

Quasi-6-day wave modulation in ionospheric currents based on ground magnetic field observations and numerical calculation

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Quasi-6-day wave modulation in ionospheric currents
based on ground magnetic field observations and
numerical calculation

(地上磁場観測および数値計算に基づく
電離層電流における準 6 日波振動現象の解明)

Kumi TAKAYAMA
3SC22202T

Abstract

Quasi-6-day wave (Q6DW) is a type of planetary wave generated by the latent heat heating associated with the cumulus convection activity in the tropics. It propagates upward into the thermosphere and interacts with the ionosphere, and it has been confirmed from satellite observations to affect the equatorial electrojet (EEJ). The neutral wind associated with the Q6DW produces the quasi-6-day variation in the electric field/current system, then quasi-6-day variation in magnetic northward (H) and magnetic eastward (D) components of ground magnetic field could be modulated.

Therefore, we investigated on the Q6DW modulations on other ionospheric currents besides EEJ such as solar quiet (Sq) currents and inter-hemispheric field-aligned currents (IHFACs) by analyzing ground magnetic field data. The IHFACs flow from the ionosphere of one hemisphere to the other hemisphere through the magnetosphere, to resolve the non-uniformity of ionospheric conductivities between hemispheres. Therefore, unraveling the atmosphere-ionosphere-magnetosphere coupling processes by elucidating the Q6DW modulation on these currents.

To accomplish this, we used ground magnetic field data from MAGnetic Data Acquisition System/Circum-pan Pacific Magnetometer Network (MAGDAS/CPMN), Geospatial Information Authority of Japan (GSI), and International Real-time Magnetic Observatory Network (INTERMAGNET). The H and D components of ground magnetic field at 15 stations within the 210 geomagnetic longitude band during magnetic quiet period of 2010-2011 were analyzed. Also, we used data including the neutral wind velocity, current density, and magnetic field simulated by the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) during 2010-2011.

At first, we compared quasi-6-day variation in horizontal component ($\sqrt{H^2 + D^2}$) of observed magnetic field with the one in reproduced magnetic field by GAIA. From observation results, we could say that the quasi-6-day variations are strongest before and after the equinoxes, while being weak during the equinoxes. Also, they strongly develop from geomagnetic equator to low-middle latitudes of the summer hemisphere. These spatio-temporal variations agree with the seasonal and longitudinal variation as seen from the GAIA.

To extract geomagnetic variation modulated by each current, we applied principal component analysis (PCA) to the data. PCA is a statistical analysis method that can extract large components from any data and reveal its internal structure. By applying PCA, the zonal component of the Sq-EEJ current system and semidiurnal variation were seen in the H component and the IHFACs and meridional component of the Sq currents were seen in the D component. In addition, the quasi-6-day variations on the IHFACs at geomagnetic equator and low latitude in the northern hemisphere were found to be highly correlated with the Q6DW amplitudes in the lower thermosphere reproduced by GAIA. From these results, we suggest that the possibility of propagation process that the Q6DW intensifies the Sq currents in one hemisphere and weakens the Sq currents in another hemisphere, then modulates the quasi-6-day variation on the IHFACs.

In summary, the Q6DW modulated the quasi-6-day variation in the Sq-EEJ current system, IHFACs. More generally, this study highlights the complicated interactions taking place in the near-Earth environment, specifically on the processes affecting atmosphere-ionosphere-magnetosphere coupling.

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The contents of this study are shown below. In Chapter 1, the general introduction and previous studies to understand this study were described. In Chapter 2, analysis methods of ground magnetic field obtained from the MAGDAS/INTERMAGNET/GSI and numerical data reproduced by GAIA are explained. In Chapter 3, detailed explanations of PCA/ICA are also shown. Using PCA, each current modulation can be extracted from ground magnetic field data. In Chapter 4, the quasi-6-day variation in horizontal components ($\sqrt{H^2 + D^2}$) of ground magnetic field without PCA were compared with the Q6DW amplitude in zonal wind from GAIA during 2010–2011. In Chapter 5, we report that each basis function obtained by PCA corresponds to which current. Then we showed seasonal variation and longitude structure of quasi-6-day variation on Sq-EEJ current system and IHFACs. Also, the quasi-6-day variation on IHFACs at geomagnetic equator were compared with the Q6DW amplitude in the lower thermosphere during 2010–2011. In Chapter 6, we discussed propagating process of the Q6DW. In Chapter 7, the final conclusions and future perspectives in this study are described.

Chapter 1

General Introduction

1.1 Atmosphere-ionosphere coupling

Coupling process between the atmosphere and ionosphere is a key topic of understanding the complex interactions within the earth and space environments. The atmosphere forms layered structures as the altitude increases from the surface towards space, with interaction between these layers. In particular, the ionosphere, which located in the upper atmosphere, is closely linked and strongly influenced by solar wind and solar UV/EUV radiation.

The atmosphere is primarily divided into the troposphere, stratosphere, mesosphere, and thermosphere. These layers have distinct properties depending on temperature and composition, and they play a crucial role in weather phenomena and energy transport. The solar radiation causes neutral atoms and molecules to become ionized, forming a region known as the ionosphere. The ionosphere plays an essential role in reflecting and refracting radio waves, making it critical for satellite communication and GPS systems. The thermosphere and ionosphere are not independent layers; they interacted each other through energy and momentum exchange. Specifically, atmospheric waves (e.g., planetary waves, gravity waves and tidal waves) propagate from lower atmosphere to the thermosphere, influencing the ionosphere. This interaction leads to changes in ionospheric density and structure. On the other hand, solar wind and geomagnetic storms caused by solar activity disturb ionospheric plasma, affecting ionospheric currents and electric fields.

Atmospheric waves from lower atmosphere as well as solar wind and geomagnetic storms associated with solar activity, affect space weather, e.g., satellite communications and GPS accuracy. Therefore, it is important for space weather forecasting to clarify the effects of atmospheric waves of lower atmosphere to the ionosphere. Monitoring the changes in the coupling between the atmosphere and ionosphere helps us better understand environmental variations and develop measures to mitigate their impacts. Therefore, this study is important to address modern technological and societal challenges related to our wireless communication networks.

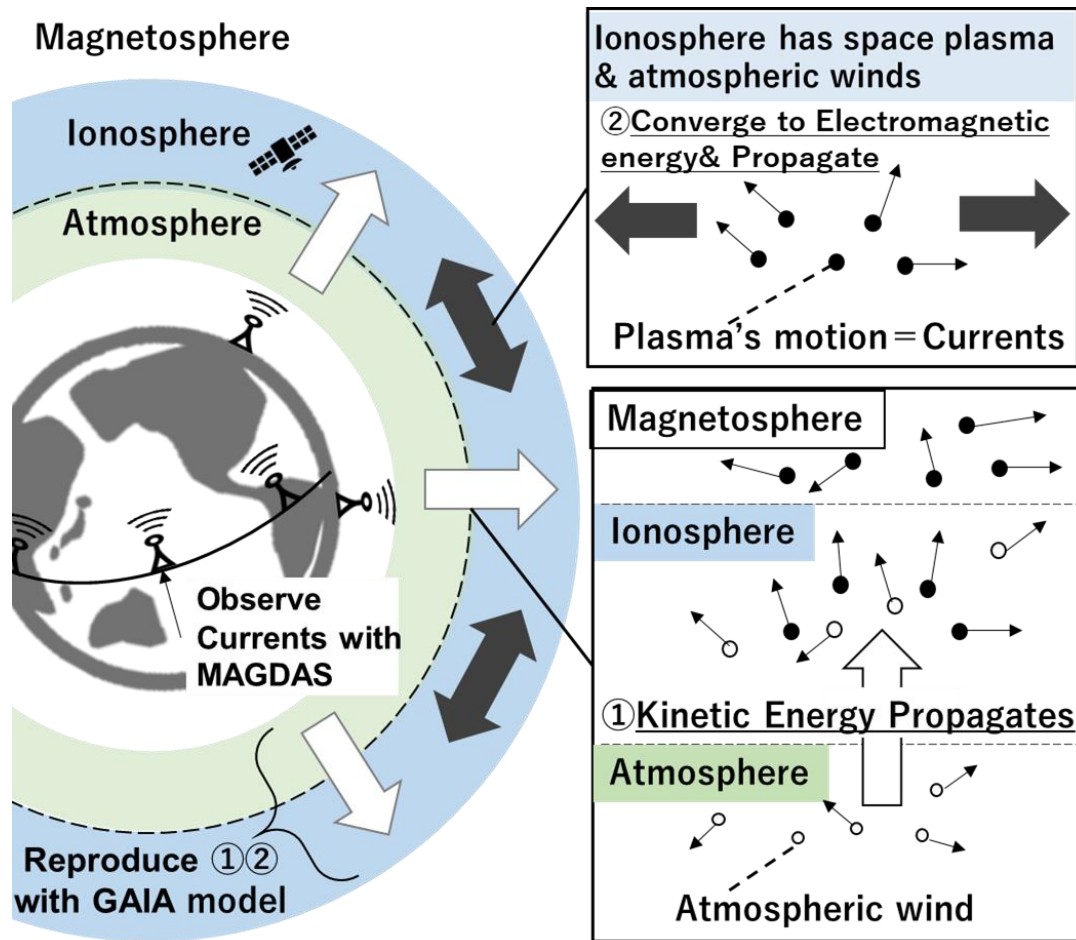


Figure 1.1. Conceptual diagram of energy conversion processes between the atmospheric wind and space plasma in the ionosphere.

1.2 Sq current system

1.2.1 Characteristics

The Solar quiet (Sq) current system had two eddy currents due to a diurnal tidal wind during daytime in the E-region ionosphere (90-150km altitudes) in the northern and southern hemispheres as shown in right panel of Figure 1.2. The eddy currents flow counterclockwise in the northern hemisphere and clockwise in the southern hemisphere [Chapman and Bartels, 1940]. It manifests in ground magnetic field data as shown in left panel of Figure 1.8.

1.2.2 Generation mechanism based on dynamo theory

Figure 1.2 presents a conceptual diagram of the ionospheric dynamo theory. The neutral wind at ionospheric altitudes undergoes large-scale atmospheric motion $\mathbf{u}$ due to thermal convection caused by solar radiation and tidal forces from the sun and the moon. When this atmospheric motion flows in collision with the ionospheric plasma, the pulling force of the neutral wind $\mathbf{u}$ (atmospheric drag) drives the drift motion of the plasma in the presence of the geomagnetic field $\mathbf{B}$. Since there is a difference in the drift motion of ions and electrons, an induced electromotive force $\mathbf{E}_i$ is generated as

$$\mathbf{E}_i = \mathbf{u} \times \mathbf{B}. \quad (1.1)$$

The $\mathbf{E}_i$ is called dynamo electric field.

As shown in Figure 1.2, the transfer of charge due to $\mathbf{E}_i$ results in the accumulation of positive charge on the morning side and negative charge on the evening side, creating a polarizing electric field $\mathbf{E}_s$. The electric field further drives the plasma drift, but when there is a collision with the neutral wind, a difference in drift motion occurs between ions and electrons, resulting in polarization currents. As a result, $\mathbf{J}$, which is the sum of dynamo currents and the polarization currents, flows in the ionosphere.

$$\mathbf{J} = \sigma \cdot [\mathbf{E}_i + \mathbf{E}_s], \quad (1.2)$$

These currents are called the Sq current system. The Sq current system forms vortex structures in the northern and southern hemispheres (NH and SH). [Maeda, 1955; Kato, 1956; Hirono and Kitamura, 1956; Stening, 1969a; Matsushita, 1969; Tarpley, 1970b; Volland, 1971b; Murata, 1974b; Mohlmann, 1976b]. Their different rotation of $\mathbf{J}$ at the NH and SH is due to different meridional wind u at the NH and SH. Most of the daily variation of the ground magnetic field can be explained by the effect of these currents.

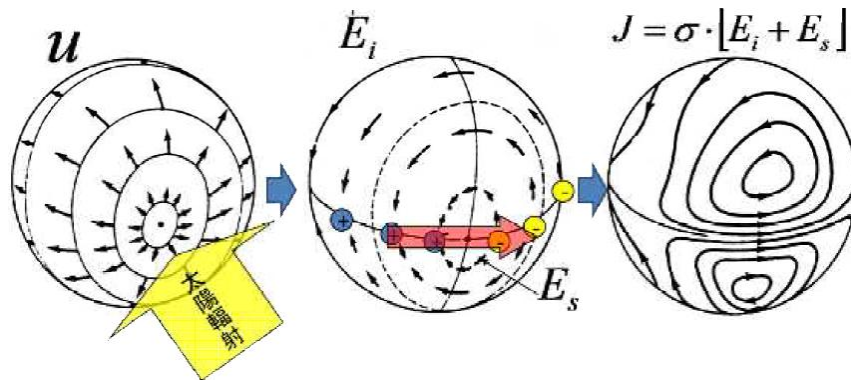


Figure 1.2. Generation mechanism of the Sq current system. A neutral wind is modulated by the solar radiation heating (left). An electric field is generated by the neutral wind and Earth's magnetic field (middle). An electric current is also generated due to the electric field (right) [modified Figure 5-17 of Obayashi, 1970].

1.3 Equatorial electrojet (EEJ)

1.3.1 Characteristics

The equatorial electrojet (EEJ) is an eastward-flowing ionospheric current located at the magnetic dip equator, which is predominant at an altitude of around 90-130 km (ionospheric E layer), as shown in Figure 1.3.

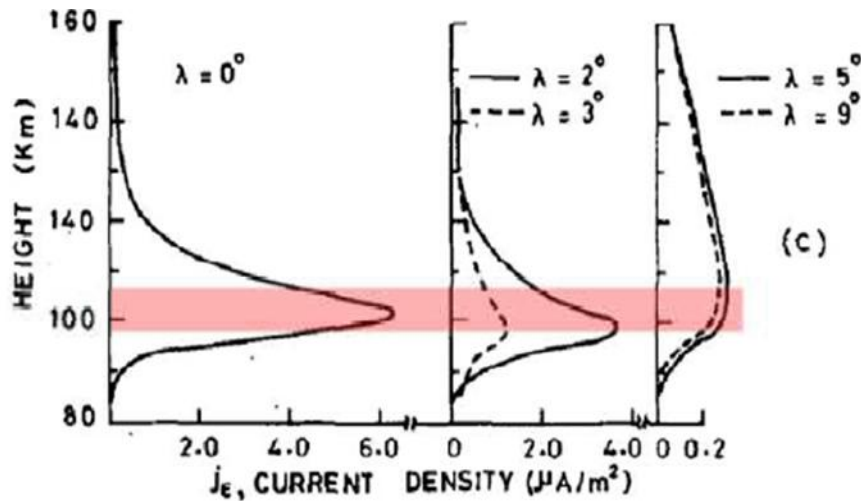


Figure 1.3. Altitude distribution of current density [Reddy et al., 1989].

Figure 1.4 presents that EEJ develops more rapidly and strongly around -3° to $+3^\circ$ in the geomagnetic equator than at lower latitudes.

