Geomagnetic Secular Variation in the Antarctic Region during 1960–1975

Takesi NAGATA*

南極域における 1960–1975 年間の地球磁場永年変化

永　田　　武*

要旨： 南緯 30° 以南に在る地磁気観測所 20 点における地球磁場 3 成分 (X, Y, Z) の 1960 年から 1975 年に至る 15 年間の永年変化を解析する．1960～1965, 1965～1970, および 1970～1975 の 3 期間を通して $\dot{Z}>150$ nT/年 に達する大きな永年変化が緯度 70°～85°S, 経度 20°W～60°E の範囲に拡っている (図 1a, b, c)．この南極域における大きな $\dot{Z}$ の分布は地球磁場双極子能率の減少の影響と同双極子の北方移動の影響の重なりの結果に基づく部分が過半を占めている．北極域においては上記 2 現象の影響が互いに打ち消し合うので異常に大きな地球磁場永年変化は見られない．

全地球面観測結果から求められた地球磁場双極子の 2 現象に基づく永年変化成分を観測値から差引いて求められた残余地球磁場永年変化 ($\Delta\dot{X}, \Delta\dot{Y}, \Delta\dot{Z}$) は，南極域においてはまだ大きく，経度 20°W～50°E 域に $\dot{Z}>50$ nT/年 の正異常，70°E～180°E 域に $\dot{Z}\leq-50$ nT/年の負異常という規則的な分布を示す (図 4a, b, c)．地球の中，低緯度帯においては残余地球磁場変化の過半部分が，非双極子地球磁場の西方移動に因る事実が知られているが，南極域においては，非双極子地球磁場西方移動の影響は検知できない．その代わり，非双極子地球磁場が 0.3%/年の割合で増大しつつあると考えると南極域残余地球磁場永年変化の約 80% を解釈することができる．

***Abstract*:** The annual mean values of the geomagnetic three components (X, Y, Z) at 20 stations located between the South Pole and the 30°S latitude circle during 15 years from 1960 to 1975 are examined to study on the geomagnetic secular variation in the southern polar region.

In each of three periods, 1960–1965, 1965–1970 and 1970–1975, the maximum positive annual rate, $\dot{Z}$, over 150 nT/year, was located in a polar area of 70°–85°S in latitude and 20°W–60°E in longitude, as shown in Figs. 1(a), (b) and (c). The major parts of the geomagnetic secular variation in the Antarctic region can be attributed to a decrease of the centered geomagnetic dipole intensity and the northward shift of the geomagnetic dipole, both effects resulting in a decrease of the total geomagnetic force (F) and an apparent increase of Z ($\dot{Z}>0$). In the north polar region, the two effects tend to cancel each other, but they are added to each other in the southern polar region.

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* 国立極地研究所. National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173.

The two effects estimated from Yukutake-Cain's global analysis of the geomagnetic field (1979) are subtracted from the observed values of $(\dot{X}, \dot{Y}, \dot{Z})$ at the Antarctic region stations. The residuals still show a considerably systematic regional secular variation pattern which can be represented by a positive anomaly of $\dot{Z}$ ($\dot{Z}>50$ nT/year) between 20°W and 50°E in longitude and a negative anomaly ($\dot{Z}\lesssim -50$ nT/year) between 70°E and 180°E in longitude in the southern polar region (Figs. 4(a), (b), (c)). The geomagnetic non-dipole field in the southern polar region has a characteristic distribution pattern which has a focus of a positive anomaly of $\Delta Z>20{,}000$ nT in an area of 60°–70°S in latitude and 10°E–70°W in longitude and a focus of a negative anomaly of $\Delta Z\sim -15{,}000$ nT around 30°S in latitude and 140°E in longitude. Roughly speaking, it appears that the non-dipole field is growing up gradually in the southern polar region.

1. Introduction

It has been pointed out (NAGATA, 1961, 1962a) that the geomagnetic secular variation was remarkably large in the southern polar region during the period around the International Geophysical Year, 1957–1958, in comparison with that in the northern polar region during the same period. For example, the secular variation rate of Z-component ($\dot{Z}$) amounted to about 180 nT/year at Syowa Station (Lat. 69–00S, Long. 39–35E) during the period. In a later study on the global distribution of the geomagnetic secular variation (NAGATA, 1962b), the writer concluded that the recent geomagnetic secular variation may be resolved into four expedient groups, namely, (a) a decrease in the magnetic moment of the centered dipole, (b) a westward drift of the non-dipole field with a speed of about 0.2 degrees/year, (c) a northward shift of the axial dipole with a speed of about 2 km/year, and (d) residual regional variations which could be attributed to a growth or a decay of the non-dipole geomagnetic fields.

In the neighbourhood of the south pole, the decrease of the centered dipole results in a decrease of the total geomagnetic force (F) and therefore an increase of the downward component of the vertical force (Z) of about 30 nT/year, and the northward shifting of the centered axial dipole causes an increase of Z of about 60 nT/year, the total amount of both effects being about $+90$ nT/year in $\dot{Z}$. In the neighbourhood of the north pole, on the other hand, the two effects on the Z component are opposite in the direction to each other, resulting in an increase of Z by $\dot{Z}\simeq +30$ nT/year. Thus, the major tendency that the $\dot{Z}$ values are remarkably large in the southern polar region can be attributed to a decrease of the magnetic moment of the centered dipole and its northward shifting.

It has been further pointed out in a previous paper (NAGATA, 1962b) that the residue after subtracting the secular variations caused by the decay and the northward shifting of the centered dipole from the observed secular variation still shows a system-

Table 1. Average geomagnetic secular variations during the periods of 1960–65, 1965–70 and 1970–75 in Antarctica.

