H* 57-64
Meanook	62.5	301.2	8	*Z* 57-64	*H* 57-64
Sitka	59.8	276.6	9	*Z* 57-63	*H* 57-63
Dombås	59.6	92.9	0	*Z* 57-64	*H* 57-64
Agincourt	57.2	350.1	5		*H* 57-64
Nurmijarvi	56.6	103.6	23	*Z* 57-64	*H* 57-64
Lovo	55.9	97.9	23	*Z* 57-64	*H* 57-64
Victoria	53.9	292.6	8	*Z* 57.7-64	*H* 57.7-64
Rude Skov	52.8	92.4	23	*Z* 57-64	
Valentia	52.1	73.8	1	*Z* 57-64	
Fredericksburg	51.8	352.2	5	*Z* 57-63	*H* 57-63
Wingst	50.9	89.1	0	*Z* 57-64	
Witteveen	50.2	87.0	0	*Z* 57-64	
Hartland	50.0	77.9	0	*Z* 57-64	*H* 57-64
Niemegk	48.8	91.3	23	*Z* 57-64	
Pruhonice	46.3	92.1	23	*Z* 60-64	
Furstenfeldbruck	44.7	89.1	0	*Z* 57-64	*H* 57-64
Wien-Kobenzl	44.3	93.0	23	*Z* 57-64	
Hurbanovo	43.7	94.4	23	*Z* 57-64	
Tihany	42.6	93.9	23	*Z* 57-64	
Logrono	40.3	77.3	0	*Z* 60-64	
Tucson	39.7	311.4	8	*Z* 57-63	*H* 57-63
Toledo	37.9	75.1	0	*Z* 57-61	
Panagyurishte	37.4	98.2	23	*Z* 57-64	*H* 57-64
Memambetsu	37.4	209.9	15	*Z* 57-64	
Almeria	34.3	75.6	0	*Z* 57-64	
San Juan	31.5	5.5	5	*Z* 57-62	*H* 57-62
Kakioka	29.9	209.9	15	*Z* 57-64	

Station	Lat.	Long.	Local midnight	Year	
Kanoya	25.7	200.8	15	*Z* 57–64	
Honolulu	21.7	267.6	11	*Z* 57–63	*H* 57–63
Paramaribo	17.9	17.0	4	*Z* 58–64	*H* 58–64
Alibag	12.1	143.1	19	*Z* 61–64	
M'Bour	10.7	57.7	1	*Z* 57–64	*H* 57–64
Tatuoca	9.6	20.8	3	*Z* 57.9–62	*H* 57.9–62
Moca	5.7	78.6	0	*Z* 58.10–64	*H* 58.10–64
Guam	4.0	212.9	15	*Z* 57.7–62	*H* 57.7–62
Kodaikanal	0.7	147.1	19	*Z* 60–64	
Huancayo	−0.6	353.8	5	*Z* 57–61	
Trivandrum	−1.1	146.4	19	*Z* 61–64	
Hollandia	−9.9	210.1	15	*Z* 57.7–62.8	*H* 57.7–62.8
Apia	−15.4	260.4	12	*Z* 57–64	*H* 57–63
Trelew	−27.8	6.3	5	*Z* 57.9–61	
Tananarive	−30.1	114.8	21	*Z* 57–64	*H* 57–64
Hermanus	−41.1	79.6	23	*Z* 57–64	*H* 57–64
Amberley	−50.0	253.6	13	*Z* 57–64	*H* 57–64
Kerguelen	−58.0	123.7	19	*Z* 59–64	
Byrd	−68.7	352.0	8	*Z* 58–61	*H* 57.8–61

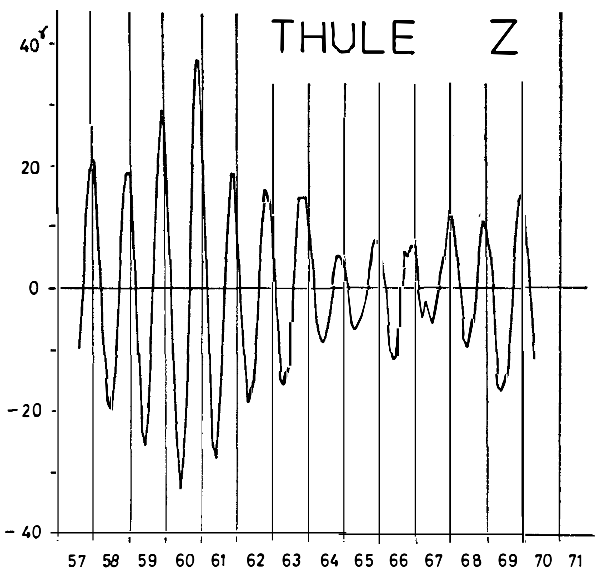

Fig. 1. Filtered monthly means of the vertical component Z of the geomagnetic field at Thule in the period 1957–1970 The vertical line indicates January of each year.

tudes calculated by HAKURA (1965). The choice of the midnight value is to avoid the influence of S_q, the amplitude of which depends on the season of the year. Another regular variation L can be reasonably neglected because of its small amplitude.