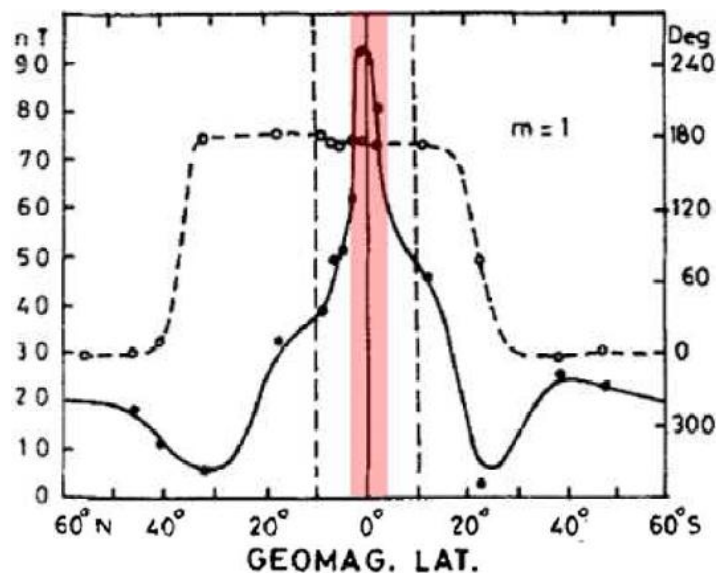


Figure 1.4. Latitudinal structure of the EEJ intensity [Reddy et al., 1989].

Figure 1.5 presents the ground magnetic field variation at Yap Island (YAP), a MAGDAS station located close to the magnetic dip equator (geomagnetic latitude (GMLAT): 0.79°N , geomagnetic longitude (GMLON): 209.84°), during a geomagnetically quiet day. The peak of the northward (H) ground magnetic field variation due to EEJ often appears at around 11:30 a.m.

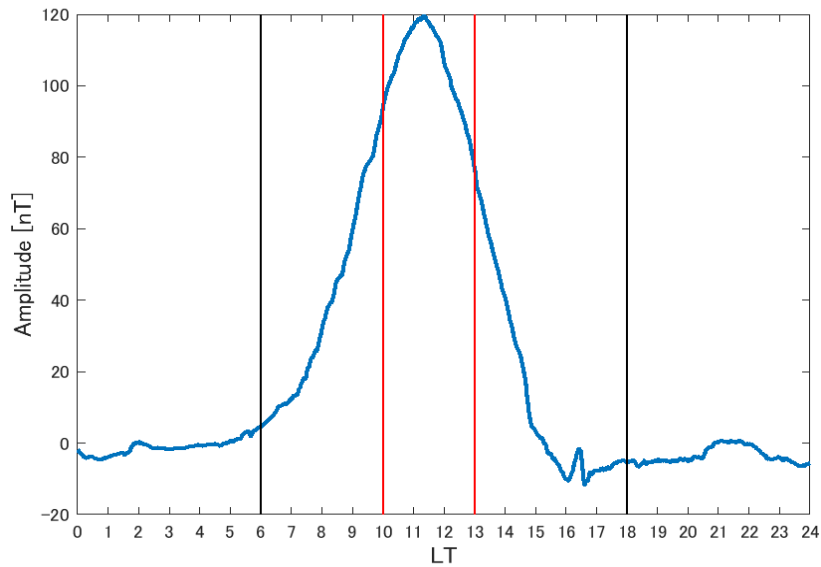


Figure 1.5. The northward component of ground magnetic field at YAP [GMLAT: 0.79°N , GMLON: 209.84°] on 8 January 2007. Red lines show at 10 and 13 LT and black lines show at 06 and 18 LT .

1.3.2 Generation mechanism

Sq current system from the northern and southern hemispheres converge at the magnetic dip equator. This generates an eastward electric field E_s at the dip equator. At the same time, the magnetic field is parallel to the ground at the dip equator, i.e. the northward magnetic field is perpendicular to the electric field. This, along with the fact that E_s is vertically restricted, creates a Hall current ($\sigma_H E_s$), which in turn generates a new vertical upward electric field E_2 . Furthermore, this electric field E_2 and magnetic field B create an eastward Hall current ($\sigma_P E_2$), which, when combined with the Pedersen currents flowing in the same direction as the electric field, drastically intensifies the eastward current as shown in Figure 1.6. This is called the Cowling effect [Chapman, 1956]. Cowling [1932] first investigated the Cowling effect in connection with the solar atmospheric physics, and Cowling and Borger [1948] adapted to the current system in the earth ionosphere especially equatorial region [Hirono, 1950] and auroral region [Boström, 1964].

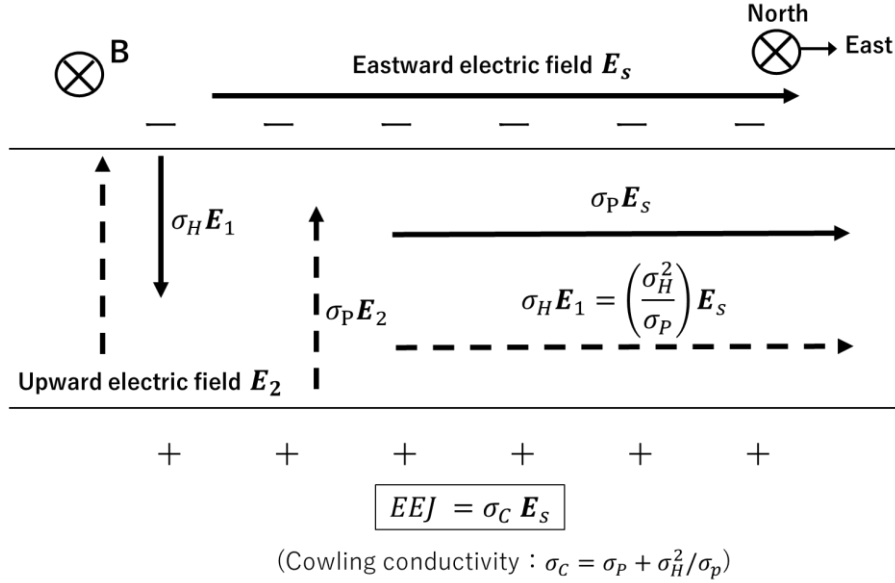


Figure 1.6. Generation mechanism of the EEJ. Ionospheric conductivity at the magnetic equator enhances due to the Hirono/Cowling effect.

Pedersen current: In the ionosphere of an internally magnetized planet, electrons and ions can travel across the magnetic field lines due to collisions with neutral particles. This generates a finite conductivity sigma perpendicular to the magnetic field lines, which generates a current called the Pedersen currents perpendicular to the magnetic field lines.

Hall current: A phenomenon in which an electromotive force manifests in a direction perpendicular to both the current and magnetic field when a magnetic field perpendicular to the currents is applied to an object in which the current is flowing.

1.3.3 Ground magnetic field modulated by the Sq-EEJ current system

The Sq current system that manifest on dayside of the ionosphere in the northern and southern hemispheres, creates a magnetic field around the current according to Ampere's law as shown in Figure 1.7. The eastward magnetic field component (Y), corresponding to the Sq current system, shows a daily variation with peaks in the morning and troughs in the evening in the northern hemisphere, and vice versa in the southern hemisphere. On the other hand, the northward magnetic field component (X) shows a trough at high latitudes and a large peak in the daytime at the magnetic dip equator and low latitudes, regardless of the north-south hemisphere.

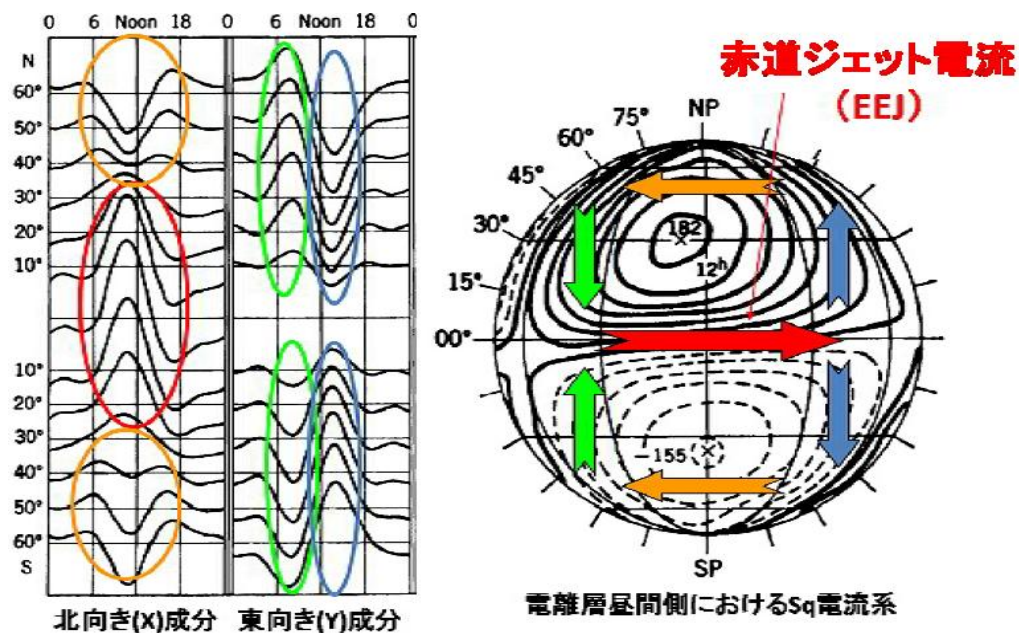


Figure 1.7. Ground magnetic field created by the Sq-EEJ current system. (Left) ground magnetic field variation created by the Sq-EEJ current system. (Right) Sq-EEJ current system in the dayside of the ionosphere *The color of the arrow in the right figure corresponds to the color of the circle in the left figure. Adapted from [Nagata and Tomatsu, 1973].

1.4 Interhemispheric field aligned currents (IHFACs)

Inter-hemispheric field-aligned currents (IHFACs) traverse from the ionosphere of one hemisphere to the other through the magnetosphere, compensating for the spatial non-uniformity of the northern and southern Sq current system [Maeda, 1974; Van Sabben, 1966; Fukushima, 1979, 1994]. Figure 1.8 presents the direction changing of the IHFACs depend on the time. These currents flow from the summer hemisphere (SH) to winter hemisphere (WH) during morning and from WH to SH during noon hours and evening [Fukushima, 1994]. It was first observed with directional shifts in the morning by Olsen (1997). However, recent studies suggest that the direction of the IHFACs in the dusk sector reverses depending on the season, which disagree with the concept of the Fukushima's model, observed by ground-based magnetometer (See Figure 1.9) and satellites (Figure 1.10) [Park et al. 2011, 2020a, 2020b; Lühr et al. 2015, 2019; Shinbori et al., 2017; Fathy et al. 2019; Ranasinghe et al., 2021]. Also, the intensity of the IHFACs peaks in February and August, and their directions reverse during April-May and November. These were observed by the Ørsted satellite and from ground geomagnetic data [Yamashita and Iyemori, 2002]. The IHFACs are comprised of both meridional and vertical currents, allowing for their observations through the horizontal, declination, and vertical geomagnetic field.

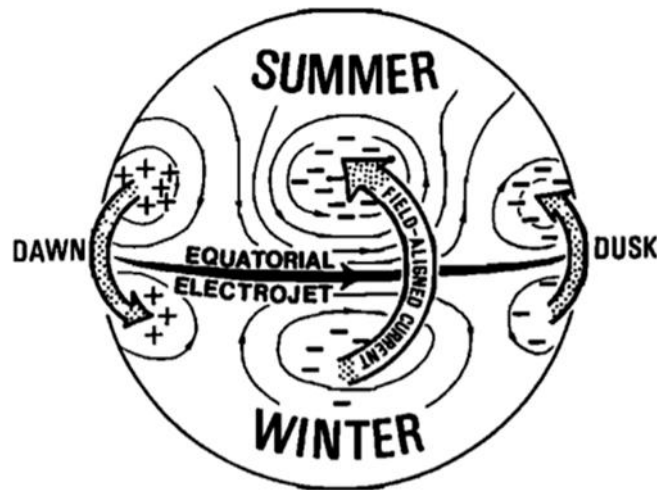


Figure 1.8. A model of interhemispheric trans-equatorial field-aligned currents in the magnetosphere at middle and low latitudes. [Fukushima, 1994]

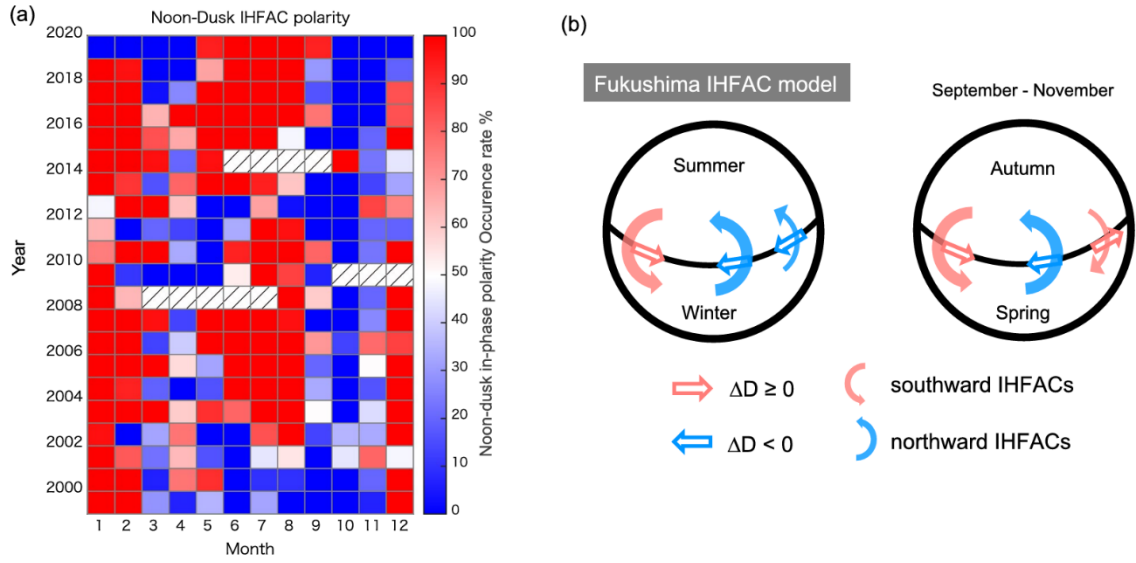


Figure 1.9. Distribution of the dusk-side IHFAC of the Fukushima's model type from 1999 to 2019. (a) The occurrence rate of the dusk-side IHFAC of the Fukushima's model type as a function of month and year. The red color indicates higher occurrence of the dusk-side IHFAC of the Fukushima's model type, which means the in-phase IHFAC polarity in both noon and dusk sectors. The blue color represents lower occurrence rate, this is equal to higher occurrences of the dusk-side IHFAC, which disagreed with the concept of Fukushima's model. The hatched areas show the no-data periods. (b) The illustration of IHFACs polarity. The left side describes the concept of Fukushima's model for the northern hemisphere in summer. The right side shows the opposite dusk-side IHFAC of the Fukushima's model type [Ranasinghe et al., 2021]