	Observatory	Latitude	Longitude	1960–65			1965–70			1970–75		
				$\dot{X}$	$\dot{Y}$	$\dot{Z}$	$\dot{X}$	$\dot{Y}$	$\dot{Z}$	$\dot{X}$	$\dot{Y}$	$\dot{Z}$
					(nT/yr.)			(nT/yr.)			(nT/yr.)	
1	Gnangara	31–47 S	115–57 E	−8.5	+1.1	−2.8	−21.2	−7.2	+5.2	−36.5	−15.5	−0.5
2	Hermanus	34–25 S	19–14 E	−66.4	+24.6	+100.2	−78.2	+36.2	+94.2	−69.8	+44.8	+91.6
3	Toolangi	37–32 S	145–28 E	−26.8	+17.0	−0.3	−33.0	+8.5	+7.5	−40.1	−2.3	+17.3
4	Amberley	43–09 S	172–43 E	−30.5	+21.5	+29.0	−32.9	+17.2	+28.1	−34.1	+15.3	+50.5
5	Trelew	43–15 S	294–41 E	−60.8	−51.3	+43.9	−68.6	−41.2	+38.2	—	—	—
6	Port aux Francais	49–21 S	70–12 E	−53.6	−33.0	−40.4	−69.3	+1.1	+19.4	−37.7	−28.0	+64.9
7	Macquarie Is.	54–30 S	158–57 E	−38.3	+24.5	+32.6	−40.2	+15.6	+33.4	−38.8	+7.2	+28.6
8	Argentine Is.	65–15 S	295–44 E	−44.3	−24.4	+88.4	−51.8	−19.9	+101.2	−54.2	−17.7	+87.6
9	Wilkes	66–15 S	110–35 E	−76.0	+3.7	+43.0	—	—	—	—	—	—
10	Mirny	66–33 S	93–01 E	−84.7	−12.5	+64.0	−56.7	−25.4	+81.2	−35.2	−24.8	+85.4
11	Dumont d'Urville	66–40 S	140–01 E	−58.0	+29.6	+39.9	−48.6	−8.4	+85.0	−51.0	−15.1	−6.1
12	Mawson	67–36 S	62–53 E	−63.2	−43.6	+82.6	−47.4	−30.7	+106.3	−25.9	−18.3	+112.2
13	Syowa Station	69–00 S	39–35 E	−29.2	−48.7	+119.4	−22.0	−23.8	+138.2	−10.2	−2.8	+143.5
14	SANAE	70–18 S	357–38 E	−19.4	−5.1	+104.7	−20.8	+19.3	+61.3	−23.7	−24.4	+90.0
15	Novolazarevs	70–18 S	357–38 E	−12.0	−15.3	+159.7	−9.9	+9.5	+111.6	−4.8	+14.8	+123.6
16	Halley Bay	75–31 S	333–23 E	+15.6	+23.9	+69.5	+25.0	+9.9	—	+14.4	−14.2	—
17	Byrd	75–59 S	240–00 E	+0.6	+13.5	+114.4	−0.8	+10.5	+106.6	—	—	—
18	Scott Base	77–51 S	166–47 E	−40.0	+28.8	+92.6	−36.6	+16.9	+88.0	−37.1	+4.8	+90.2
19	Vostok	78–27 S	106–52 E	−76.0	+3.7	+43.0	−32.2	−28.2	+101.8	−21.3	−20.4	+86.1
20	South Pole	90–00 S	346–41 E	+10.6	−24.4	+110.7	+9.9	−5.4	+121.7	—	—	—

atic distribution in the southern polar region; namely, the residual secular variation field consists of a positive focus of about 100 nT/year around lat. 70°S and long. 30°E and a negative focus of about −60 nT/year around lat. 70°S and long. 180°, both in terms of $\dot{Z}$.

Since those previous works on the geomagnetic secular variation were made on the basis of geomagnetic data obtained during a relatively short period, several years around IGY, it seems that the general characteristics of the geomagnetic secular variation in the southern polar region must be newly re-examined on the basis of observed data accumulated during a much longer time since then. Some magnetic stations established for the IGY program have already been dismantled but other stations listed in Table 1 have been continuously operated since the time of IGY to the present. For the purpose of compiling "Magnetic Maps 1975 of the Antarctic" in accordance with a proposal of the Scientific Committee on Antarctic Research (SCAR), all available data of the annual or monthly mean values of the geomagnetic three components at these Antarctic stations have been specifically collected by the Geographical Survey Institute, Japan (TAZIMA and HARUYAMA, 1979). During the course of compiling the Antarctic magnetic maps for the epoch of 1975, the isoporic charts for the three geomagnetic components were also compiled by putting specifically heavy weights on data of 21 magnetic stations located south of the 30°S latitude circle in order to evaluate the most reasonable isoporic charts for reducing geomagnetic values observed at various epochs in the southern polar region to those in 1975 (TAZIMA and HARUYAMA, 1979).

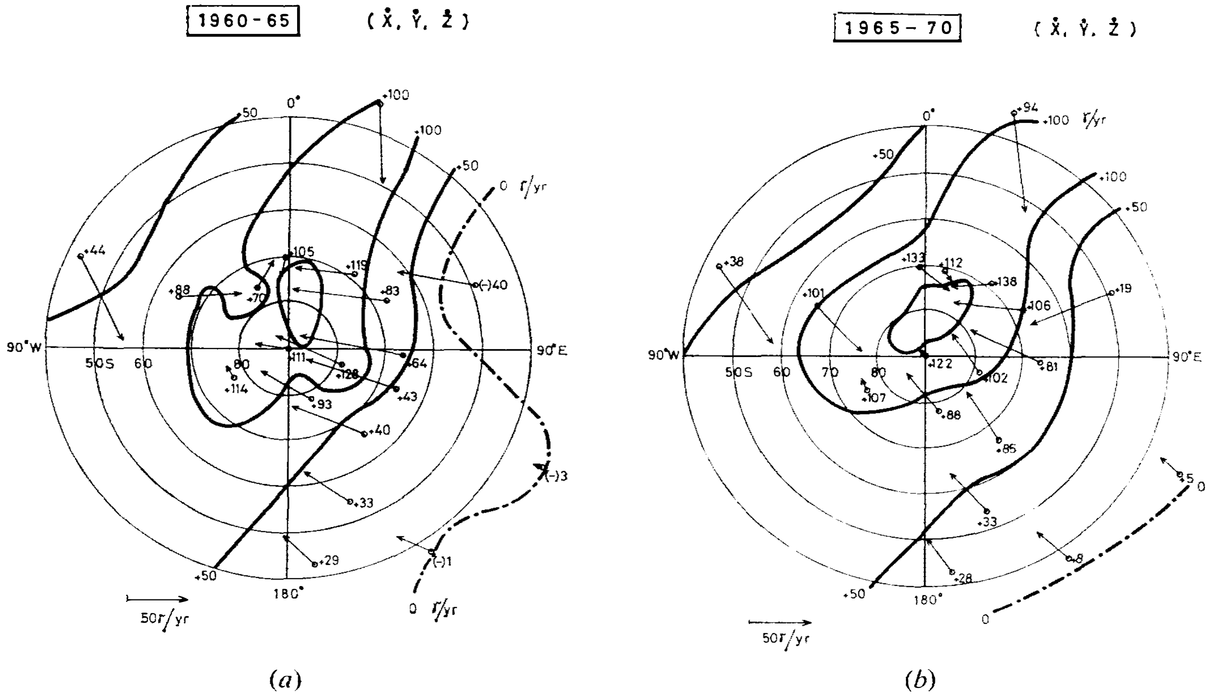
In the present study, those collected Antarctic geomagnetic data for a period of 15 years from 1960 to 1975 will be re-examined with emphasis on a possible interpretation of the geomagnetic secular variation distribution over the southern polar region for the period of 15 years.

2. Data and Method of Analysis

Among the 20 magnetic stations listed in Table 1, the annual mean values of geomagnetic three components were available from 12 stations (Gnangara, Hermanus, Toolangi, Amberley, Trelew, Macquarie Is., Wilkes, Mawson, SANAE, Byrd, Scott Base, and South Pole), while their monthly mean values were obtained from 8 other stations (Port aux Francais, Argentine Is., Mirny, Dumont d'Urville, Syowa, Novolazarev, Halley Bay and Vostok). In the case that the monthly mean values only were prepared by respective observatory staffs, their annual mean values have been evaluated from these monthly mean values for each year.

As for the geomagnetic three components, the northward (X), the eastward (Y) and the downward (Z) components are selected for the purposes of possible theoretical interpretations of the geomagnetic secular variation anomalies as well as a comparison of the present results with previous ones (NAGATA, 1962b).