We denote by M_i the observed monthly-mean value in the i-th month. In order to remove a possible short-term fluctuation of M_i values, we take the 3-month running averages S_i, *i.e.*

$$S_i=(M_{i-1}+M_i+M_{i+1})/3.$$

If the secular variation is approximated by a linear change within a year, the annual variation can be obtained from a series of S_i-values through calculating

$$F_i=[S_i-(S_{i-6}+S_{i+6})/2]/2.$$

Fig. 1 shows the F_i-values for Z at Thule (+87.7°), which reveal a clear annual variation.

From the data set of F_i at a given station we determine the amplitude A (in nT) and phase θ (in months) of the annual variation (abbreviated hereafter to AV) at that station by the least square method to fit the F_i values with

$$AV=A\cos(t-\theta)$$

where t is given in months reckoned from January.

The values of A and θ at Thule (+87 7°) and Honolulu (+21 7°) are compared for the three cases, *i.e.* the M_i values are the monthly means of all days, five quiet days, and five disturbed days respectively. As will be seen in Table 2, the phase is always the same, although the amplitude is different in the three classes, especially for H. Throughout this paper the monthly means of all days have been used for the analysis of AV because of the fixed phase regardless of the choice of days.

Table 2. Amplitudes and phases of the annual variations at Thule(87.7°) and Honolulu(21.7°) for three data sets.

Station	Element	5D days		All days		5Q days	
		Amp (γ)	Phase (Month)	Amp (γ)	Phase (Month)	Amp (γ)	Phase (Month)
Thule	H	37 3	6 4	21 8	6 2	10.6	6 2
1957–1961	Z	20 5	11 8	26 2	12 0	19 2	11 9
Honolulu	H	10.0	4 2	5 4	4 9	3.7	5 6
1957–1963	Z	4 8	7 4	3 4	7 3	2 9	7 3

3. Worldwide Distribution of the Annual Variation

The calculated amplitudes and phases of *AV* for *H* and *Z* are plotted against the corrected geomagnetic latitude in Fig. 2, where we recognize the following characteristics.

1) Amplitude for *H*: This is great in the polar regions; it is maximum away from the pole (such as Thule +87.7°, Resolute Bay +84.3°), but at latitudes of 75–80° (such as Godhavn +77.7°, Baker Lake +75.1°) the amplitude for *H* decreases with latitude, and it is nearly constant at low latitudes (lower than 30°)

2) Phase of *AV* for *H*: At middle and low latitudes the phase for *H* is approximately given by θ=6.0, *i.e.* the maximum value of *H* takes place in June and the minimum in December. In the low-latitude region of the northern hemisphere *H* becomes maximum in spring with a slight phase shift in comparison with the middle-latitude data.

3) Amplitude for *Z*: This is remarkably large in the polar regions. It decreases with decreasing latitude to a minimum at about 40°, and it increases towards the equator.