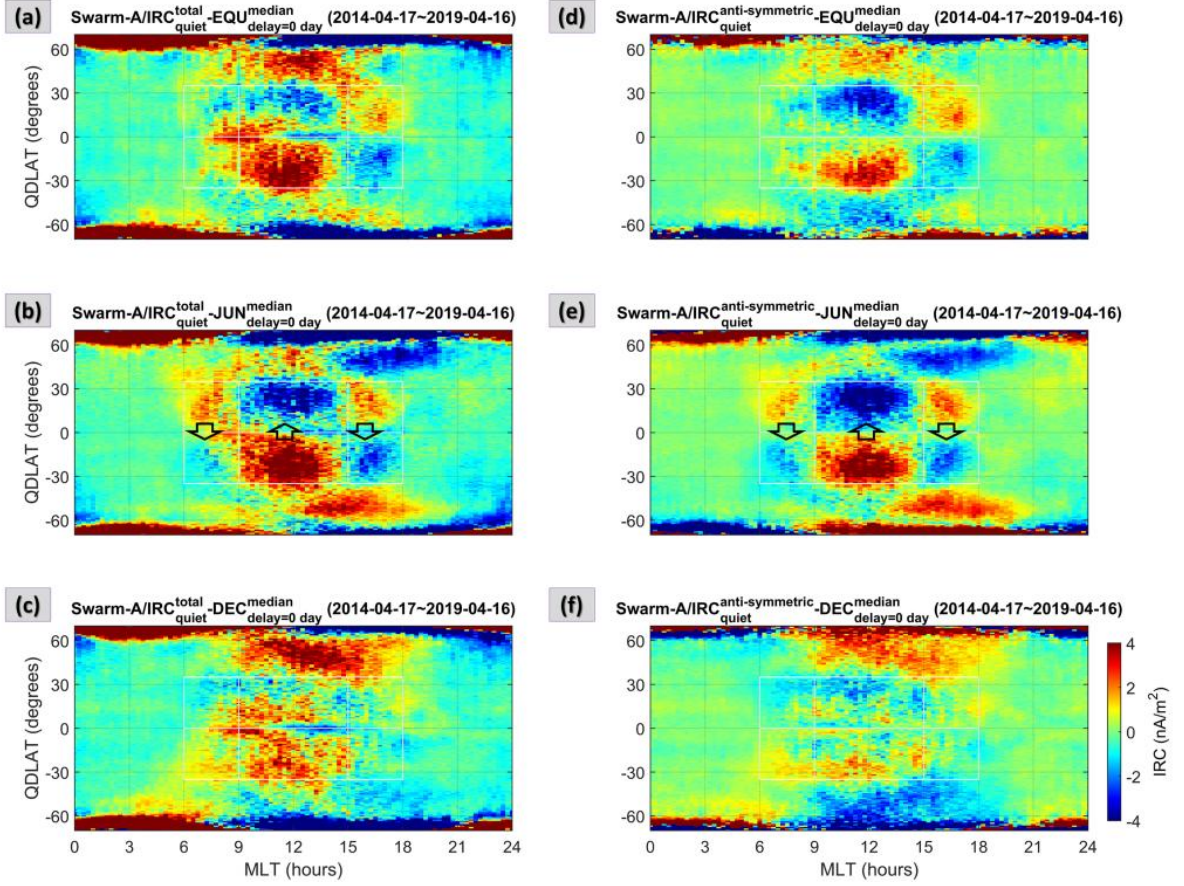


Figure 1.10. Radial current density estimated from Swarm - Alpha magnetic data as a function of MLAT and MLT. Each row from the top again corresponds to combined equinox, June solstice, and December solstice. The left column (a–c) corresponds to the original bin averages of radial current density. The right column (d–f) presents hemispherical antisymmetric components extracted from the left column. [Park et al., 2020]

1.5 Quasi-6-day wave (Q6DW)

Planetary waves propagating westward with zonal wavenumber 1 are global oscillations of the atmosphere and have periods of about 2, 6, 10 and 16 days. They are generally considered as normal mode Rossby waves and represent resonant or free oscillations of the atmosphere. The existence of the waves is predicted by classical theories of atmospheric waves [Longuet-Higgins, 1968]. The latitudinal structures of waves propagating westward with zonal wave number 1 (zonal wave number 2) with period of 6, 10, 16 (4, 6, 9) days are corresponding to (1, 1), (1,

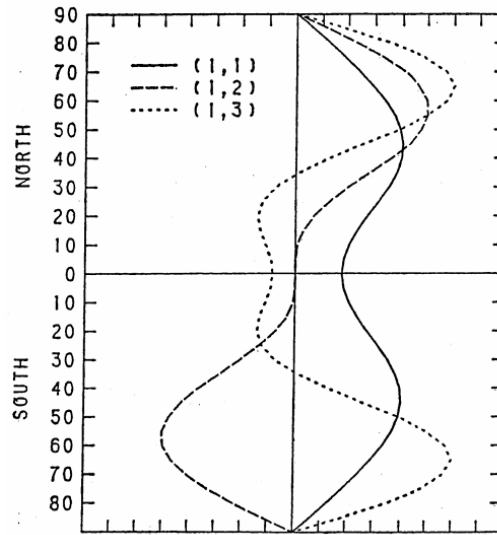


Figure 1.11. Hough function with equivalence height = 10km. [Hirota, 2000]

2), (1, 3) mode of Hough functions respectively as shown in Figure 1.11.

Quasi-6-day waves (Q6DWs) is one of the normal mode planetary waves. The Q6DWs generated by latent heat released during cumulus convection activity in the tropics [Miyoshi Hirooka, 1999]. They intensify before and after the equinoxes in the mesosphere and lower thermosphere region and reaches a minimum at the solstices (Liu, et al., 2004). The zonal and meridional winds due to the Q6DW have a peak at the equator and middle latitudes, respectively.

The Q6DW observed in the geopotential height at 40°N as shown in Figure 1.12 [In Hirota and Hirooka, 1984].

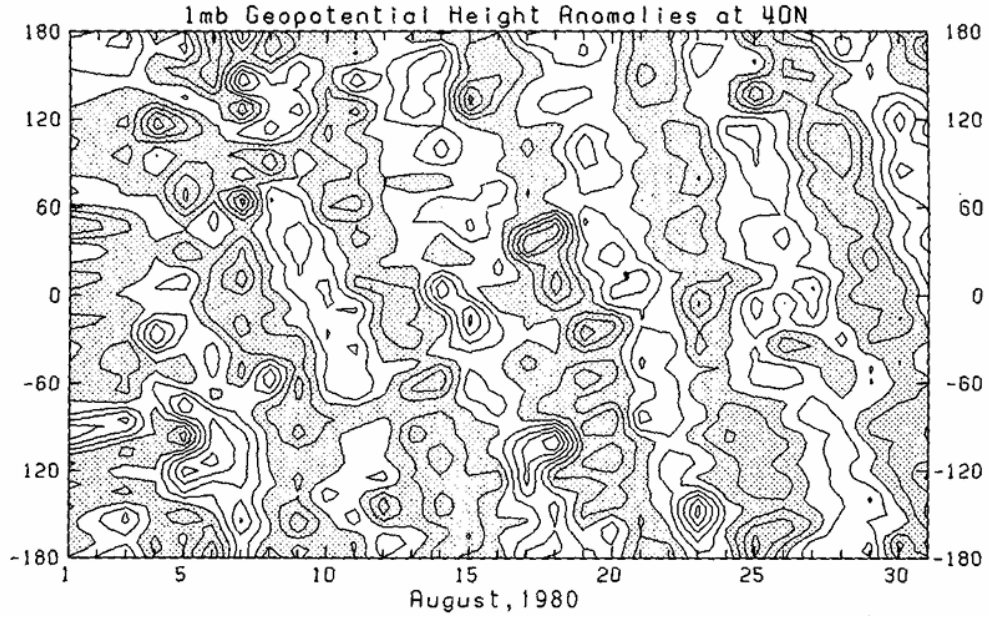


Figure 1.12. Longitude-time section of the deviation of 1 mb geopotential height from the time and zonal average at 40°N for August 1980. Shaded regions denote negative anomalies. The contour interval is 50m. [Hirota and Hirooka, 1984]

Satellite observations revealed that Q6DW propagates into the E region heights, influencing the equatorial electrojet (EEJ) as shown in Figure 1.13 and Figure 1.15 [Yamazaki, Stolle, Matzka, Alken, 2018]. Figure 1.13a and 1.13b present the EEJ intensity during September 2006 as observed by the CHAMP satellite. The amplitude of the quasi-6-day variation in the EEJ intensity has strong longitudinal variability. Figure 1.15d presents the same intensity of Figure 1.15a predicted by the empirical model, EEJM. Figure 1.15e presents that the EEJ have a variation with zonal wavenumber 1 and period of 6 days, indicating the Q6DW modulation. Also, ground-based magnetometers also showed the quasi-6-day variation in EEJ as shown in Figure 1.14.

The Q6DWs drive the dynamo electric field and currents in E region of the ionosphere at a 90-to 150-km altitude. The variation of the geomagnetic field due to that current variation can be shown theoretically by the Ampere-Maxwell equation.

$$\nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t} \quad (1.3)$$

where H is the magnitude of geomagnetic field, j is the current density, and D is the electric flux density.

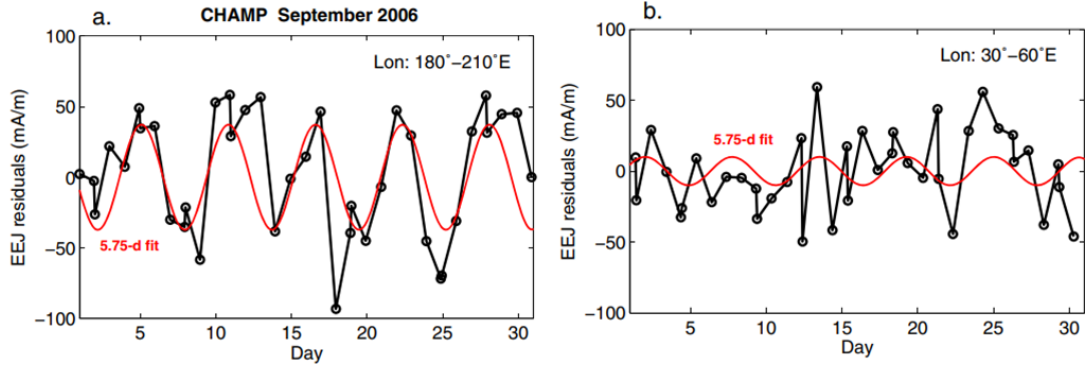


Figure 1.13. Equatorial electrojet (EEJ) intensity during September 2006 as observed by the CHAMP satellite at (a) $180^\circ - 210^\circ\text{E}$ and (b) $30^\circ - 60^\circ\text{E}$ longitudes. Also plotted in each panel is the least squares fit of the 5.75-day Fourier curve. [Yamazaki et al., 2018]

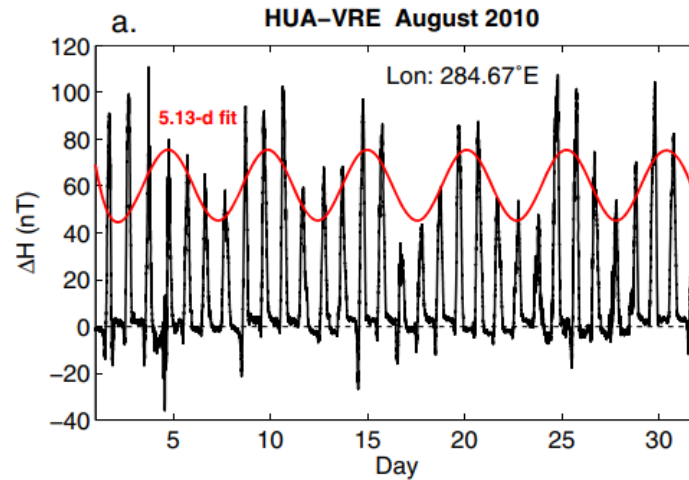


Figure 1.14. ΔH (H at Huancayo [HUA] minus H at Villa Remedios [VRE]) as observed by ground-based magnetometers during August 2010. The quasi-dipole latitude is 0.28° at HUA and -5.00° at VRE for the year 2010. The red line is the least squares fit of the 5.13-day Fourier curve. [Yamazaki et al., 2018].