The annual mean value data of X, Y and Z have been prepared for as long period as possible and at as many stations as possible within the southern polar region. At the present stage, however, it appears that 15 years from 1960 to 1975 are the maximum possible period for obtaining the necessary simultaneous data from the majority of



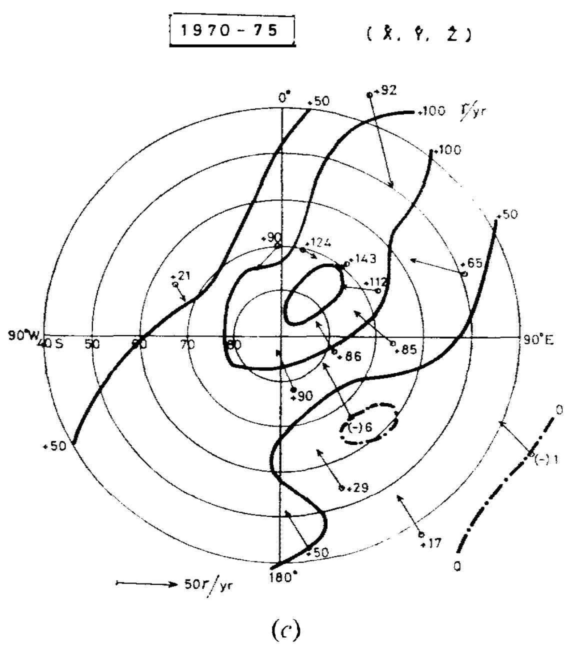


Fig. 1. Isoporic charts ($\dot{X}$, $\dot{Y}$, $\dot{Z}$) in the southern polar region south the 40°S latitude circle. Contour: $\dot{Z}$ in unit of γ/year. Arrow: ($\dot{X}$, $\dot{Y}$) vector. (a) 1960–1965, (b) 1965–1970, (c) 1970–1975.

magnetic stations in this region. The whole period of 15 years is divided into three periods of equal length, *i.e.* 1960.0–1965.0, 1965.0–1970.0 and 1970.0–1975.0, and the mean annual variation rates of the three components, i.e. $\dot{X}$, $\dot{Y}$, and $\dot{Z}$, are derived for each period. In Table 1, the mean annual rates, $\dot{X}$, $\dot{Y}$, and $\dot{Z}$, thus obtained for the three periods are summarized. Unfortunately the geomagnetic data at Halley Bay and Wilkes are not available after 1967 and 1966 respectively, and those at Trelew, Byrd and South Pole also are not available after 1970, 1969 and 1971 respectively.

Using these data of ($\dot{X}$, $\dot{Y}$, $\dot{Z}$), the isoporic charts of $\dot{Z}$ are compiled for the three periods, as shown in Figs. 1(a), (b) and (c), where the horizontal vectors of ($\dot{X}$, $\dot{Y}$) also are illustrated. It is assumed in compiling these isoporic charts that the source of geomagnetic secular variation concerned is located within the earth's interior and the secular variation can be derived from a scalar potential field. In spherical coordinates (r, θ, λ) where r, θ and λ denote respectively the geocentric distance, the co-latitude measured from the north pole and the longitude, therefore, the following conditions are numerically required; namely,

$$\dot{X}=\left(\frac{\partial \dot{W}}{r\partial\theta}\right)_{r=R}, \quad \dot{Y}=\left(\frac{-\partial \dot{W}}{r\sin\theta\partial\lambda}\right)_{r=R}, \quad \dot{Z}=\left(\frac{\partial \dot{W}}{\partial r}\right)_{r=R},$$

where $\dot{W}$ denotes the annual change rate of scalar potential $W(r, \theta, \lambda)$ and R is the earth's mean radius.

3. Decay and Northward Shifting of the Geomagnetic Centered Dipole

It seems clear in Figs. 1(a), (b) and (c) that a conspicuous focus of positive value of $\dot{Z}$ of about +150 nT/year was present throughout the three periods on a little equatorward side in the polar cap region in a section between 10°W and 60°E longitude. It can be noted further in these figures that the positive anomaly zone of $\dot{Z}$ is extended along the 40°E—140°W meridian in the southern polar region.

The global geomagnetic secular variation characteristics during a period from 1940 to 1973 have recently been studied in fair detail by YUKUTAKE and CAIN (1979) by analyzing the geomagnetic secular variations observed at 37 magnetic stations located between 69.24°N and 43.15°S in latitude. Among the magnetic data at 20 stations in the southern polar region analyzed in the present study, data at four stations, Gnangara, Hermanus, Toolangi and Amberley, are included in their analyses. It seems likely that the main concern of these two workers was to separate the internal and external origins of the geomagnetic secular variation in order to examine a possible relation of the external origin part of geomagnetic secular variation to the solar activity. The main concern of the present study, however, is to examine the major characteristics of anomalously large geomagnetic secular variation in the southern polar region, the largest parts of which certainly originate within the earth's interior. The results of Yukutake-Cain's analysis have given the annual rates of geomagnetic secular variation of internal origin in terms of the spherical harmonic coefficients, $g_1^{0(i)}$, $g_1^{1(i)}$, $h_1^{1(i)}$ and $g_2^{0(i)}$, for a period from 1941 to 1973. The average values of $\dot{g}_1^{0(i)}$, $\dot{g}_1^{1(i)}$, $\dot{h}_1^{1(i)}$ and $\dot{g}_2^{0(i)}$ for the three periods, 1960–1965, 1965–1970 and 1970–1975, derived from the Yukutake-Cain analyses, are given in Table 2.

($\dot{g}_1^{0(i)}$, $\dot{g}_1^{1(i)}$, $\dot{h}_1^{1(i)}$) represent the centered dipole component of annual secular variation, while $\dot{g}_2^{0(i)}$ represents the southward shifting velocity (u) of the centered axial dipole expressed as

$$\dot{g}_2^{0(i)} = -2g_1^0 \frac{u}{R} . \tag{1}$$

If we assume that the geomagnetic secular variation pattern can be represented only by the two effects, the isoporic chart of $\dot{Z}_0$ together with the vector arrow presentation of ($\dot{X}_0$, $\dot{Y}_0$) in the southern polar region for a period of 1960–1970 can be illustrated as shown in Fig. 2, where the average values of the spherical harmonic coefficients for 1960–1970, such as $\dot{g}_1^{0(i)}=17.1$, $\dot{g}_1^{1(i)}=9.0$, $\dot{h}_1^{1(i)}=-3.3$ and $\dot{g}_2^{0(i)}=-20.9$ nT/year, are adopted for the numerical computation. Comparing Figs. 1(a), (b) and (c) with Fig. 2, a general characteristics of the geomagnetic secular variation in the southern polar region shown in Fig. 1 that a focus of large positive values of $\dot{Z}$ is located near the south pole and the horizontal vectors ($\dot{X}$, $\dot{Y}$) tend to converge toward the south pole can be qualitatively explained by the secular variation model of ($\dot{X}_0$, $\dot{Y}_0$, $\dot{Z}_0$) illustrated in Fig. 2. However, the observed maximum value of $\dot{Z}$ near the south pole is considerably larger than that of $\dot{Z}_0$ and the magnitude of vector ($\dot{X}$, $\dot{Y}$) is much larger than that of vector ($\dot{X}_0$, $\dot{Y}_0$) in the southern polar cap area.