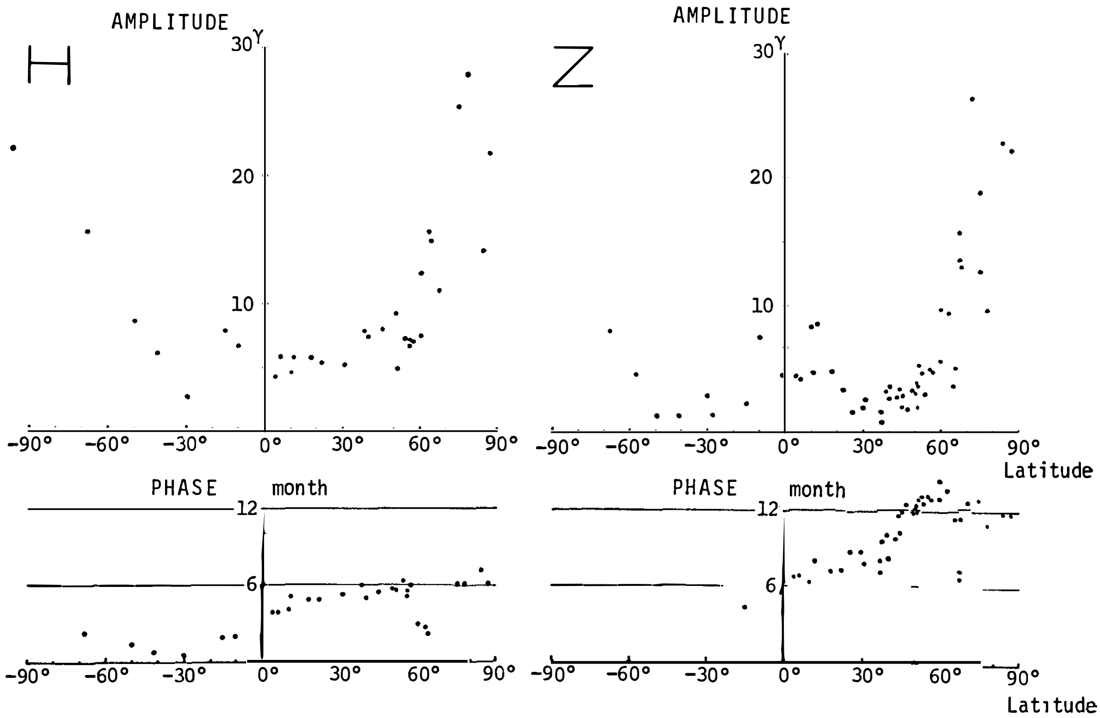

Fig. 2. Amplitudes and phases of the annual variations for H and Z plotted against the corrected geomagnetic latitudes.

4) Phase for Z: At latitude above 50° in the northern hemisphere $\theta=12$, and $\theta=6$ near the equator with a gradual phase shift at middle and low latitudes.

5) At some stations in the auroral zone (latitude 60–70°), the phase differs from the tendencies described in 2) and 4). This was noted by MALIN and ISIKARA (1976), who ascribed it to a north-south oscillation of the mean latitude of the westward auroral electrojet during the course of a year.

6) Although only some stations so far have been analyzed for the southern hemisphere, the seasonal trend seems to be the same with the same characteristics as for the northern hemisphere.

AV at middle and low latitudes is also clearly observed in general, but with much smaller amplitude (~5 nT) in comparison with high-latitude stations However it must be mentioned that at some stations AV is sometimes irregular especially for H, so that the present method of calculating A and θ is not always adequate for determining AV This comes from the fact that AV for H varies with year at some stations in its series of data for longer than one sunspot cycle, and it sometimes becomes undetectable during the course of solar-cycle variation.

4. The Annual Variations in High Latitudes

The typical AV at high latitudes is shown in Figs. 3 and 4 with the H and Z data at Resolute Bay (+84 3°) and Baker Lake (+75 1°) along with the yearly average of the Zürich sunspot number and the geomagnetic activity index ΣKm.

At Resolute Bay, AV in both H and Z is very regular, and shows a modulation of amplitude which is nearly parallel to the geomagnetic activity rather than to the sunspot number. However, the amplitude maximum does not always appear for H and Z in the same year The tendency at Mould Bay (+80.6°) during 1963–1974 is very similar to that for Resolute Bay.

At Baker Lake the systematic AV can be found only for H, with a clear amplitude-modulation as in the case of Resolute Bay. AV for Z is not at all smooth During the years 1957–1964, Z was enhanced in winter, but after 1965 the amplitude of AV decreased, and the phase changed completely to show a maximum in summer. A similar tendency of phase change in AV can be seen also in the AV for Z in Godhavn (+77.6°).

AV may be classified into P-type (P stands for polar region) and A-type (A for auroral region) with the following definition:

P-type: H is most enhanced in summer. Z is most depressed in summer.