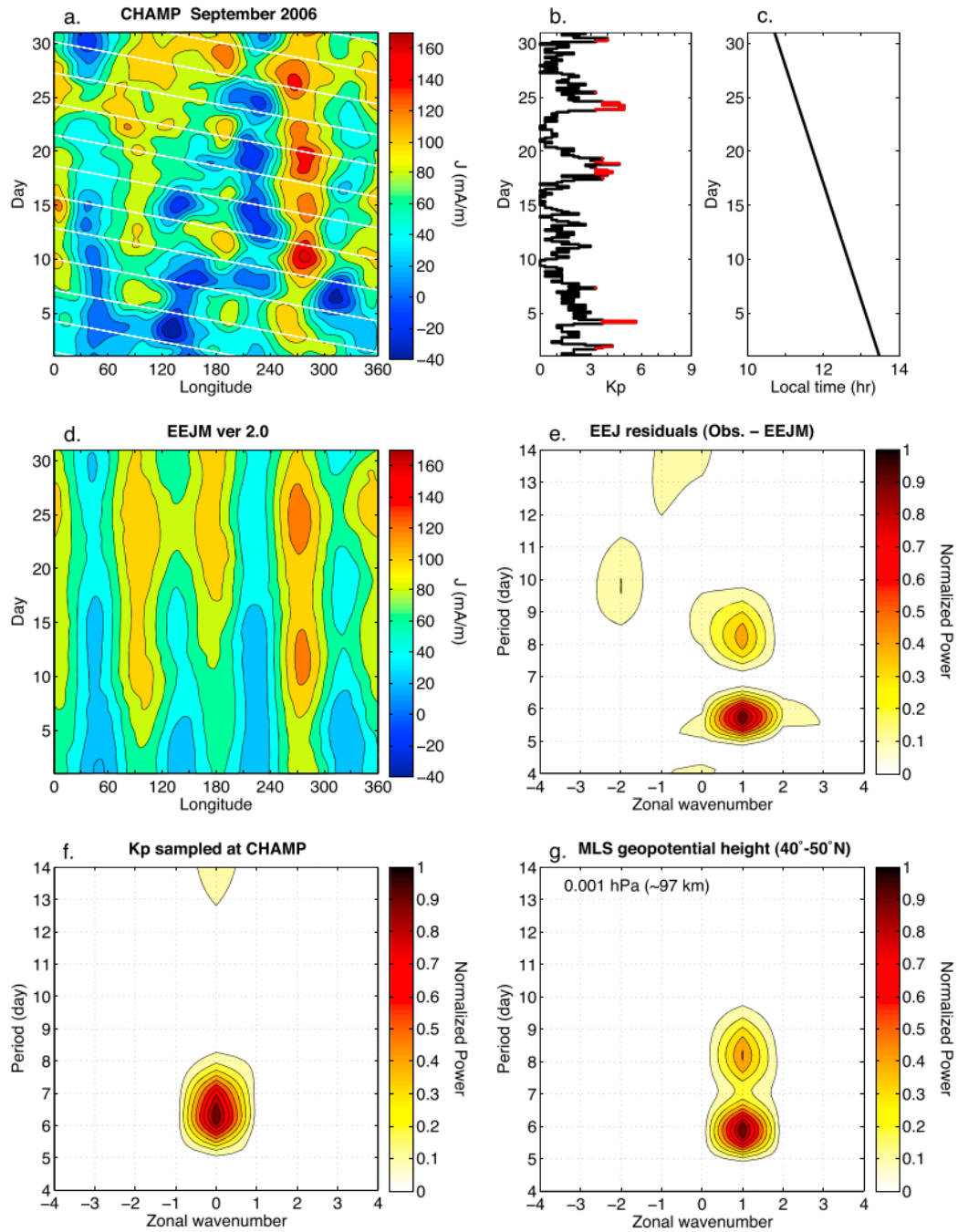


Figure 1.15. (a) EEJ intensity during September 2006 as observed by the CHAMP satellite. The white lines represent the zero contour for the westward propagating 5.75-day wave with zonal wavenumber $s = 1$, indicating the phase propagation of the wave. (b) Geomagnetic activity index K_p . The red color indicates the periods of relatively high geomagnetic activity ($K_p > 3^\circ$). (c) Local solar time of the CHAMP measurements. (d) Same as (a) except for the empirical model, EEJM. (e) Period versus wavenumber (positive for westward propagating) spectrum for the residual equatorial electrojet intensity (observations minus EEJM predictions). The spectral power is normalized to the peak value. (f) Same as (e) except for the K_p index sampled at the times of the CHAMP measurements of the equatorial electrojet. These K_p values were analyzed as if they were variable spatially as well as temporally, according to the longitudes and times of the CHAMP measurements of the equatorial electrojet. (g) Same as (e) except for the Microwave Limb Sounder (MLS) geopotential height measurements at 0.001 hPa (~97-km height) in the latitude range 40°–50°N by the Aura satellite. [Yamazaki et al., 2018].

Chapter 2

Dataset and Method for monitoring ionospheric variation

To investigate the Q6DW modulation in the ionospheric currents, we mainly used 1-minute data of ground magnetic field from the MAGnetic Data Acquisition System (MAGDAS)/the International Real-time Magnetic Observatory Network (INTERMAGNET) and 30-minute or 1-hour data of neutral wind/current density/magnetic field simulated by the Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA). In this chapter, we describe the observational data that we used, and the analysis methods.

2.1 Geomagnetic field measured by magnetometers

2.1.1 MAGnetic Data Acquisition System (MAGDAS)

MAGDAS project, which has the global network of magnetometers, was constructed by Kyushu University in collaboration with about many international organizations along the 210° magnetic meridian and magnetic dip equator as shown in Figure 2.1 (Yumoto and the 210 MM Magnetic Observation Group, 1996; Yumoto and the CPMN Group, 2001; Yumoto and the MAGDAS Group, 2006, 2007; <http://data.i-spes.kyushu-u.ac.jp/>). The ground magnetic field, expressed by horizontal (H), declination (D), and vertical (Z) components, are digitized by using the field-canceling coils for the dynamic range of

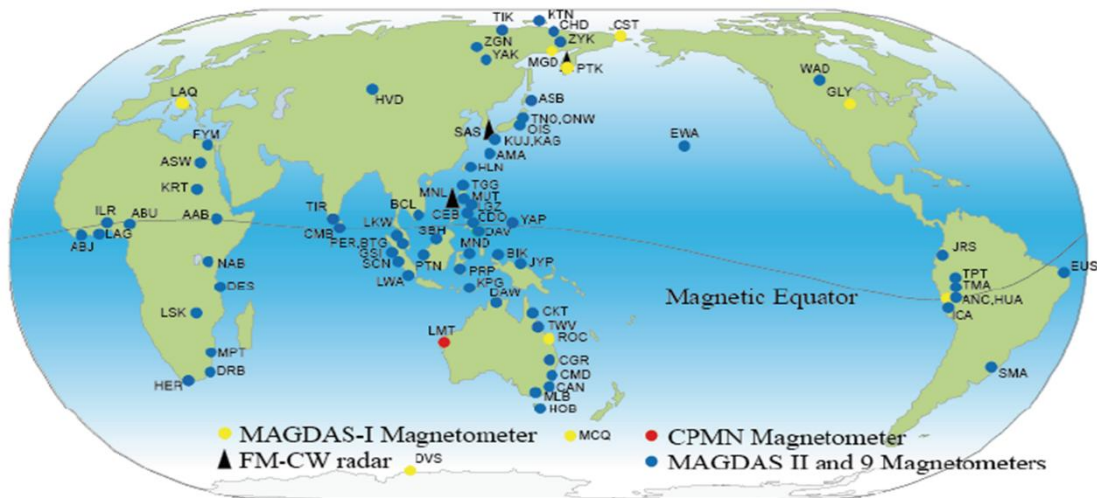


Figure 2.1. Observation map of MAGDAS/CPMN.

$\pm 64,000\text{nT}/16\text{bit}$. The H, D, Z axes indicate geomagnetically northward, eastward, and vertically downward, respectively.

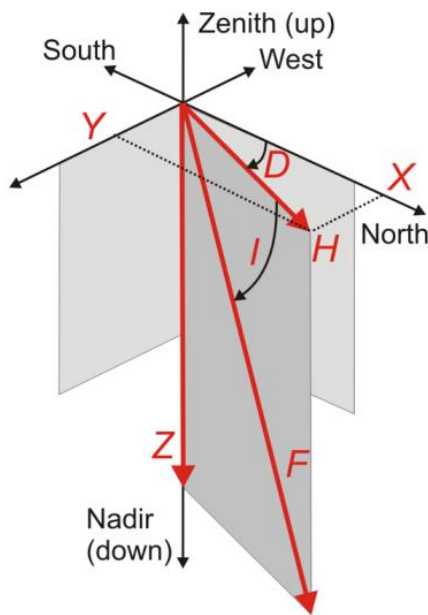
2.1.2 International Real-time Magnetic Observatory Network (INTERMAGNET)

INTERMAGNET program exists to establish a global network of cooperating digital magnetic observatories, adopting modern standard specifications for measuring and recording equipment, in order to facilitate data exchanges and the production of geomagnetic products in close to real time (<http://www.intermagnet.org>). The data used the XYZ coordinate. The X, Y, Z axes indicate geographically northward, eastward, and vertically downward, respectively as shown in Figure 2.2. Also, INTERMAGNET differs from MAGDAS in that it expresses D as angles. When used with MAGDAS, it needs to be adjusted according to the equation below. D' is the geomagnetically eastward component in nT.

$$D (^{\circ}) = \arctan(Y/X), \quad (2.1)$$

$$H (\text{nT}) = X*\cos(D)+Y*\sin(D), \quad (2.2)$$

$$D' (\text{nT}) = Y*\cos(D)-X*\sin(D). \quad (2.3)$$



- $X = H*\cos(D)$
- $Y = H*\sin(D)$
- $Z = F*\sin(I)$
- $H = F*\cos(I)$
- $H = \text{SQRT}(X^2 + Y^2)$
- $F = \text{SQRT}(X^2 + Y^2 + Z^2)$
- $\tan(D) = Y/X$
- $\tan(I) = Z/H$

Figure 2.2. Geomagnetic components [INTERMAGNET Technical Reference Manual].

2.1.3 Geospatial Information Authority of Japan (GSI)

North on a map and north on a compass are misaligned. In order to determine the north of a map using a compass when climbing a mountain, GSI obtains this misalignment by geomagnetic surveying. The angle of this misalignment is called the declination(D). The declination angle can be found on topographic maps and on magnetic maps showing declination angles throughout Japan. This information is also used in electronic compasses for smart phones and in the calculation of sunshade restrictions in the field of architecture (https://www.gsi.go.jp/buturisokuchi/geomag_index.html).

As same with the MAGDAS data, they serve data with HDZ coordinate and D is in nT. But the HDZ value measures the amount of change in the geomagnetic field, absolute values must be calculated.

2.1.4 Station List and map for Chapter 3

Data set is geomagnetically quiet days with Kp index ≤ 2 and Dst index ≥ -20 nT of Jun in 1992-2004 (68 days).

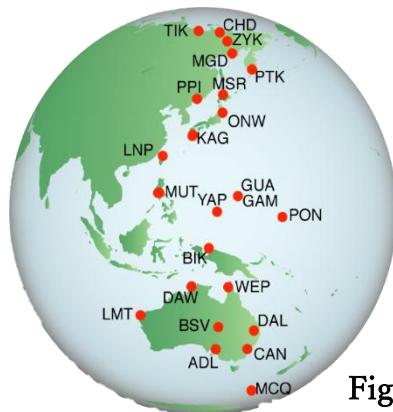
Selected dates in Chapter 3.1 are 24 Jun 1999 and 12 December 1999.

Selected dates in Chapter 3.2 are added 8 Jun 1996, 18 December 2003, and 6 March 2004.

Table 2.1. MAGDAS/CPMN* magnetometers (24 stations)

Station Name	Code	GLAT(deg)	GLON(deg)	GMLAT(deg)	GMLON(deg)
Tixie	TIK	71.59	128.78	65.81	197.23
Chokurdakh	CHD	70.62	147.89	64.81	212.53
Zyryanka	ZYK	65.75	150.78	59.74	217.14
Magadan	MGD	59.97	150.86	53.62	219.1
St.Paratunka	PTK	52.94	158.25	46.27	226.37
Moshiri	MSR	44.37	142.27	37.38	213.65
Popov Island	PPI	42.98	131.73	36.38	204.04
Onagawa	ONW	38.43	141.47	31.24	212.93
Kagoshima	KAG	31.48	130.72	24.45	202.65
Lunping	LNP	25	121.17	18	193
Muntinlupa	MUT	14.37	121.02	6.39	192.49
Guam	GUA	13.58	144.87	5.64	215.81
Guam	GAM	13.58	144.87	5.64	215.81
Yap	YAP	9.3	138.5	0.5	209.69
Pohnpei	PON	7	158.33	0.27	229.44
Biak	BIK	-1.08	136.05	-9.74	207.64
Weipa	WEP	-12.68	141.88	-21.93	214.69
Darwin	DAW	-12.4	130.9	-22.05	203.02
Learmonth	LMT	-22.22	114.1	-33.53	185.37
Birdsville	BSV	-25.54	139.21	-36.08	213.34
Dalby	DAL	-27.18	151.2	-36.61	227.2
Canberra	CAN	-35.3	149	-45.69	226.56
Adelaide	ADL	-34.67	138.65	-46.18	214.06
Macquarie Island	MCQ	-54.5	158.95	-64.46	248.41

*CPMN (Circum-pan Pacific Magnetometer Network) is previous project of MAGDAS.

**Figure 2.3.** Station map of Table 2.1

2.1.5 Station List and map for Chapter 4.2

Year: 2010-2011 (2 years)

Table 2.2. MAGDAS magnetometers (8 stations, red dot in below map)

Station Name	Code	GLAT(deg)	GLON(deg)	GMLAT(deg)	GMLON(deg)
Ashibetu	ASB	43.46	142.17	36.43	213.39
Cebu	CEB	10.36	123.91	2.53	195.06
Kototabang	KTB	-0.2	100.32	-10.63	171.93
Moshiri	MSR	44.37	142.27	37.28	213.34
Pare Pare	PRP	-3.6	119.4	-12.38	190.75
Rikubetsu	RIK	43.48	143.76	36.32	214.67
Tuguegarao	TGG	17.66	121.76	10.26	193.05
Yap Island	YAP	9.5	138.08	1.49	209.06

Table 2.3. INTERMAGNET magnetometer (7 stations, blue dot)

Station Name	Code	GLAT(deg)	GLON(deg)	GMLAT(deg)	GMLON(deg)
Alice Springs	ASP	-23.77	133.88	-32.51	208.54
Canberra	CNB	-35.32	149.36	-42.29	227.18
Charters Towers	CTA	-20.09	146.3	-27.63	221.34
Guam	GUA	13.59	144.87	5.48	216.08
Kakadu	KDU	-12.69	132.47	-21.64	206
Kanoya	KNY	31.42	130.88	22	201.2
Phuyhuy	PHU	21.03	105.95	10.92	178.25

Table 2.4. GSI magnetometer (4 stations, black dot)

Station Name	Code	GLAT(deg)	GLON(deg)	GMLAT(deg)	GMLON(deg)
Akaigawa	AKA	43.07	140.82	34.31	208.93
Haramachi	HAR	37.62	140.95	28.91	209.75
Okinawa	OKI	26.63	128.13	17.07	199
Yoshiwa	YOS	34.47	132.17	25.11	202.13

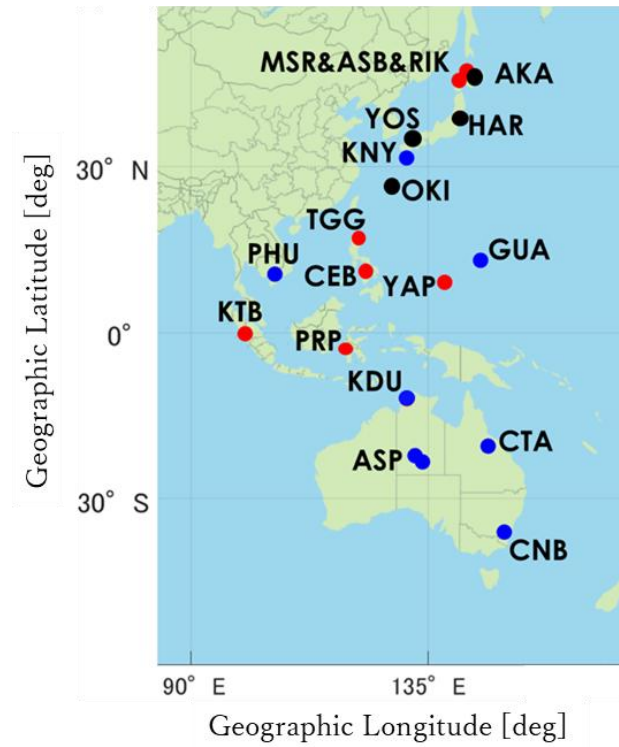


Figure 2.4. Station map of Table 2.2-2.4

2.1.6 Station List and map for Chapter 5

Year: 2007-2011 (5 years)

Table 2.5. MAGDAS and INTERMAGNET magnetometers (9 stations)

Station Name	Code	GLAT(deg)	GLON(deg)	GMLAT(deg)	GMLON(deg)
Moshiri	MSR	44.37	142.27	35.72	210.01
Kanoya	KNY	31.42	130.88	22.56	201.72
Phuthuy	PHU	21.03	105.95	10.92	178.25
Guam	GUA	13.59	144.87	5.48	216.08
Yap	YAP	9.50	138.08	0.79	209.84
Davao	DAV	7.00	125.4	-2.57	197.49
Kototabang	KTB	-0.20	100.32	-10.10	172.41
Kakadu	KDU	-12.99	132.47	-21.64	206.00
Alice Springs	ASP	-23.77	133.88	-32.51	208.54

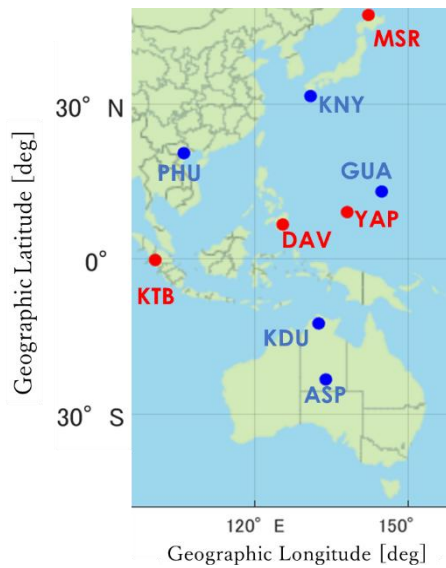


Figure 2.5. Station map of Table 2.5.
(Red) MAGDAS stations and
(Blue) INTERMAGNET stations.