The model geomagnetic secular variations ($\dot{X}_0$, $\dot{Y}_0$, $\dot{Z}_0$) derived from $\dot{g}_1^{0(i)}$, $\dot{g}_1^{1(i)}$, $\dot{h}_1^{1(i)}$ and $\dot{g}_2^{0(i)}$ only are evaluated at the individual magnetic stations using the numeri-

Table 2. Average annual secular variation rates of spherical harmonic coefficients of the geomagnetic field, $\dot{g}_1^{0(i)}$, $\dot{g}_1^{1(i)}$, $\dot{h}_1^{1(i)}$ and $\dot{g}_2^{0(i)}$ for 1960–1965, 1965–1970 and 1970–1975.

Period	$\dot{g}_1^{0(i)}$	$\dot{g}_1^{1(i)}$ (nT/year)	$\dot{h}_1^{1(i)}$	$\dot{g}_2^{0(i)}$
1960–1965	18.6	6.8	−2.0	−21.6
1965–1970	15.4	11.2	−4.6	−20.1
1970–1975	16.7	11.7	−6.7	−19.3

(after YUKUTAKE and CAIN, 1979)

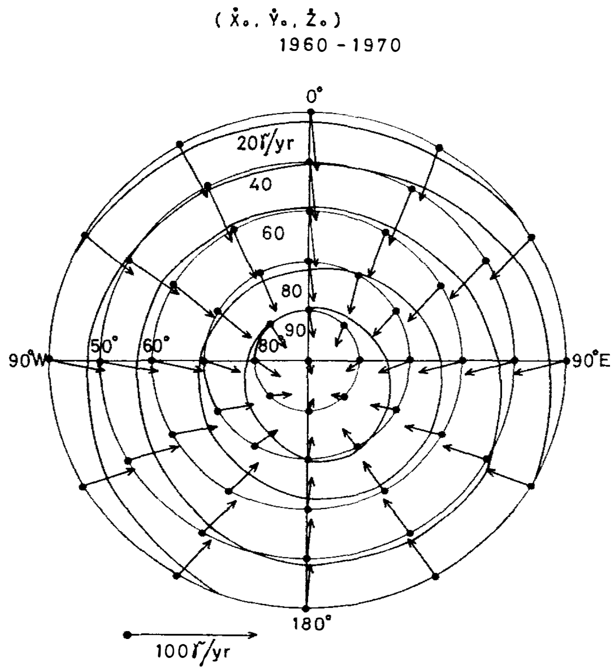


Fig. 2. A hypothetical isoporic chart ($\dot{X}_0$, $\dot{Y}_0$, $\dot{Z}_0$) caused by the secular change of the geomagnetic dipole in the southern polar region south the 40°S latitude circle. Contour: $\dot{Z}_0$ in unit of γ/year. Arrow: ($\dot{Y}_0$, $\dot{Z}_0$) vector.

cal values of these spherical harmonic coefficients given in Table 2 for the three periods, 1960–1965, 1965–1970 and 1970–1975. For example, $\dot{Z}_0$ values thus obtained are compared with the observed values of $\dot{Z}$ for the individual stations in Fig. 3. As shown in the figure for the period of 1960–1965, the observed values of $\dot{Z}$ are within a ± 30 nT/year deviation zone from the corresponding $\dot{Z}_0$ values at 12 stations, whereas $\dot{Z}$-values are larger than $\dot{Z}_0$ by more than 30 nT/year at Syowa (SY), Novolazarevs (NO) and Hermanus (HE), while Z values are more than 30 nT/year smaller than $\dot{Z}_0$ at Port aux Francais (PF), Toolangi (TO), Dumont d'Urville (DD), Wilkes (WK) and Macquarie Is. (MC). Similarly, $\dot{Z} > \dot{Z}_0 + 30$ nT/year at Syowa, Novolazarevs, Hermanus, SANAE (SN), South Pole (SP) and Argentine Is. (AI), whereas $\dot{Z} < \dot{Z}_0 - 30$ nT/year at Macquarie Is. and Toolangi for the period of 1965–1970, and $\dot{Z} > \dot{Z}_0 + 30$ nT/year at Syowa, Novolazarevs, Hermanus and Mawson (MA) and $\dot{Z} < \dot{Z}_0 - 30$ nT/year at Dumont d'Urville and Macquarie Is. for the period of 1970–1975. Those magnetic stations where $\dot{Z} > \dot{Z}_0 + 30$ nT/year are located in a sector between 70°W and 65°E in longitude, whereas those of $\dot{Z} < \dot{Z}_0 - 30$ nT/year are located in a sector between 70°E and 180°E in longitude. Particularly, observed values of $\dot{Z}$ are always larger than $\dot{Z}_0 + 30$ nT/year throughout the three periods at Hermanus, Syowa and Novolazarevs which are located in a sector between 10°E and 40°E in longitude.

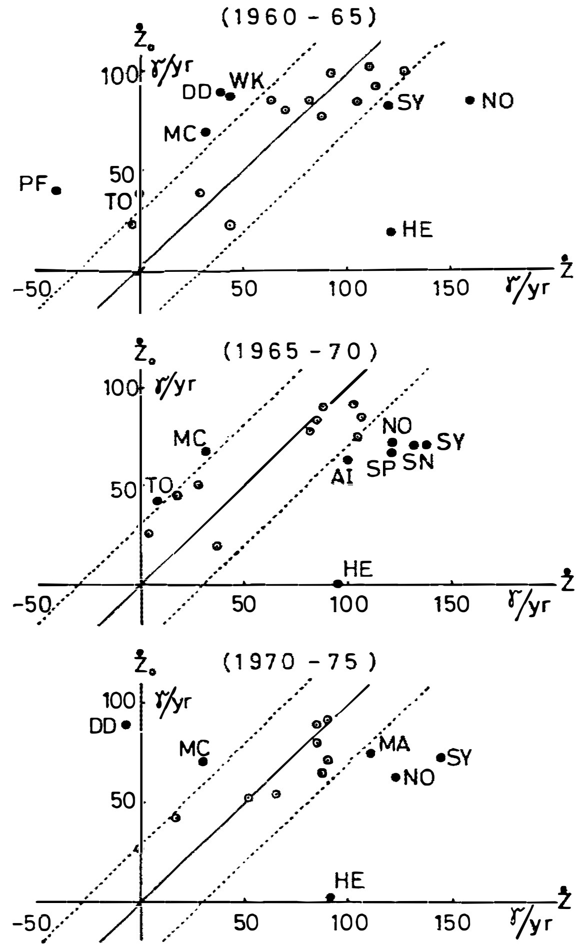


Fig. 3. Correlation diagram between $\dot{Z}_0$ and $\dot{Z}$ at 20 Antarctic stations for three periods, 1960–1965, 1965–1970 and 1970–1975.