A-type: H is most depressed in summer. Z is most enhanced in summer

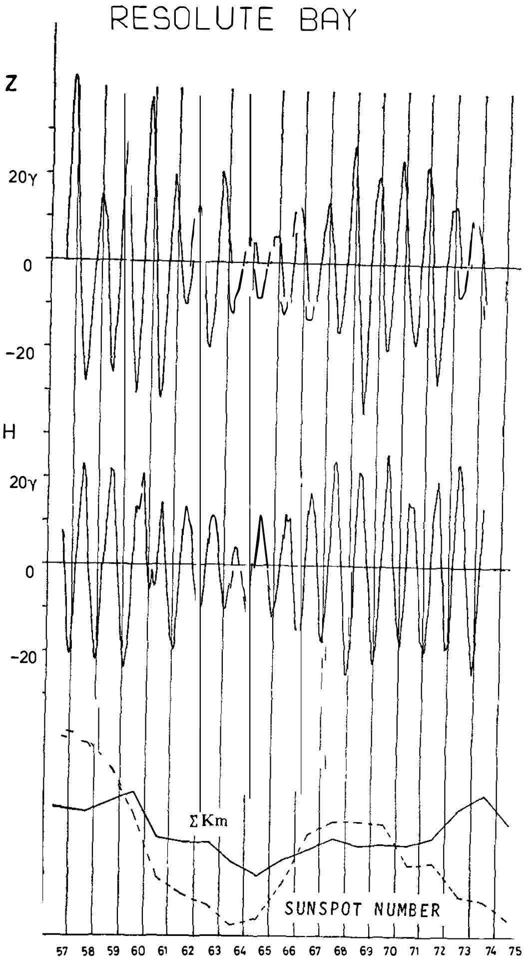

Fig. 3. Filtered monthly means for Z and H at Resolute Bay in the period 1957–1974, with the yearly means of Zurich sunspot number and geomagnetic index Σ Km.

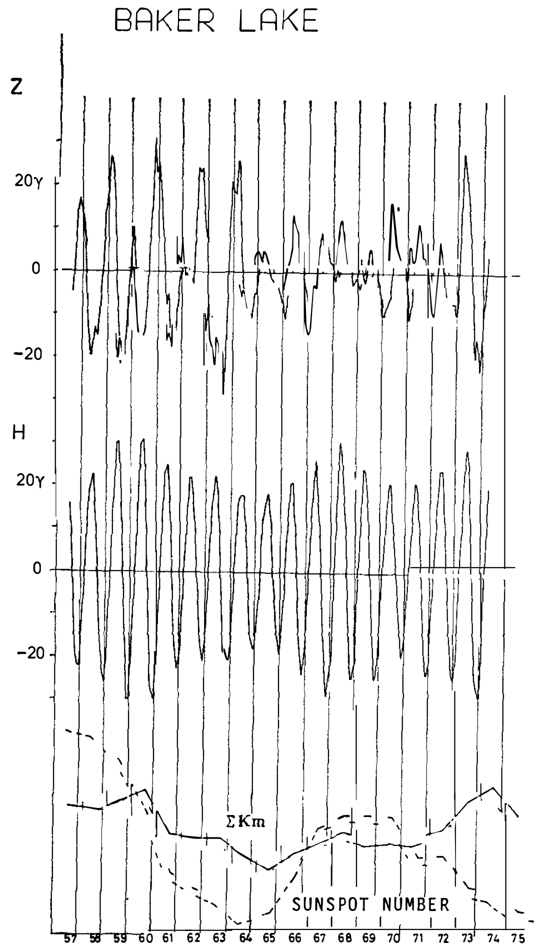

Fig. 4 Filtered monthly means for Z and H at Baker Lake in the period 1957–1974, with the yearly means of Zurich sunspot number and geomagnetic index Σ Km.

Figs 5 and 6 show the latitudinal dependence of P- and A-types of *AV* for *H* and *Z*, for the chain of Canadian stations. In the *AV* for *H*, it is clearly P-type at 84.3° (Resolute Bay) and 75.1° (Baker Lake) in the north and at 53.9° (Victoria) in the south, but the data at 68.2° (Great Whale River) is of a clear A-type. On the other hand, the *AV* for *Z* is P-type at 84.3° (Resolute Bay), 58.5° (Ottawa) and 57.6° (St. John's), whereas it is clearly A-type at 70.0° (Fort Churchill) and 68.2° (Great Whale River). The A-type region for *Z* is situated at latitudes higher than the A-type region for *H*. This tendency may be well explained by a model proposed by MALIN and ISIKARA (1976) that the laitude of westward auroral electrojet in the nighttime is slightly lower in summer than