2.2 Simulated data

2.2.1 Ground-to -Topside Model of Atmosphere and Ionosphere for Aeronomy (GAIA)

An atmosphere-ionosphere coupled model (GAIA) has been developed to simulate the behavior of the whole atmosphere. This model is a powerful tool for research on unresolved issues in the field of the upper atmosphere, such as the coupling of the upper and lower atmospheres of the Earth. In addition, they input observation-based data into GAIA to reproduce realistic upper-atmosphere variations (<https://gaia-web.nict.go.jp/>).

Each domain model is combined through a "coupling control routine" as shown in Figure 2.6. The coupling control routine handles the exchange of physical variables between domain models, coordinate transformation, control of common parameters and processes, input/output, etc.

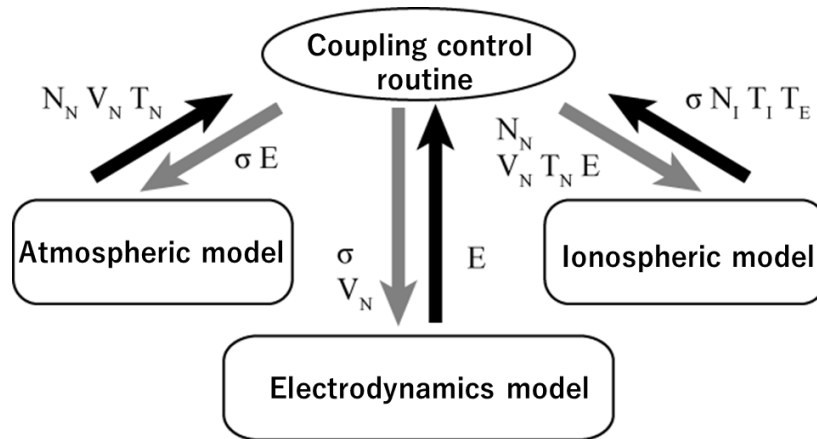


Figure 2.6. How to combine each domain model. [from GAIA HP]

We used neutral wind velocity, current density, and magnetic field at 132.5° longitude from -60° to +60° in geographic latitude for 2007-2011 as shown in Table 2.6. The current density is combined dynamo current and polarized current. Equations 1a~c in [Jin, 2009] are solved under the conditions of no current divergence and equal potential along the magnetic field lines. Also, the magnetic fields were estimated through the current densities by Dr. Fujita of Meteorological University.

Table 2.6. Variable Information

Variable name	Explanation	Unit	Dimension ^{*1}	Coordinate ^{*2}
gu	eastward neutral wind velocity	m/s	(glon,glat,pres)	gcm
gv	northward neutral wind velocity	m/s	(glon,glat,pres)	gcm
cup	eastward(phi dir.) current density	Am ⁻²	(glon, glat, alt)	cpl
cut	southward (theta dir.) current density	Am ⁻²	(glon, glat, alt)	cpl
bip	eastward(phi dir.) magnetic field	T	(glon,glat)	cpl
bit	southward (theta dir.) magnetic field	T	(glon,glat)	cpl

*1 --- “glon” and “glat” mean geographic longitude and latitude, respectively. “alt” and “pres” mean altitude and atmospheric pressure coordinates, respectively.

*2 --- Two coordinate systems “cpl” and “gcm” are explained in Table 2.7.

Table 2.7. Coordinate Systems from description of GAIA database

coordinate system	direction	coverage range	number of grid	resolution (grid size)
cpl	geographic longitude	0 to 360 degs	145	2.5 degs
	geographic latitude	90 to -90 degs	91	2.0 degs
	altitude	0 to 1866.7 km	81	10 to 100 km
	time (in each day)	0.25 to 23.75 hrs	48	0.5 hrs
gcm	geographic longitude	0 to 360 degs	128	~2.8 degs
	geographic latitude	87.86 to -87.86 degs	64	~ 2.8 degs
	pressure (vertical)	997.5 to 1.017×10^{-9} hPa	150	0.2 scale height
	time (in each day)	0.5 to 23.5 hrs	24	1.0 hrs

2.3 Analysis method

2.3.1 Equivalent current method

The horizontal component of the ground magnetic field $\sqrt{H^2 + D^2}$ calculated from the magnetic northward (H) and magnetic westward (D) component of ground magnetic field is rotated 90° clockwise by the equivalent current method to estimate the current vector (Figure 2.7). In this study, the vertical downward (Z) component of the magnetic field variation is used as an indicator of the vorticity of the current by drawing the pseudo color contour plot of it in the background.

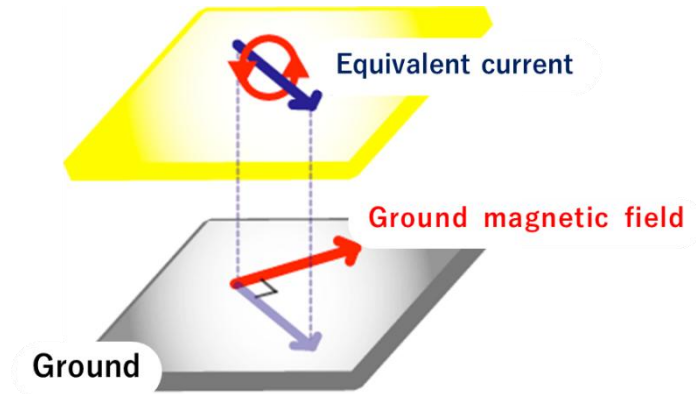


Figure 2.7. Relationship between the horizontal component of the ground magnetic field and the equivalent current

2.3.2 Principal component analysis (PCA)

Principal component analysis (PCA), which is a method of reducing multivariate data into multiple principal components that are uncorrelated with each other, is mainly used to understand the internal structure of data and to remove noise. Previous studies used PCA, to the H component to separate the geomagnetic daily variation such as the Sq current system/EEJ and the abnormal field variations [Vertlib and Wagner, 1970; Golovkov et al., 1978; Rajaram, 1980; Xu, 1989; Alex et al., 1998]. Also, the D components was analyzed by PCA, in addition to the H component to determine the latitude of the Sq focus and the horizontal structure of the 2-day variation [Rajaram, 1983; Yamada, 2009; Gurubaran, 2002]. Yamada (2002) applied PCA to the Z component of geomagnetic field for 2-day,

3-day, and 5-6-day variations. The variations are probably originated from planetary waves in the ionosphere. Owolabi (2021) calculated the Sq current function from geomagnetic field, applied PCA to it, and compared with the Sq current system predicted by the artificial neural network model.

In this study, it was used to more accurately extract magnetic field variations modulated by ionospheric currents. By applying PCA to a variance matrix, we can extract each principal component as shown in Figure 2.8. The number of dimensions of the matrix equal the number of quiet days. As a pre-processing step before making the variance matrix, we subtract the linear interpolation of averaged magnetic field during local time (LT) = 18:00-6:00 (night side) at each station as the local disturbance component. Also, we replaced those not within the confidence interval [0.00035 0.9995] with NaN. Then we overlapped the quiet day data $\mathbf{q}$ excluding disturbed days ($K_p > 2$ or $Dst < -20\text{nT}$ at any time) to form a variance matrix $\mathbf{Q}$. The data $\mathbf{q}$ is not standardized for extracting the IHFACs, meridional component of Sq currents as they are.

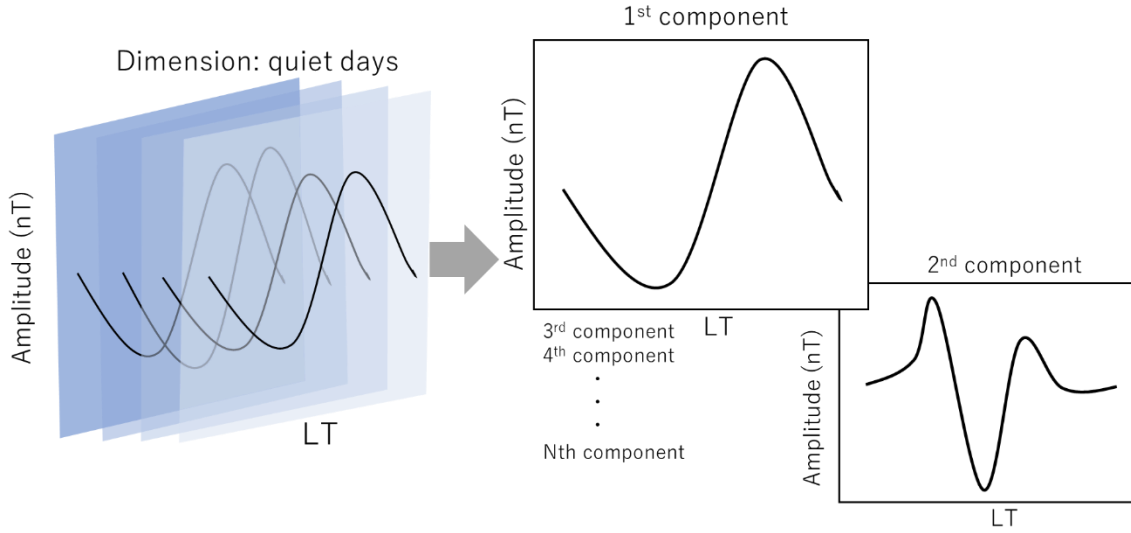


Figure 2.8. Conceptual diagram of PCA.

$$\mathbf{q} = \begin{pmatrix} q_1(t) \\ \vdots \\ q_k(t) \end{pmatrix}, \quad (2.4)$$

$$\mathbf{Q} = (\mathbf{q} \mathbf{q}^T) = \begin{pmatrix} q_1(t) \cdot q_1(t) & \cdots & q_1(t) \cdot q_k(t) \\ \vdots & \ddots & \vdots \\ q_k(t) \cdot q_1(t) & \cdots & q_k(t) \cdot q_k(t) \end{pmatrix}, \quad (2.5)$$

where T denotes the transpose of a matrix or vector.

But the inner product $(\cdot)$ is defined as follows,

$$(x(t) \cdot y(t)) = \frac{1}{N} \sum_{t=1}^N x(t)y(t), \quad (2.6)$$

where N is 1440 because 1-minute value data is used.

To solve the eigenvalue problem of the variance matrix, we diagonalized as follows,

$$\mathbb{E} P^T Q P = \begin{pmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_k \end{pmatrix}, \quad (2.7)$$

where λ_k is k -th eigenvalue of variance matrix Q .

Since we want to find the principal components that best represent the variation of the daily quiet variation, we choose the diagonal matrix P so that the eigenvalues λ , which correspond to the power of the principal components, are arranged in descending order.

$$\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_k \geq 0 \quad (2.8)$$

$$\mathbb{E} P^T P = E \quad (2.9)$$

where E is the identity matrix.

We define the principal component $\mathbf{l}$ of the daily change as follows,

$$\mathbf{l} = \begin{pmatrix} l_1(t) \\ \vdots \\ l_k(t) \end{pmatrix}. \quad (2.10)$$

The principal components are represented by the diagonal matrix P as follows, since they are the orthogonalized source of the quiet days data set $\mathbf{q}$

$$\mathbf{l} = \mathbb{E} P^T \mathbf{q} \quad (2.11)$$

Using equations (2.4) and (2.8),

$$(\mathbf{l} \cdot \mathbf{l}^T) = \begin{pmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_k \end{pmatrix}, \quad (2.12)$$

We define the basis function $\mathbf{b}$ as follows,

$$\mathbf{b} = \begin{pmatrix} b_1(t) \\ \vdots \\ b_k(t) \end{pmatrix}. \quad (2.13)$$

Since the basis function $\mathbf{b}$ is obtained by normalizing the principal component $\mathbf{l}$,

$$\mathbf{b} = \begin{pmatrix} \frac{1}{\sqrt{\lambda_1}} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{\sqrt{\lambda_k}} \end{pmatrix} \mathbf{l}, \quad (2.14)$$

$$(\mathbf{b} \cdot \mathbf{b}^T) = E, \quad (2.15)$$

where E is the identity matrix.

Next, the amplitude of each basis function $b_k(t)$ is obtained by performing the inner product of the data $q(t)$ for the given day,

$$\rho_k = (b_k(t) \cdot q(t)). \quad (2.16)$$

By superimposing the first five principal components $\mathbf{l}$ obtained, the basic component l' in the original data $q_k(t)$ is obtained,

$$l' = \sum_{k=1}^5 \rho_k b_k. \quad (2.17)$$

To summarize method to apply PCA, we create a variance matrix Q for each station for H/D/Z. Then we apply PCA to extract each principal component of each station and normalize the principal components to create basis functions.

By taking the inner product of each basis function and the data for a given day, the amplitude of each basis function is obtained as daily score. Then, we create each principal component by multiplying the daily scores with the basis function. Also, we add the first through fifth principal components as the "Basic component". Then, we defined the subtraction of the basic component from the original data as the higher order component.

As an example, Fig. 2.9 shows flowchart for applying PCA to quiet day data set of BSV for December and the obtained principal components, basis functions and power of principal components, respectively. Focusing on the power of the principal components, the power of the first principal component was dominant, and the power including up to the fifth principal component accounted for more than 99% of the total power. The higher-order principal components with very small power are considered to be disturbance components that could not be removed in the preprocessing steps. Therefore, in this study, principal

components and basis functions up to the fifth principal component are used in the representation of quiet day changes.