Except for these geomagnetically anomalous stations, where $\dot{Z} > \dot{Z}_0 + 30$ nT/year or $\dot{Z} < \dot{Z}_0 - 30$ nT/year, observed geomagnetic secular variation, $\dot{Z}$, in the southern polar region can be approximately represented by the global geomagnetic secular variation characteristics consisting of a decrease of the centered dipole moment and the northward shifting of the dipole. Annual rates of the decrease of $g_1^{0(i)}$, $g_1^{1(i)}$, $h_1^{1(i)}$, an increase of $g_2^{0(i)}$ and the northward shifting velocity $(-u)$ estimated by (1) are summarized in Table 3.

As shown in Table 3, the geomagnetic centered dipole is not only continuously decreasing in its moment but its direction is gradually changing with time in a systematic way and it appears that the northward shifting velocity of the centered dipole is slowly diminishing during the period of 15 years concerned. According to recent results of the analysis of MAGSAT vector data (LANGEL *et al.*, 1980), however, $-g_2^0$ value is still continuously increasing at a rate of about 25 nT/year and $\sqrt{(g_1^0)^2+(g_1^1)^2+(h_1^1)^2}$

Table 3. Annual rates of change of $g_1^{0(i)}$, $g_1^{1(i)}$, $h_1^{1(i)}$ and $g_2^{0(i)}$ and the northward shifting velocity $(-u)$ of the centered dipole.

	1960–1965	1965–1970	1970–1975	
$\dot{g}_1^{0(i)}/g_1^{0(i)}$	-5.97×10^{-4}	-4.96×10^{-4}	-5.39×10^{-4}	
$\dot{g}_1^{1(i)}/g_1^{1(i)}$	-2.24×10^{-3}	-3.74×10^{-3}	-3.97×10^{-3}	
$\dot{h}_1^{1(i)}/h_1^{1(i)}$	-3.51×10^{-4}	-8.09×10^{-4}	$-11.8\ \times10^{-4}$	
$\dot{g}_2^{0(i)}/g_2^{0(i)}$	1.35×10^{-2}	1.18×10^{-2}	1.04×10^{-2}	
$-u=\dfrac{\dot{g}_2^{0(i)}}{2g_1^{0(i)}}R$	2.21	2.06	1.98	(km/yr.)
$\dot{M}/M$	-6.11×10^{-4}	-5.35×10^{-4}	-5.88×10^{-4}	
$\dot{\lambda}_0$	-0.046	-0.068	-0.067	(degree/yr.)
$\dot{\theta}_0$	-0.002	-0.010	-0.013	(degree/yr.)

value is still decreasing at a rate of 27 nT/year for the period from 1975 to 1980 too. Hence a large geomagnetic secular variation caused by $\dot{g}_1^{0(i)}$, $\dot{g}_1^{1(i)}$, $\dot{h}_1^{1(i)}$ and $\dot{g}_2^{0(i)}$, approximately illustrated in Fig. 2, is still taking place in the southern polar region.

4. Growth of the Non-Dipole Geomagnetic Field

All the effects of a decay of the moment, a change of the direction and the northward shifting of the geomagnetic centered dipole upon the geomagnetic secular variation pattern will be defined in the present work as the secular variation field caused by the centered dipole. Although the northward shifting of the centered axial dipole should produce negative values of $\dot{g}_n^{0(i)}$ $(n\geqq3)$ too, their magnitudes are negligibly small in the present discussions.

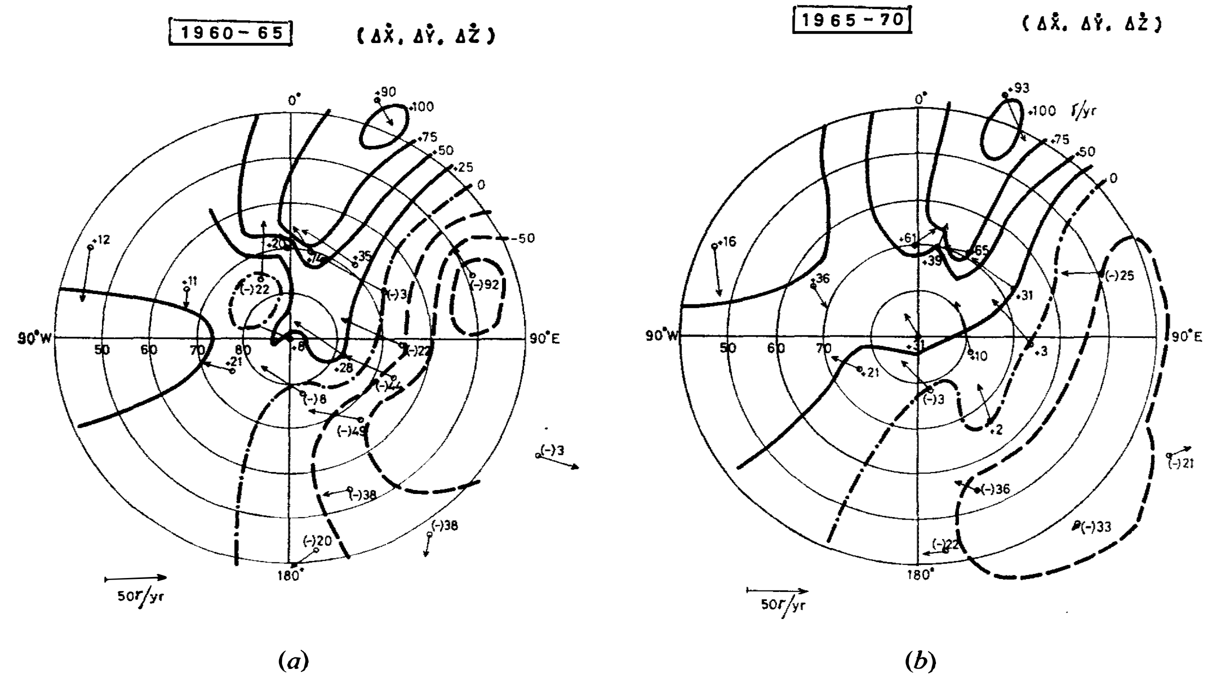
Thus, $(\dot{X}_0, \dot{Y}_0, \dot{Z}_0)$ derived from $\dot{g}_1^{0(i)}$, $\dot{g}_1^{1(i)}$, $\dot{h}_1^{1(i)}$ and $\dot{g}_2^{0(i)}$ only, can be assumed to approximately represent the geomagnetic secular variation field caused by the centered dipole. The residual secular variation field patterns $(\Delta\dot{X}, \Delta\dot{Y}, \Delta\dot{Z})$ defined by $(\Delta\dot{X}=\dot{X}-\dot{X}_0, \Delta\dot{Y}=\dot{Y}-\dot{Y}_0, \Delta\dot{Z}=\dot{Z}-\dot{Z}_0)$ are summarized in Table 4 and illustrated in Figs. 4(a), (b) and (c) for the three periods. It appears throughout the three periods that the residual secular variation field $(\Delta\dot{X}, \Delta\dot{Y}, \Delta\dot{Z})$ in the southern polar region can be schematically presented by a positive anomaly area of $\Delta\dot{Z}$ associated with the corresponding horizontal vector anomaly $(\Delta\dot{X}, \Delta\dot{Y})$ in a sector between 10°W and 50°E in longitude which is extended towards the 90°W–150°W direction, and a negative anomaly area of $\Delta\dot{Z}$ in a sector between 70°E and 180°E in longitude. The main characteristics of the $\Delta\dot{Z}$ distribution patterns for the three periods are essentially the same as those of the non-zonal part of the non-drifting component of $\dot{Z}$ distribution around the south pole for the period of 1955–1960 (NAGATA, 1962b).