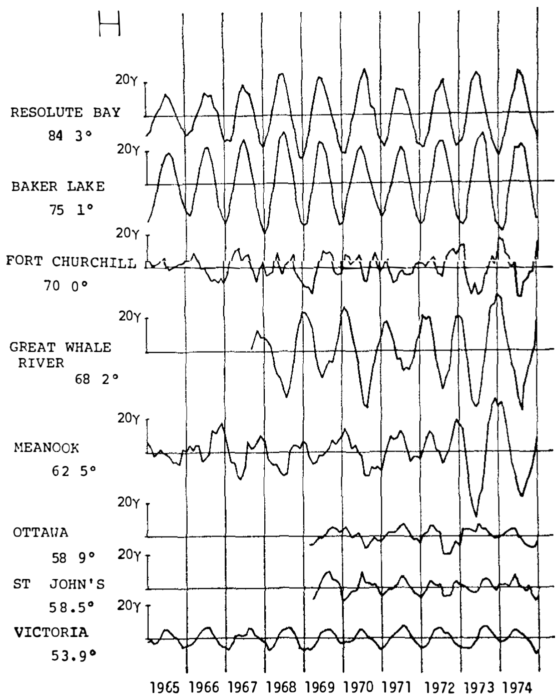

Fig. 5. Filtered monthly means for H at Canadian magnetic observatories in the period 1965–1974, arranged with the corrected geomagnetic latitude.

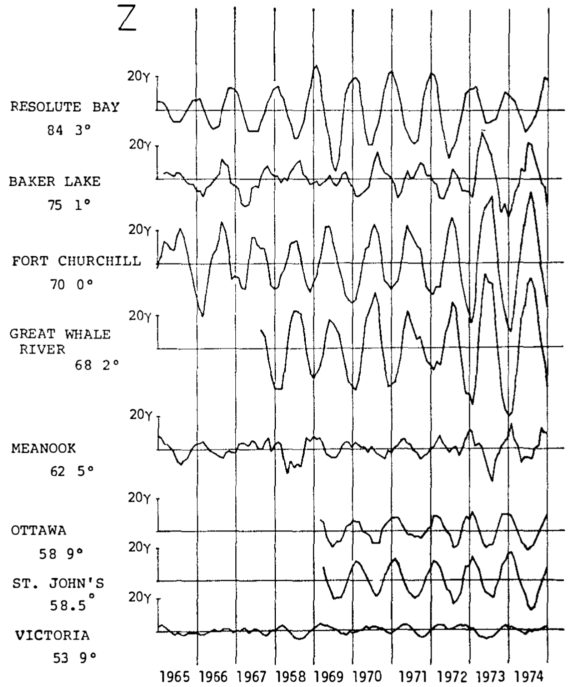

Fig. 6. Filtered monthly means for Z at Canadian magnetic observatories in the period 1965–1974, arranged with the corrected geomagnetic latitude.

in winter.

The transition between the A- and P-type regions is also checked for the Scandinavian meridian, as shown in Table 3 with the data during 1957–1964. The transition boundary for H is situated a little equatorward of the boundary for Z, similar to the observed tendency in the Canadian region.

Special attention must be paid to the modulation of AV amplitude, which is not always the same for all observatories. At the stations very near to the geomagnetic pole it shows a clear sunspot-cycle modulation (as shown in Figs. 1, 3 and 4), but the amplitude of AV in the auroral zone becomes greater during the declining stage of sunspot numbers. This example indicates that the AV amplitude and phase must be more carefully examined for a long period over one solar cycle.

Table 3. Types of annual variations in Scandinavia Meridian, 1957–1964.

Station	Geomagnetic latitude	Type for H	Type for Z
Tromso	66.3°	A	A
Sodankyla	63.4°	A	A, P
Dombås	59.6°	A	P
Nurmijarvi	56.6°	P	P
Lovö	55.9°	P	P

5. Dependence of AV on IMF in the Polar Regions

It has been demonstrated that the B_y-component of interplanetary magnetic field (IMF) influences the geomagnetic field variations in the polar cap (MANSUROV and MANSUROVA, 1971; SVALGAARD, 1973). Here we study the dependence of the polar magnetic field on B_z-component of IMF, following the method used by FRIIS-CHRISTENSEN and WILHJELM (1975). The hourly values of the geomagnetic field-components H and Z near local midnight in 1968 at four stations (Thule +87.7°, Resolute Bay +84.3°, Godhavn +77.6°, and Baker Lake +75.1°) are analyzed for their dependence on B_y and B_z values (2-hour average of the hour concerned and the preceding hour), taken from the Data Book by KING (1977). The intervals with large standard deviation of IMF are omitted in the present study. All hourly values of the geomagnetic field are sorted into nine classes according to the simultaneous B_y (<0, 0, >0) and B_z (<0, 0, >0) values. Since the B_y-effect is small at local midnight and it is nearly of the same magnitude with opposite sign for positive and negative B_y, the B_y-effect may be reasonably cancelled if we take the monthly means without regarding B_y. Through this process we study here the effect of B_z alone. The monthly means at the four stations for three classes of B_z (*e.g.* $B_z<0$, 0, >0) are shown in Fig. 7, in which the following characteristics can be noticed.