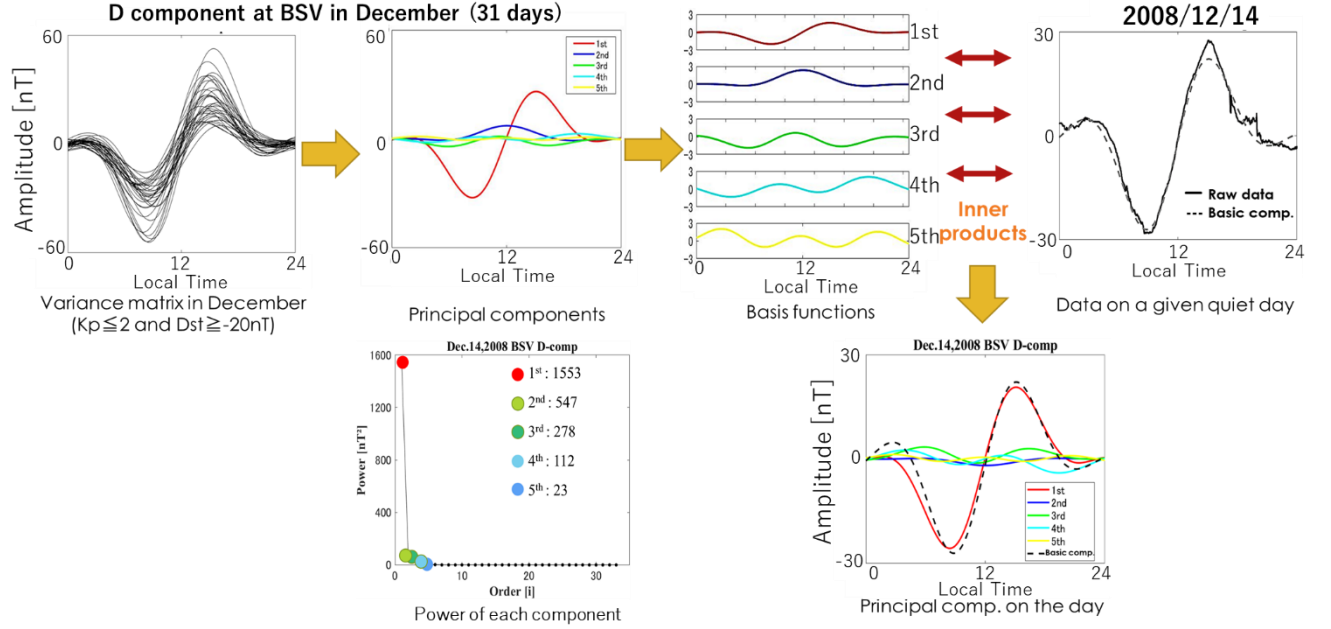


Figure 2.9. Flowchart of applying PCA to the ground magnetic field data. As an example, we show Birdsville (BSV, [GMLAT: -36.08°, GMLON: 213.34°]) in 12/14/2008. Power is λ_k .

2.3.3 Analysis of GAIA data for Chapter 4

The data is 4-D matrix with dimensions of longitude, latitude, altitude, and time.

【The Q6DW distribution in zonal and meridional winds as a function of geographic latitude and time】

To analyze the Q6DW amplitude in eastward and northward neutral wind velocities, the following method is applied: First, a Fast Fourier Transform (FFT) was applied in the longitudinal direction at each latitude to extract the westward-propagating component with zonal wavenumber 1. Next, the FFT with a 30-day sliding window, shifting by 15 days in time direction, was applied at each latitude to isolate the variations within the 4.5–7-day period. Finally, the Q6DW amplitude was calculated.

【The Q6DW distribution in zonal and meridional winds as a function of geographic latitude and altitude】

Use same methods as above at each altitude.

【The quasi-6-day variation in zonal and meridional current as function of geographic longitude and time】

To analyze the amplitude of quasi-6-day variation in eastward, southward, and upward current densities, the following steps were undertaken: First, one month of data at a specific latitude was used. The daytime peak in the zonal current and the difference between the maximum and minimum values of the meridional currents were extracted at each longitude and altitude of 100-130km. Then, the FFT was applied in the longitudinal direction at each altitude to isolate the westward-propagating component with zonal wavenumber 1. The data was subsequently integrated in the altitude at each longitude to obtain daily values. Since geomagnetic latitudes vary slightly at each geographic longitude, 'gmag_gaia model' (data file provided by Prof. Miyoshi) was used to determine the precise geomagnetic latitudes.

【The quasi-6-day variation in horizontal magnetic field as function of geomagnetic latitude and time】

To analyze the amplitude of quasi-6-day variation in eastward and southward magnetic fields, the analysis was conducted as follows: Data with a longitude of 130° E and magnetic latitude range from -35° to +35° were used for comparison with ground magnetic field observational data. The FFT with a 30-

day sliding window, shifting by 7.5 days, was applied at each latitude, and the amplitudes within the 4.5-7-day period were summed to calculate the weekly amplitude of the quasi-6-day variation. Finally, a 5-year average was computed for each week. Principal component analysis is omitted because GAIA does not include the disturbance component included in the ground magnetic field observational data.

2.3.4 How to extract the quasi-6-day variation in the Sq-EEJ current system, IHFACs, and other variations for Chapter 5

We applied PCA to the H and D components to identify variations of ionospheric currents and estimate the quasi-6-day variation amplitude in the principal components using FFT to depict spatiotemporal profile of the variation as follows: We subtract the averaged magnetic field during LT = 18:00-06:00 (night side) at each station as the local disturbance component. Also, we subtract the EDst index*¹ from the H component and the SYM-D index*² from the D component as the global disturbance components. Then we overlap the data of quiet days excluding disturbed days (Kp index*³ > 2 and Dst index*⁴ < -20nT) to form a variance matrix, apply PCA to it, and extract basis functions (BFs). We determine the Sq current system and IHFACs from the structure of BFs as follows: BF with sign changing around noon is the Sq current system and BF with sign changing around 09 LT and 15 LT is the IHFACs. We calculate the daily scores and variation amplitude from the equation below with BFs corresponding to each kind of currents at each station.

$$\text{Daily scores} = \text{Daily data} \cdot \text{BFs} \quad (2.16)$$

$$\text{Variation amplitudes (nT)} = \text{BFs (nT)} \times \text{Daily scores} \quad (2.17)$$

We apply the Fast Fourier Transform (FFT) to the 1826 variation amplitudes with the 30-day sliding window shifting by 7.5 days and add up the amplitudes of the 4.5-7-day period to obtain the weekly amplitude of the quasi-6-day variation on each current. Then we take the weakly average of the amplitude during 2007-2011 (5 years).

*1: EDst index is the Equatorial Disturbance in storm time maid by the MAGDAS/CPMN real-time data [Uozumi et al., 2008; Fujimoto et al., 2016].

*2: SYM-D index is the longitudinally symmetric D component, made by World Data Center for Geomagnetism, Kyoto (<https://wdc.kugi.kyoto-u.ac.jp/aeasy/asy.pdf>).

*3: Kp index is an important measure for the energy input from the solar wind to Earth, made by GFZ Helmholtz Centre, Potsdam (<https://kp.gfz-potsdam.de/en/>)

*4: Dst index represents the axially symmetric disturbance magnetic field at the dipole equator on the Earth's surface, made by World Data Center for Geomagnetism, Kyoto (<https://wdc.kugi.kyoto-u.ac.jp/dst/dir/index.html>).

2.3.5 How to extract the quasi-6-day variation in the IHFACs around geomagnetic equator for Chapter 5.5

We used the D component of the ground magnetic field data from the MAGDAS and INTERMAGNET. The data used in this study are Yap Island (YAP; Geographical latitude 9.5°N , Geographical longitude 138.08°E , Geomagnetic latitude 0.79°N , Geomagnetic longitude 209.84°E) and Guam (GUA; Geographical latitude 13.59°N , Geographical longitude 144.87°E , Geomagnetic latitude 5.48°N , Geomagnetic longitude 216.08°E) station observed during 2010-2011. The 2 years are low solar activity period with the average of F10.7 indices = 96.63. The data sampling rate was one minute.

We applied PCA to the D component to identify the quasi-6-day variation in each PCA component. The methods are similar with Chapter 2.3.4, but some methods are different to compare with the Q6DW amplitude in zonal and meridional wind reproduced by GAIA as follows: Subtract linear-interpolated moving average of the ground magnetic field during 21:00-03:00 LT as nighttime baseline from the original component of each day. We apply FFT to the daily scores with the 20-day sliding window to obtain the amplitude with quasi-6-day period (a period of 5-7 days). Finally, we calculate correlation coefficients between the quasi-6-day variation of the daily scores in the two basis functions with the Q6DW amplitude around 110km averaged at geographic latitude 10°S - 10°N (30°N - 40°N) in zonal (meridional) wind.

Chapter 3

Application Results of PCA

3.1 Basic components and Higher order components

Basic component is the sum of the first through fifth components and higher order component is the subtraction of the basic component from the original data. We visualized the basic and higher-order components calculated by applying PCA to the magnetic field using the equivalent current method described in Chapter 2.3.1 as shown in Figures 3.1 and 3.2. Color of the background shows the magnitude of the vertically downward (Z) component of ground magnetic field.

In both figures, basic components accurately extract the Sq-EEJ current system that is main daily variation of ground magnetic field. The Sq-EEJ current system is enhanced in the summer hemisphere. This is caused by the high ionospheric conductivity in the summer hemisphere due to the stronger solar radiation. The higher-order component in Figure 3.1 shows currents flowing from the high latitudes to geomagnetically equatorial region, which might be due to some of

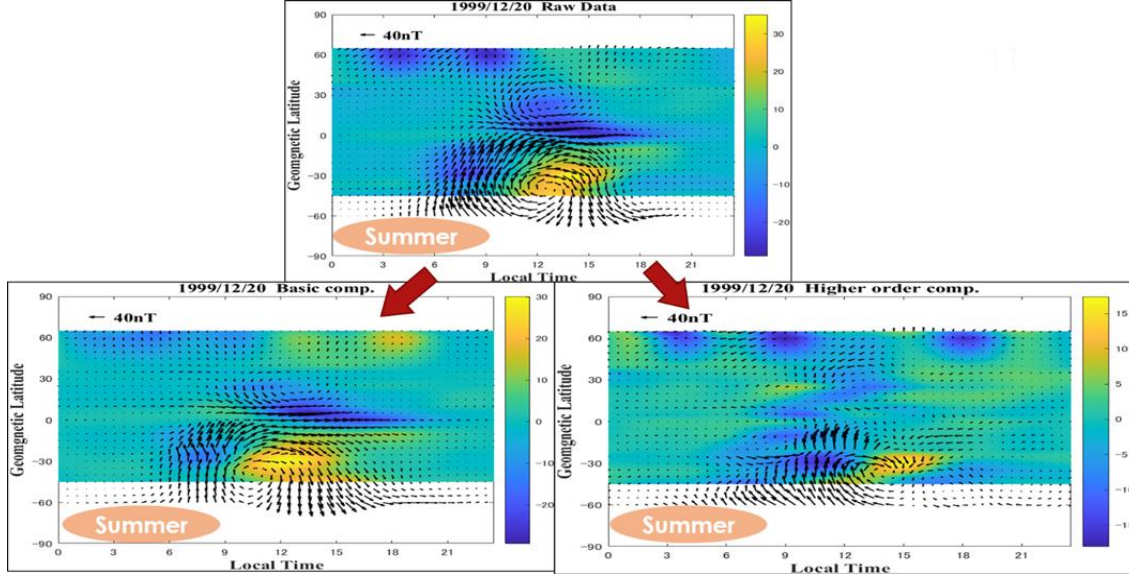


Figure 3.1. Equivalent currents structure after separation by the PCA on quiet day of 20 December 1999. (Top) Raw data and (Bottom row) basic component and higher order component. Arrows indicate horizontal magnetic field replaced by equivalent currents. Color of the background shows magnitudes of the vertically downward (Z) component of ground magnetic field. Unit of the color bar is “nT”.

atmospheric tidal winds or the electric field entering from the magnetosphere, but details remain unclear.

Also, higher order component in Figure 3.2 presents two current vortices during 06-17 LT from -10° to 40° in GMLAT with vortex centers around 10°N . They also appear to spring from the geomagnetic equator. The boundary between two current vortices is at around 11 LT. These features are thought to be due to some of atmospheric tidal winds, which will be explained in the next section, but they are affected by mainly seen in the sixth principal component. More detailed analysis which focus each component is needed.

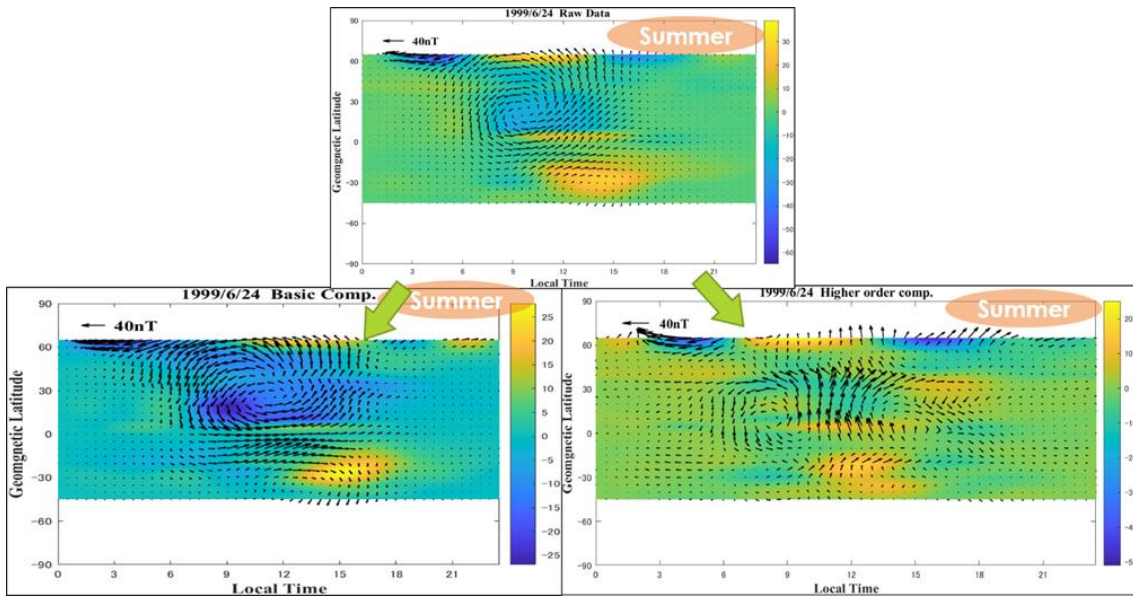


Figure 3.2. Same as Figure 3.1 except for 24 Jun 1999.

3.2 Each principal component

We focus the first through third principal components since the power of component was enough high. We applied PCA to each station, thus each basis function is different with the others.

The first principal component shows the Sq-EEJ current system on all days analyzed. This study is the first to visualize the global structure of the Sq-EEJ current system using stations in both hemispheres. Also, the Z component of background in left panel of Figure 3.3 changes for negative to positive at 9 am at around 30°S in GMLAT, which means that the IHFACs changes its direction around 9 am. On the other hand, right panel of Figure 3.3 presents the local time

distance between each center of the Sq current vortexes, which may cause the IHFACs to tilt in the longitude direction.