Table 4. Residual geomagnetic secular variations during the periods of 1960–65, 1965–70 and 1970–75 in Antarctica.

	Observatory	1960-65			1965-70			1970-75		
		$\Delta\dot{X}$	$\Delta\dot{Y}$	$\Delta\dot{Z}$	$\Delta\dot{X}$	$\Delta\dot{Y}$	$\Delta\dot{Z}$	$\Delta\dot{X}$	$\Delta\dot{Y}$	$\Delta\dot{Z}$
		(nT/yr.)			(nT/yr.)			(nT/yr.)		
1	Gnangara	+34.0	−4.1	−25.3	+14.1	−15.3	−21.4	−2.1	−23.1	−26.0
2	Hermanus	−17.4	+20.5	+89.8	−32.3	+28.2	+93.0	−24.0	+34.6	+90.3
3	Toolangi	+15.4	+14.8	−37.5	+1.1	+6.0	−33.5	−7.0	−3.5	−24.6
4	Amberley	+10.7	+22.7	−20.0	+0.4	+20.4	−22.2	−1.5	+20.4	−1.6
5	Trelew	−11.6	−46.0	+11.7	−21.3	−33.0	+17.7	—	—	—
6	Port aux Francais	−9.0	−40.1	−91.8	−29.9	−11.0	−25.4	+0.1	−14.7	+19.8
7	Macquarie Is.	−2.5	+23.9	−38.2	−14.3	+15.9	−35.5	−12.6	+9.3	−41.3
8	Argentine Is.	−7.5	−19.1	+10.5	−19.7	−11.9	+36.4	−15.0	−10.1	+21.4
9	Wilkes	−48.4	−1.9	−43.9	—	—	—	—	—	—
10	Mirny	−53.1	−19.1	−21.8	−33.4	−36.3	+2.9	−14.1	−36.1	+7.4
11	Dumont d'Urville	−33.0	+26.8	−49.3	−31.2	−12.1	+1.5	−35.5	−11.1	−89.5
12	Mawson	−32.0	−50.5	−2.5	−19.4	−42.8	+31.0	+0.3	−32.0	+37.2
13	Syowa Station	+3.0	−54.6	+35.3	+9.0	−34.1	+64.9	+23.2	−15.4	+70.5
14	SANAE	+14.0	−6.8	+20.1	+14.3	+19.3	+61.3	+11.6	−30.6	+18.5
15	Novolazarevs	+20.3	−18.6	+74.1	+23.4	+2.7	+38.7	+28.2	+5.8	+50.7
16	Halley Bay	+42.8	+25.2	−22.1	—	—	—	—	—	—
17	Byrd	+18.9	+20.4	+20.9	+15.5	+22.5	+21.0	—	—	—
18	Scott Base	−29.7	+29.2	−7.6	−32.7	−7.3	+30.6	−34.3	+8.6	−1.6
19	Vostok	−45.7	−14.5	+28.2	−24.8	−37.6	+9.9	−16.2	−29.6	−3.7
20	South Pole	+16.8	−24.8	+8.3	+21.9	−7.3	+30.6	—	—	—

Since the fact that the westward drift of the non-dipole field is one of the major sources of the geomagnetic secular variation has been almost certainly established at least in the low and middle latitude zones, (*e.g.* BULLARD *et al.*, 1950; YUKUTAKE, 1962; NAGATA, 1962b, 1965), there should be a possibility that the residual geomagnetic secular variation ($\Delta\dot{X}$, $\Delta\dot{Y}$, $\Delta\dot{Z}$) is largely due to the westward drift of non-dipole field. The IGRF magnetic charts for 1965.0 (ZMUDA, 1971) as well as the SCAR Antarctic magnetic charts for 1975.0 (GEOGRAPHICAL SURVEY INSTITUTE, 1978) show a non-dipole positive anomaly sector of Z between 80°W and 60°E in longitude and a non-dipole negative anomaly sector of Z between 100°E and 160°W in longitude in the southern polar region.

The non-dipole geomagnetic field at epoch of 1960.0 is compiled from data observed at the magnetic stations listed in Table 1 on an assumption that the non-dipole field is originated in a magnetic source located within the earth's interior, as illustrated



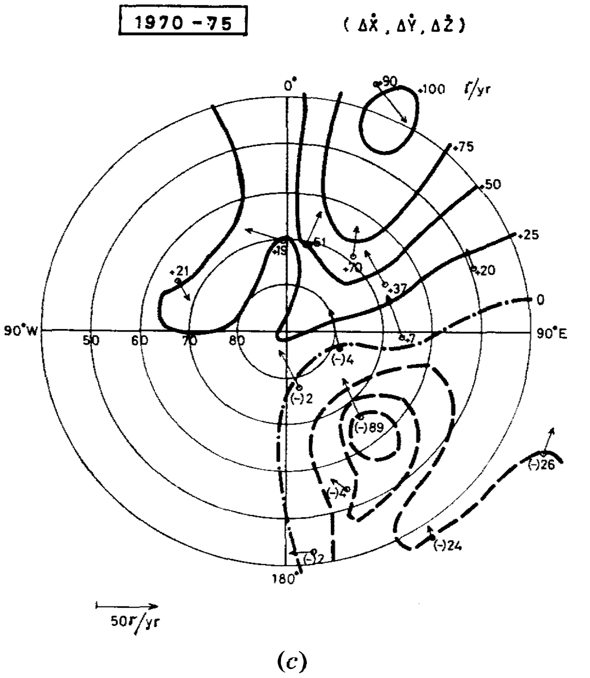


Fig. 4. Isoporic charts ($\Delta\dot{X}$, $\Delta\dot{Y}$, $\Delta\dot{Z}$) of the non-dipole secular geomagnetic secular variation in the southern polar region south the 40°S latitude circle. Contour: $\Delta\dot{Z}$ in unit of γ/year. Arrow: ($\Delta\dot{X}$, $\Delta\dot{Y}$) vector. (a) 1960–1965, (b) 1965–1970, (c) 1970–1975.

by the non-dipole component of $Z(\Delta Z)$ in Fig. 5. In this figure, the non-dipole geomagnetic field in the southern polar region consists of a negative Z region extending from 110°E to 180°E and a positive Z region extending over the whole remaining area and having the maximum Z peak between 70°S and 55°S in latitude and between 0° and 70°W in longitude. The general characteristics of the non-dipole field shown