1) *AV* for *H* is enhanced when $B_z<0$. This tendency near the pole can be ascribed partly to the intensification of the twin-vortex current in summer (FRIIS-CHRISTENSEN and WILHJELM, 1975). *AV* for *H* also exists when $B_z>0$.

2) At Resolute Bay and Thule the monthly mean values of *H* when $B_z<0$

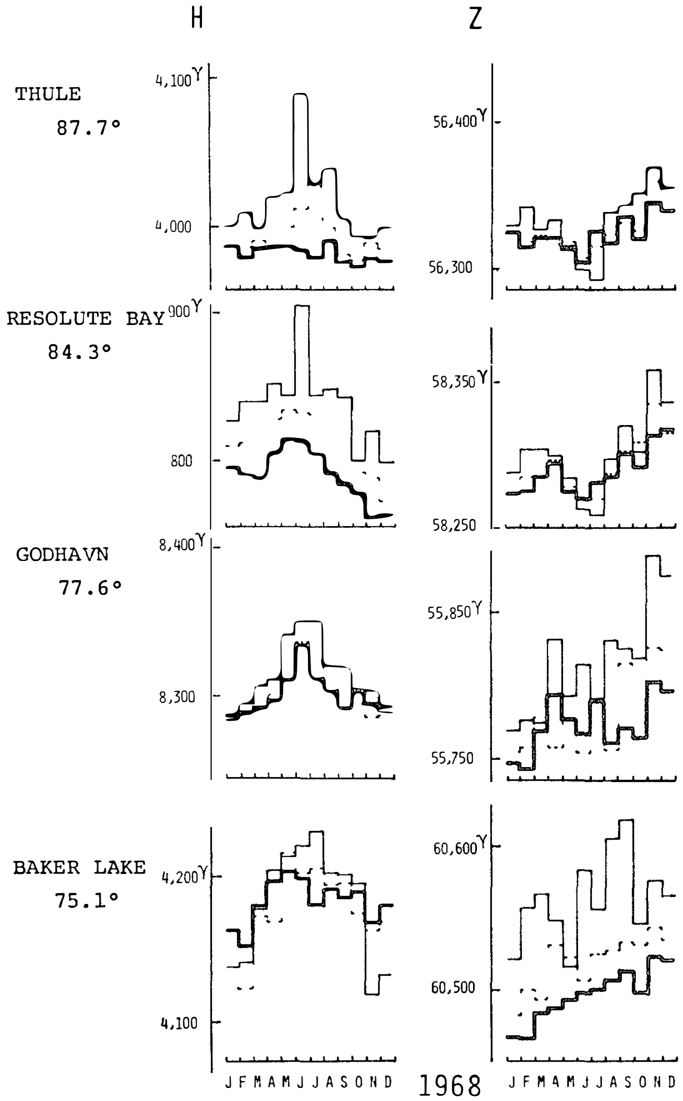

Fig. 7. Monthly means of the geomagnetic field H and Z classified by B_z of interplanetary magnetic field in 1968. Heavy lines represent the case $B_z>1\gamma$ Solid lines represent the case $B_z<-1\gamma$, and broken lines $B_z\sim0\gamma$.

are higher in comparison with the cases when $B_z>0$ in all seasons. At Baker Lake the monthly mean values of H when $B_z<0$ are smaller in winter and larger in summer than in the cases when $B_z>0$.

3) AV in Z is enhanced at Resolute Bay and Thule when $B_z<0$, although the enhancement is not as noticeable as that for H. At Godhavn and Baker Lake we cannot find any clear AV in all B_z-classes.

4) At Thule and Resolute Bay the monthly mean values of Z are higher in winter and lower in summer when $B_z<0$. At Godhavn and Baker Lake the monthly mean values are higher in all seasons when $B_z<0$.

Summarizing these observational results, we have to bear in mind that some local current system responsible for AV in the polar regions is enhanced where $B_z<0$, with slight modification of the current pattern. The current pattern is being examined with the analysis of AV at local times other than midnight.

Acknowledgments

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