Figure 3.4 presents two days when the second principal components appeared current vortexes even though the basis functions are different at each station. On these days, two current eddies were seen in one hemisphere, with the peak at a latitude lower than 30°N and the eddy boundary near 11 LT. This feature might be modulated by the $(2, 2)^*$ mode of atmospheric semidiurnal tidal winds as shown in Figure 3.6. The $(2, 2)$ mode is one of the semidiurnal tidal modes, and the $(2, 2)^*$ mode included the effect of ion drag on the $(2, 2)$ mode.

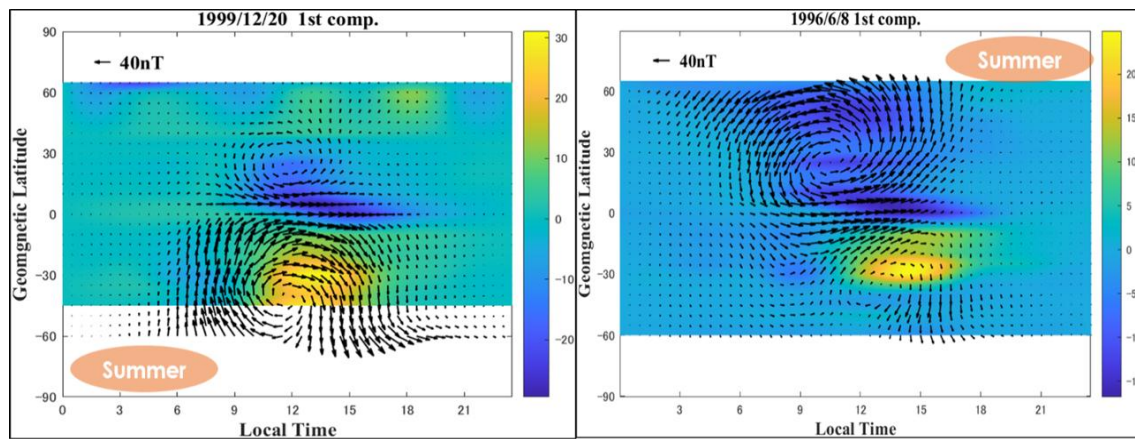


Figure 3.3. Equivalent current of the first principal component. (Left): on 20 December 1999. (Right): on 8 Jun 1996.

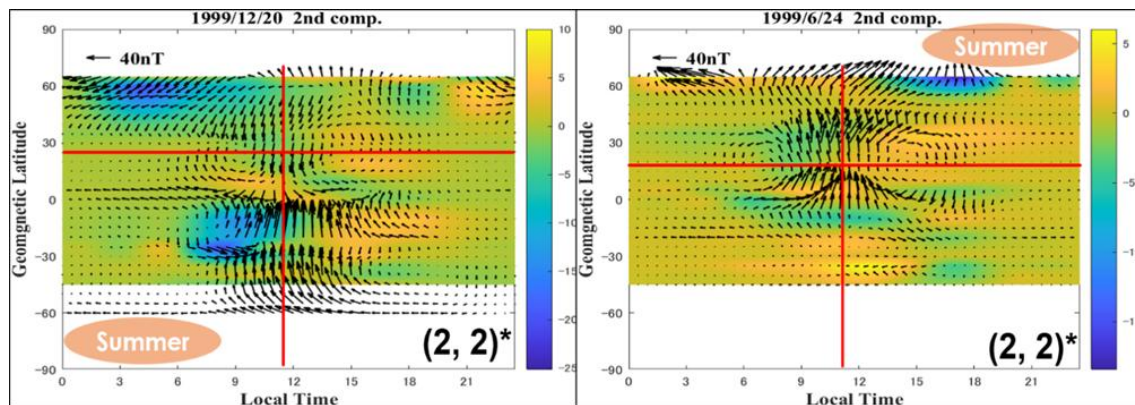


Figure 3.4. Equivalent current of the second principal component. (Left): on 20 December 1999. (Right): on 24 Jun 1996. Vertical Red line shows the boundary of current vortexes and horizontal red line shows GMLAT of center of current eddies.

The third principal component, as well as the second principal component, showed two current eddies in one hemisphere. In particular, the peak of the current eddies on left panel of Figure 3.5 is at higher than 30°S in GMLAT, which may have the characteristics of the $(2, 4)$ mode combined with those of the $(2, 2)^*$ mode. The basis function of each station does not necessarily show the same mode of the atmospheric tidal winds, thus it is difficult to identify the specific mode from other components. In addition, various semidiurnal modes are mixed, and the predominant mode changes with altitude as shown in Figure 3.7, so they may appear superimposed when seen in the ground magnetic field data. Therefore, similar variations are not necessarily seen on all quiet days.

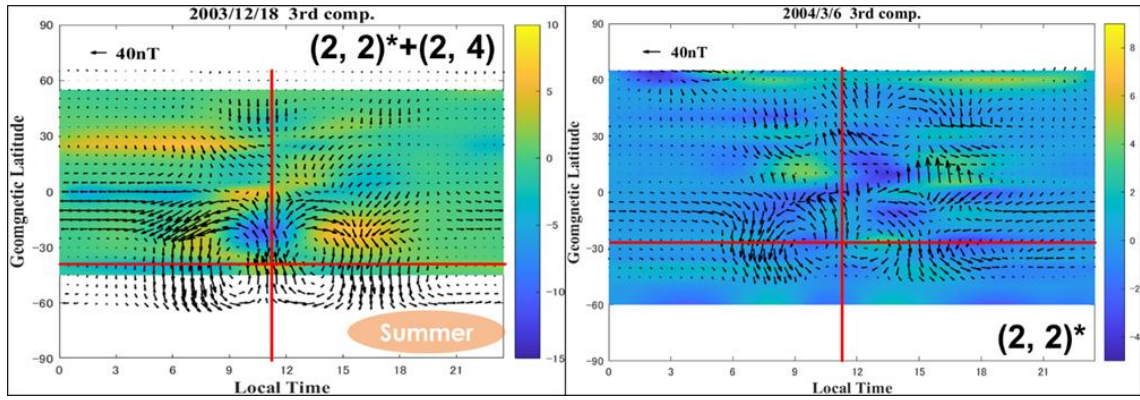


Figure 3.5. Equivalent current of the third principal component. (Left): on 18 December 2003. (Right): on 6 March 2004.

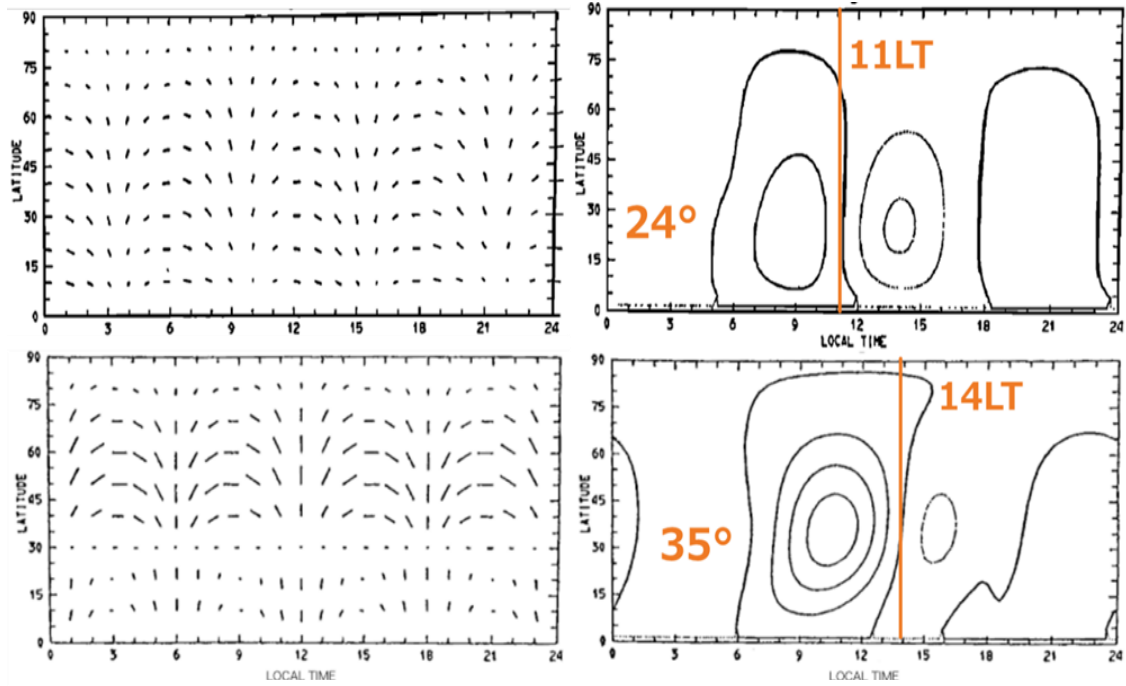


Figure 3.6. (Top left panel): $(2, 2)^*$ wind pattern at 130-km altitude. A vector length equal to 5° of latitude represents a wind speed of 50 m/s. (Top right panel): Current function for the $(2, 2)^*$ wind. Contour spacings are 10 kA. Current flows counterclockwise for solid contours and clockwise for dotted contours. (Bottom left panel): $(2, 4)$ wind pattern at 115-km altitude. (Bottom right panel): Current function for the $(2, 4)$ wind. Orange line/the local time shows the current eddy boundaries and the degree shows the latitude of the eddy center. [modified Figure 8 and Figure 10 of Richmond et al., 1976].

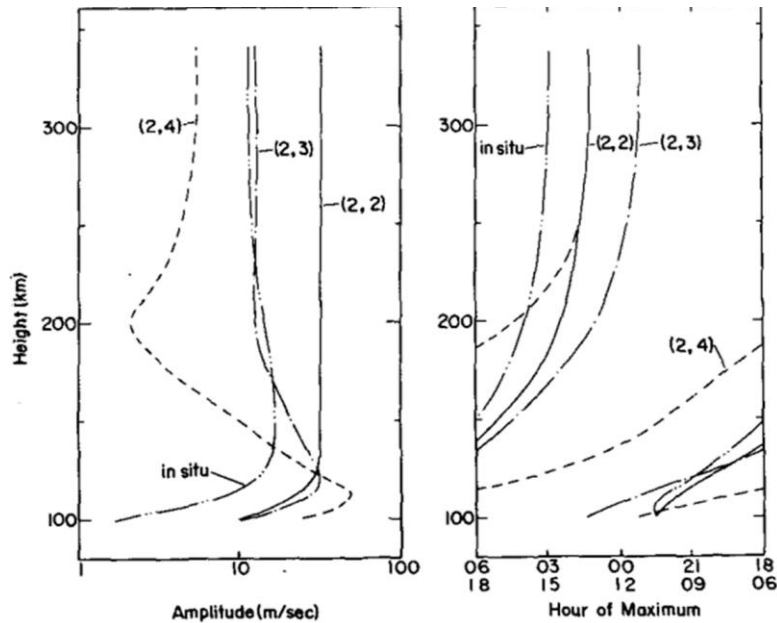


Figure 3.7. Amplitude and phase of northerly velocities as a function of height for various modes at 45° summer latitude. From S. -S. Hong et al. (1975).

Chapter 4

Ionospheric structure of Q6DW and quasi-6-day variation with GAIA

4.1 Simulated results

4.1.1 The Q6DW distribution in zonal and meridional winds as a function of geographic latitude and time

We checked the Q6DW amplitude in zonal and meridional wind around 110km altitudes, which correspond to the E layer of ionosphere. Figure 4.1 presents geographic latitude versus time structures of the Q6DW in zonal and meridional winds simulated by GAIA. The Q6DW in zonal wind develops mainly from the geographic equator to middle latitudes around 30° in northern and southern hemispheres. On the other hand, the Q6DW in meridional wind develops from middle to high latitudes in both hemispheres. Also, the Q6DW in zonal and meridional wind develops strongly before and after equinoxes as described by previous studies.

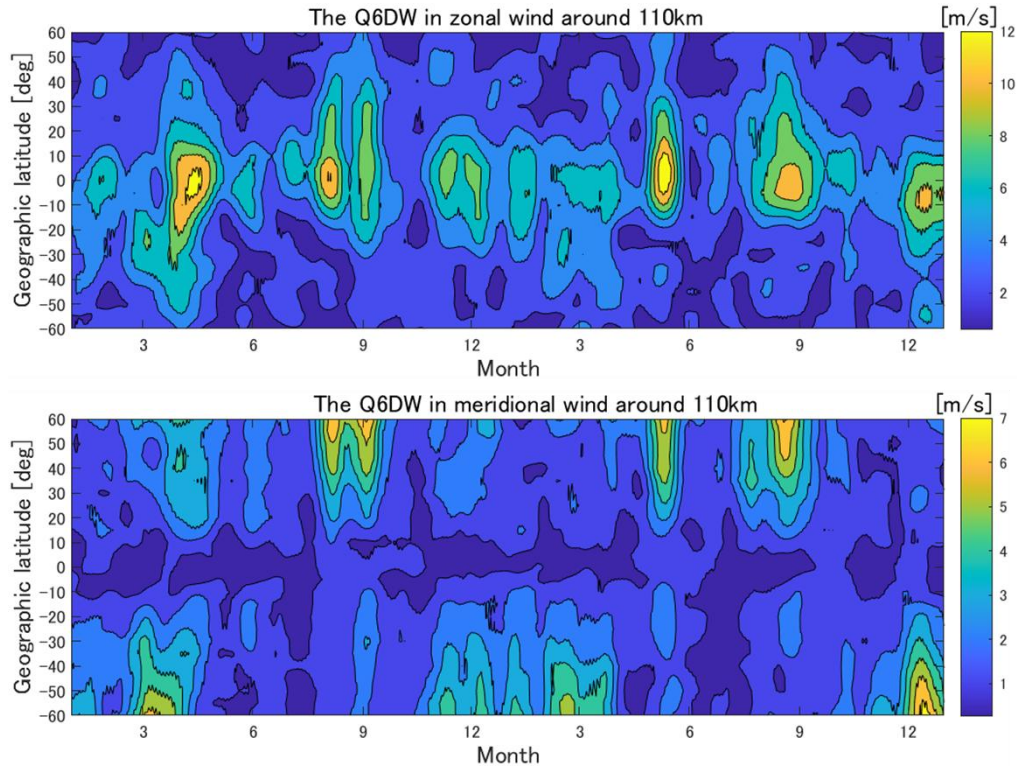


Figure 4.1. The Q6DW amplitudes in zonal wind (top) and meridional wind (bottom) around 110km altitudes in 2010-2011. Contour interval is 3 m/s.

4.1.2 The Q6DW distribution in zonal and meridional winds as a function of geographic latitude and altitude

Figures 4.2 show the latitude-height profiles of the zonal and meridional wind components of the Q6DW on 13 April 2010. The Q6DW in zonal wind develop at 90-120km altitudes, and the one in meridional wind develop mainly at 75-150km altitudes. The altitudes are on the ionospheric E layer, which conductivity (=current density) is high as shown in Figure 1.3. In this study, we compared the Q6DW amplitude in zonal wind around equator and in meridional wind around middle latitude with quasi-6-day variation in ionospheric currents at the magnetic equator and low latitudes.