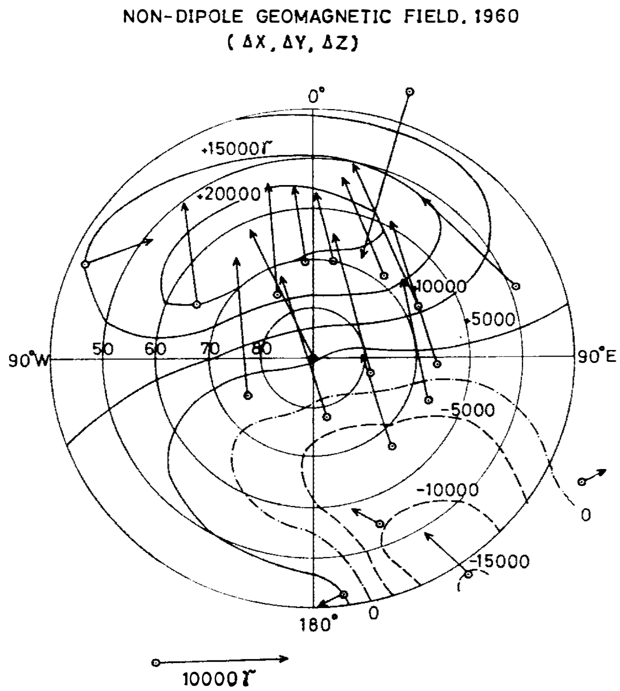


Fig. 5. Non-dipole geomagnetic field (ΔX, ΔY, ΔZ) in the southern polar region south the 40°S latitude circle for 1960. Contour: ΔZ in unit of γ. Arrow: (ΔX, ΔY) vector.

in Fig. 5 are in good agreement with those of the IGRF magnetic charts for 1965.0 and the Antarctic magnetic charts for 1975.0. Although the general tendency of westward drift of non-dipole geomagnetic field can be intuitively observed in comparison of the isoporic charts for $\dot{X}$, $\dot{Y}$ and $\dot{Z}$ with the corresponding non-dipole magnetic field (ΔX, ΔY, ΔZ) in the middle and low latitude zones, no clear evidence can be observed for suggesting a westward drift tendency in comparison of Fig. 4 with Fig. 5 in the southern polar region. Actually, the $\dot{Z}$ distribution which can be derived from the westward drift of the non-dipole field shown in Fig. 5 will be negative in a sector from 40°W through 0° to 140°E and positive in a sector from 40°W through 180° to 140°E in the southern polar region from 50°S to 90°S. Such a general tendency of the westward drift component of geomagnetic secular variation has already been illustrated in a previous paper (NAGATA, 1962b). Fig. 6 illustrates a hypothetical isoporic chart of $d\dot{Z}$ for the Z-component in the southern polar region which can be derived only from a hypothetical westward drift of the non-dipole field shown in Fig. 5 with an average drift velocity of 0.2 degrees/year (YUKUTAKE, 1962; NAGATA, 1962b). If the possible effect of westward drift of non-dipole field upon the secular variation pattern is subtracted from the ($\Delta\dot{X}$, $\Delta\dot{Y}$, $\Delta\dot{Z}$) charts shown in Fig. 4, a positive anomaly of $\Delta\dot{Z}$ in a sector between 10°W and 50°E and a negative anomaly of $\dot{Z}$ in a sector be-

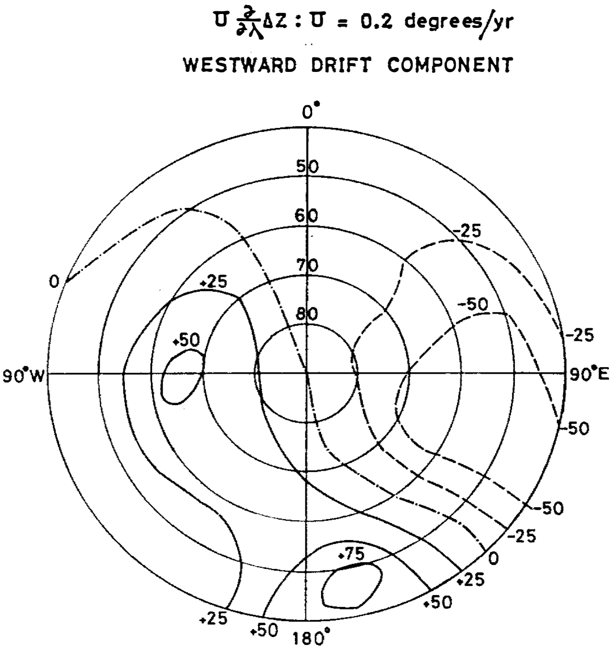


Fig. 6. Hypothetical isoporic chart of $d\dot{Z}$ caused by the westward drift of the ΔZ-component of the non-dipole geomagnetic field alone in the southern polar region south the 40°S latitude circle (in unit of γ/year).

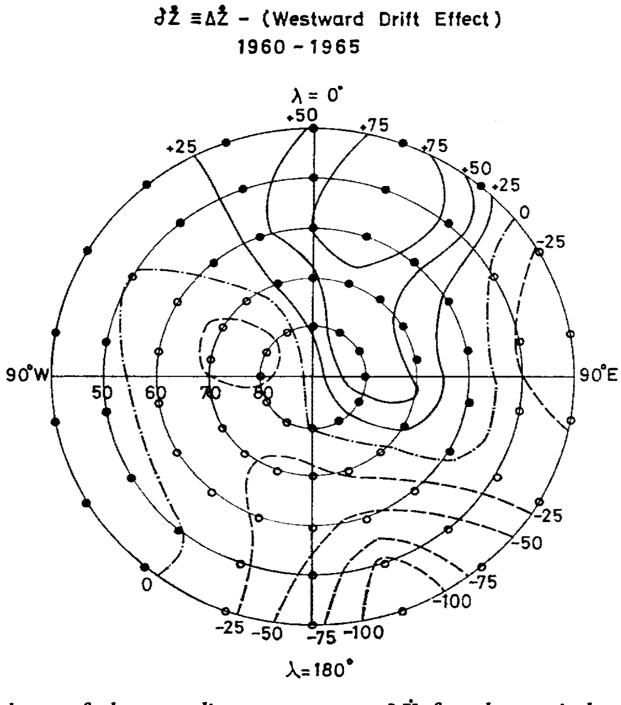


Fig. 7. Isoporic chart of the standing component $\delta\dot{Z}$ for the period of 1960–1965 in the southern polar region south the 40°S latitude circle, where $\delta\dot{Z}=\Delta\dot{Z}-d\dot{Z}$. (In unit of γ/year).

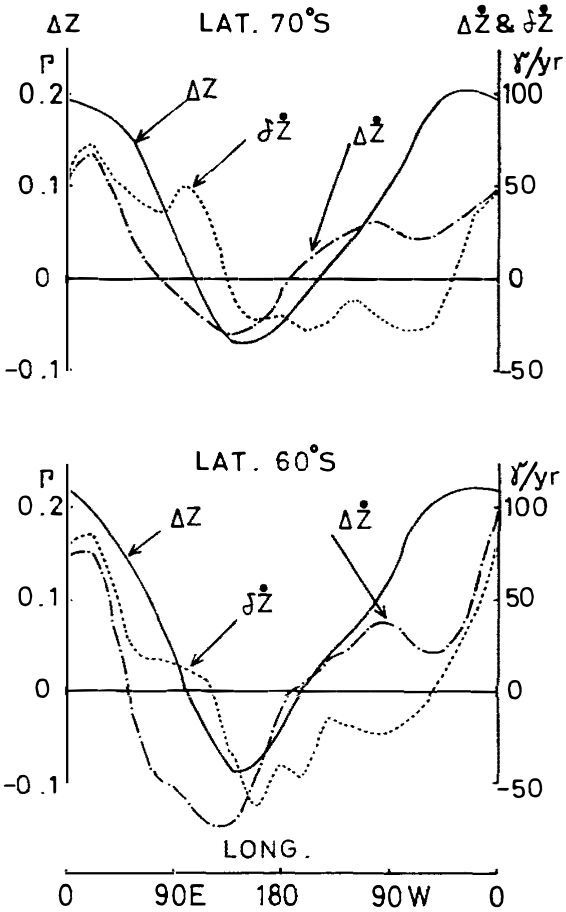


Fig. 8. Comparison of the distribution of ΔZ, $\Delta\dot{Z}$ and $\delta\dot{Z}$ along 70°S and 60°S latitude circles.

tween 140°E and 180°E will be more emphasized, though it appears that the positive $\Delta\dot{Z}$ in a sector between 40°W and 170°W and the negative $\Delta\dot{Z}$ in a sector between 60°E to 140°E in Fig. 4 could be largely attributed to the westward drift effect, as shown by a chart of $\delta\dot{Z}=\Delta\dot{Z}-d\dot{Z}$ in Fig. 7.

When the possible effect of westward drift of non-dipole field is taken into account, therefore, the residual secular variation anomaly ($\delta\dot{X}$, $\delta\dot{Y}$, $\delta\dot{Z}$) may be represented by a positive anomaly of $\delta\dot{Z}$ in a sector between 10°W and 50°E and a negative anomaly of $\delta\dot{Z}$ in a sector between 140°E and 180°E in the southern polar region. A comparison of Fig. 7 with Fig. 5 will suggest that the larger part of $\delta\dot{Z}$ corresponds to an enhancement of the Z-component of the non-dipole field. Fig. 8 illustrates the distribution of ΔZ, $\Delta\dot{Z}$ and $\delta\dot{Z}$ along latitude circles of 60°S and 70°S for example, where the annual rate of a growth of the non-dipole field can be estimated as about 0.3%/year. However, the correlation coefficients between $\Delta\dot{Z}$ and ΔZ are 0.90 and 0.80 on 70° and 60° latitude circles respectively, whereas those between $\delta\dot{Z}$ and ΔZ are 0.41

and 0.73 respectively. This result may suggest that the larger parts of $\Delta\dot{Z}$ are mostly due to an enhancement of the non-dipole field (ΔZ) and no positive evidence to indicate the westward drift of the non-dipole field can be observed in the southern polar region. When the westward drift of the non-dipole geomagnetic field is ignored, the annual rate of a growth of the non-dipole field is estimated to be 0.3–0.5%/year in the southern polar region.

5. Interpretative Discussions

It has already been known with regard to the distribution of geomagnetic secular variation in the low and middle latitude zones and the northern polar region of the earth (*e.g.* YUKUTAKE, 1962; NAGATA, 1962b) that the recent geomagnetic secular variation pattern consists of a change in the intensity and direction of the centered dipole, a northward shifting of the centered dipole, the westward drift of the non-dipole field and a growth or a decay of the non-dipole field, the last component being named by YUKUTAKE (1962) the standing component of geomagnetic secular variation. On the other hand, only a little has been known about the geomagnetic secular variation pattern in the southern polar region except few provisional data and their analysis (*e.g.* NAGATA, 1961, 1962a, b, 1965). It does not seem that the geomagnetic data dealt with in the present study are sufficiently large in number of observations to discuss in detail the geomagnetic secular variation in the southern polar region, particularly in a sector between 90°W and 180°W in longitude. It may be clear in the present study, however, that a large positive anomaly of $\dot{Z}$, larger than +150 nT/year in $\dot{Z}$, is present in the neighbourhood of the south pole throughout the period of 1960–1975. The major parts of the anomalously large values of $\dot{Z}$ in the southern polar region are attributable to an additional effect of the decay of the magnetic moment and the northward shifting of the geomagnetic centered dipole, as discussed in Section 3. It has been pointed out (NAGATA, 1965) that longitude (λ_0) of the geomagnetic north pole has been moving westward with an angular velocity of about 0.06 degrees/year, whereas its colatitude (θ_0) has been kept approximately constant since 1829. During the period of 1960–1975 also, the annual rate of a decrease of the centered dipole magnetic moment ($\dot{M}/M$) is 0.05–0.06% per year, and the annual angular velocity of a westward precessional rotation of the centered dipole ($\dot{\lambda}_0$) is 0.05–0.07 degrees/year, whereas θ_0 is kept approximately constant, as shown in Table 3. As already mentioned, the centered dipole is still continuing its northward shifting with a velocity of about 2 km/year (Table 3) during the same period. Although a theoretical interpretation of the decay, the westward precessional rotation and the northward shifting of the geomagnetic centered dipole has not yet been fully established, it may be concluded that the major parts of the anomously large geomagnetic secular variation observed in the southern polar region are attributable to the global characteristics of the centered dipole which is represented by $(\dot{X}_0, \dot{Y}_0, \dot{Z}_0)$ shown in Fig. 2.

The residual secular variation field $(\Delta\dot{X}, \Delta\dot{Y}, \Delta\dot{Z})$ obtained by subtracting the dipole-origin field $(\dot{X}_0, \dot{Y}_0, \dot{Z}_0)$ from the observed field $(\dot{X}, \dot{Y}, \dot{Z})$ is not particularly large in magnitude compared with the geomagnetic secular variation features in the low and middle latitude zones and in the northern polar region. In terms of $\dot{Z}$, large foci of the recent geomagnetic secular variation are negative anomalies in the Atlantic Ocean and in the Southern Indian Ocean and positive anomalies over the southern polar region and over the northern polar region (*e.g.* YUKUTAKE, 1962, 1979; NAGATA, 1962b, 1965). In all the other studies on the geomagnetic secular variation except Nagata's ones, however, the large isoporic anomaly over the southern polar region is generally ignored, probably because geomagnetic data in this region were hardly available. As for the isoporic anomalies in the Atlantic Ocean and the Southern Indian Ocean, the westward drift of non-dipole field with a drift velocity of about 0.2 degrees/year can well stand for their major parts (YUKUTAKE, 1962; NAGATA, 1962a, b; YUKUTAKE, 1979). From a theoretical viewpoint, however, it may not be certain whether the westward drift of non-dipole field can be dominant in the polar regions around the earth's rotation axis too, though the existing theory of the westward drift of geomagnetic field (BULLARD *et al.*, 1950; ROCHESTER, 1960) on the basis of an earth's interior model consisting of a rigid mantle and rigid outer and inner cores appears to stand well for the geomagnetic secular variation behaviours in the low and middle latitude zones where the angular momentum of materials near the core's boundary is dominantly large.

On the other hand, the observed growth of the non-dipole geomagnetic field in the southern polar region has already been theoretically suggested (NAGATA and RIKITAKE, 1961) as due to a growth of a poloidal magnetic field produced by a deformation of a toroidal magnetic field caused by convective motions within the earth's core. According to the result of the theoretical work, a growth rate of 0.5%/year of a poloidal magnetic field is possible at the maximum stage of its growth.

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