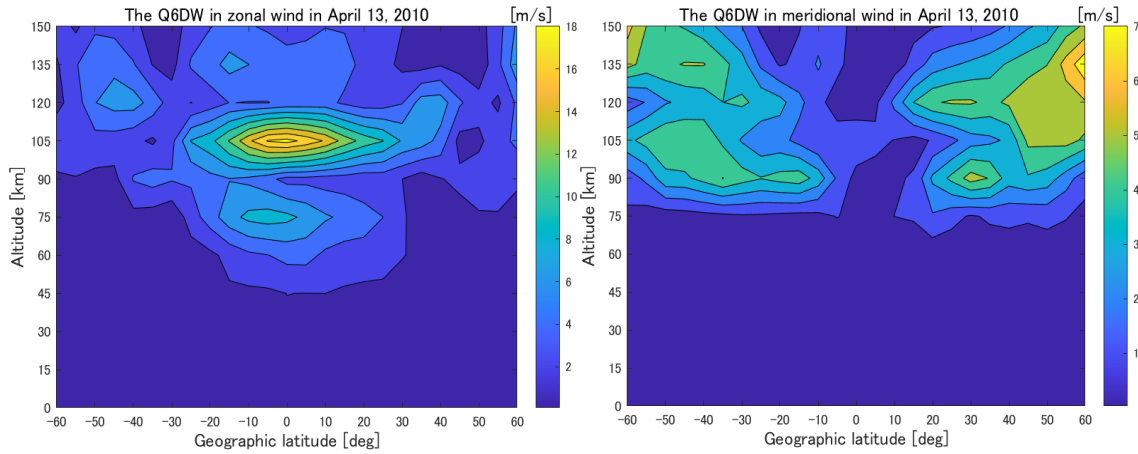


Figure 4.2. The Q6DW amplitudes in zonal wind (left) and meridional wind (right) in April 13, 2010 at geographic longitude of 132.5°E.

4.1.3 The quasi-6-day variation in zonal and meridional current as function of geographic longitude and time

In order to verify whether the effect of Q6DW manifests in ionospheric currents at middle latitudes in the northern and southern hemispheres, the quasi-6-day variation in zonal and meridional current as function of geographic longitude and time at geomagnetic latitude of 20°N, 20°S, 30°N and 30°S are shown in Figures 4.3 and Figure 4.4. The difference from the Figure 1.15a is that only zonal wavenumber 1 is extracted instead of all zonal wavenumber components. Both figures show that the maximum peaks occur at a period of about 6 days, suggesting the influence of Q6DW. The Q6DW has a symmetric structure about geographic equator, as suggested by the Hough function. However, it is noteworthy that

Figure 4.3 (Left) and 4.4 (Left) are not symmetric about the equator. These results are not geographic latitude, so it's not necessarily symmetrical.

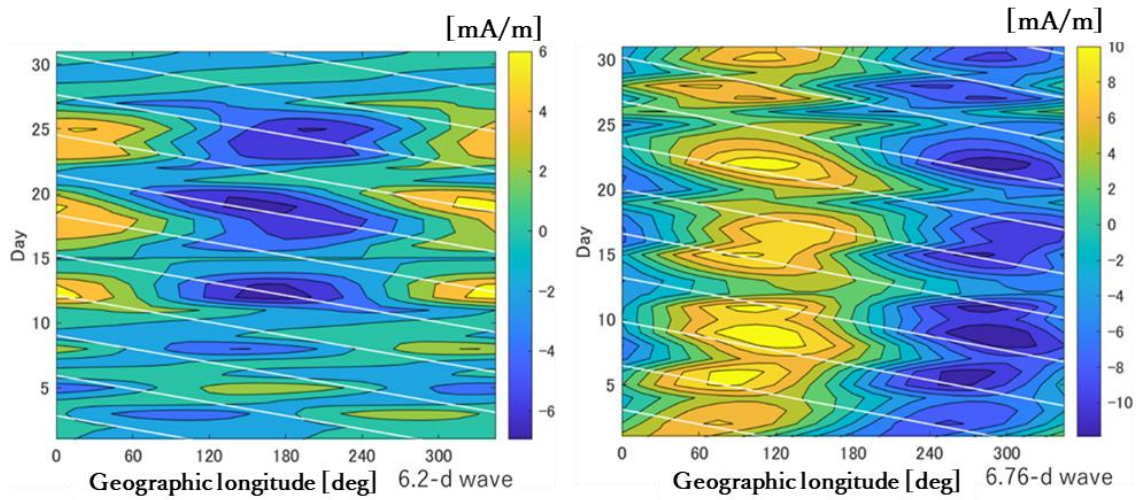


Figure 4.3. Current density with zonal wavenumber 1 integrated at 100-130km altitudes in May 2007. White lines show the phase propagation of periodic wave. (Left): Zonal current density at geomagnetic latitudes of 20°N (Right): Meridional current density at geomagnetic latitudes of 30°N in GMLAT.

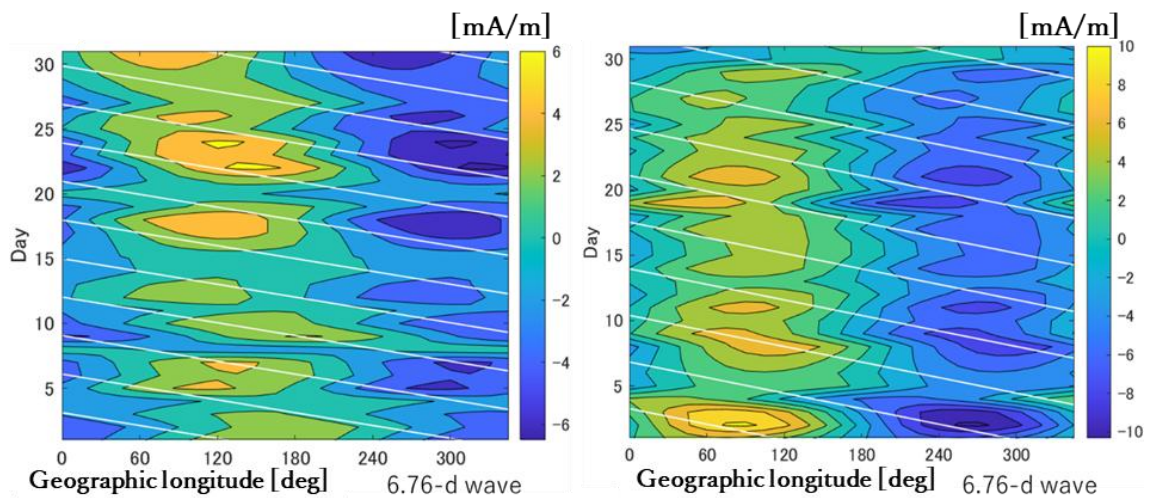


Figure 4.4. Same with Figure 4.3 except for (Left) at geomagnetic latitude of 20°S (Right) at geomagnetic latitude of 30°S in GMLAT.

4.2 Comparison of the quasi-6-day variation of magnetic field in GAIA and MAGDAS/INTERMAGNET

Figure 4.5 presents the Q6DW amplitude in zonal wind and the quasi-6-day variation in horizontal magnetic field observed by MAGDAS/INTERMAGNET and GAIA. We compared them and summarized similarities and differences below.

The Q6DW peaks in April and August-September 2010, May and September 2011 coincide with the quasi-6-day variation around magnetic equator in MAGDAS/INTERMAGNET. The Q6DW peaks in Jun and October 2011 coincide with the quasi-6-day variation around magnetic equator in GAIA. These results mean whether the Q6DW or tidal waves with period of about 6 days has a stronger effect depends on the season. Also, the quasi-6-day variation of magnetic field is not always strong in the Japan sector since the Q6DW modulation has longitude dependence [Yamazaki et al., 2018]. The quasi-6-day variation simulated by GAIA developed to middle latitudes in the summer hemisphere since the ionospheric currents become strong due to solar radiation.

The spatio-temporal structure of the quasi-6-day variation of GAIA and MAGDAS/INTERMAGNET are different. That would be due to the facts that GAIA uses a tilted dipole magnetic field model rather than the International Geomagnetic Reference Field model, which is closer to reality, and that polar inputs have no time variation.

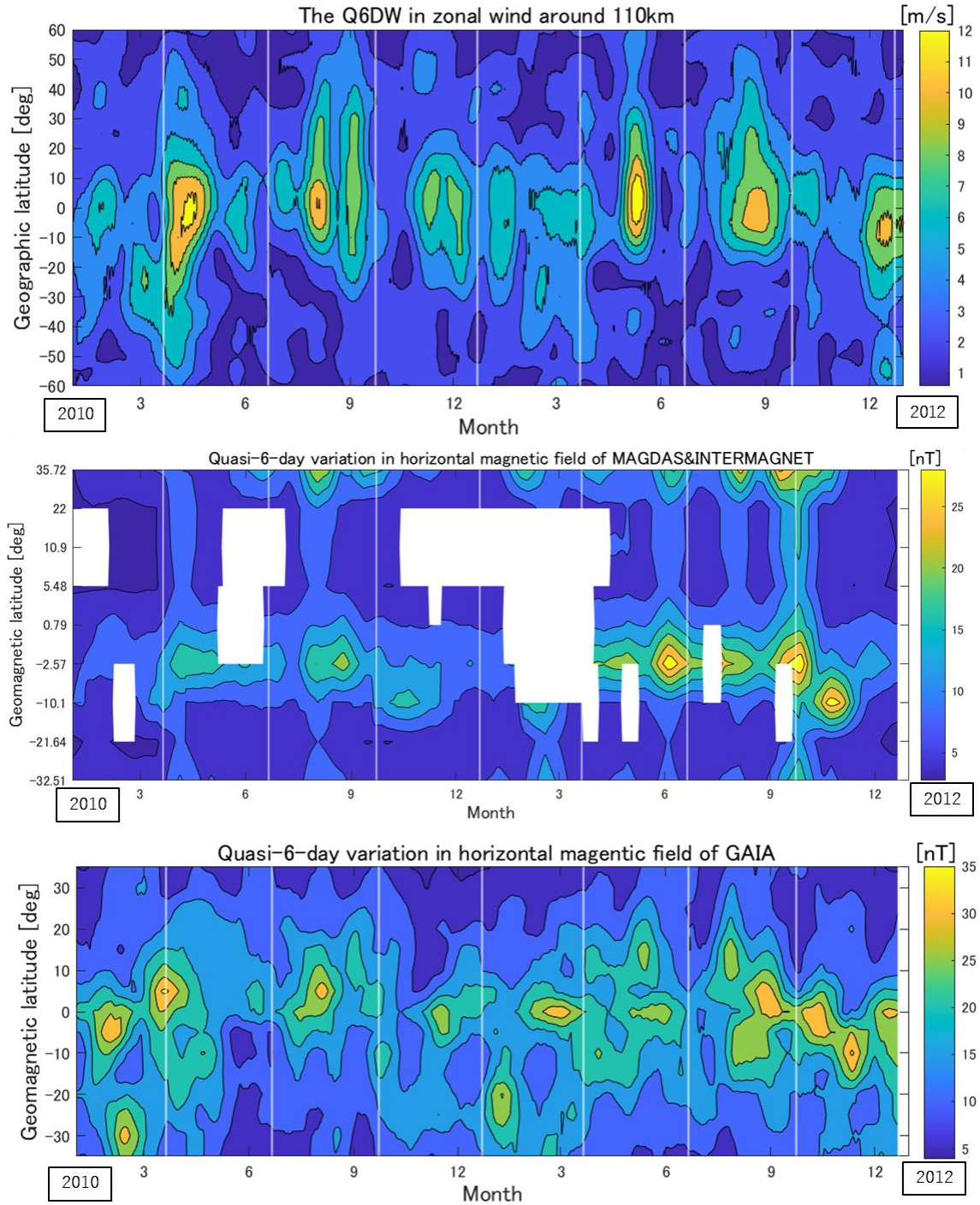


Figure 4.5. (Top panel) The Q6DW amplitude in zonal wind and the quasi-6-day variation amplitude in horizontal magnetic field in 2010-2011 (Middle panel) observed by MAGDAS/INTERMAGNET (Bottom panel) simulated with GAIA. White lines were written every equinox.

Chapter 5

Geomagnetic structure of quasi-6-day variation with PCA

5.1 Which current is the first and second basis functions?

We show basis functions at YAP and KDU. Figure 5.1 presents the first basis function of YAP (geomagnetic latitude of 0.79°N) and KDU (geomagnetic latitude of 21.64°S). In left panel, the H component of YAP has a maximum around 12 LT and the D component changes its sign around 09 LT and 16 LT. From these characteristics, they are considered to be variation associated with the EEJ and recent studies' model of IHFACs [Park et al., 2020; Ranasinghe et al. 2021] at geomagnetic equator, respectively. The model of IHFACs which flow from the summer hemisphere (SH) to winter hemisphere (WH) during the morning and from the WH to SH during the noon hours and evening. In right panel, the H component of KDU has a positive peak around 12 LT and the D component change its sign around 12 LT. They show variation associated with the Sq current system at middle latitude.

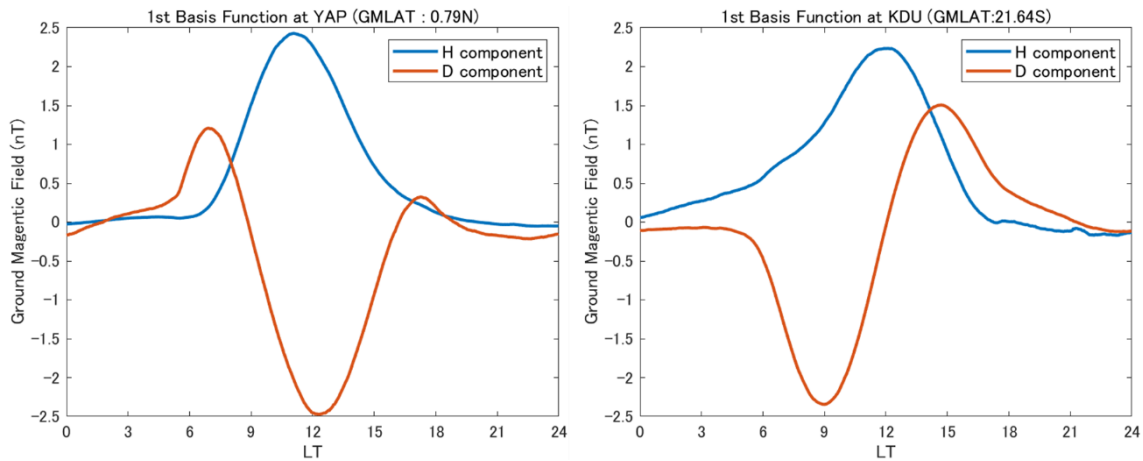


Figure 5.1. The first basis function of the H and D components of (Left panel) YAP and (Right panel) KDU.

Figure 5.2 presents the second basis function at YAP and KDU. In the left panel, the H and D components of YAP change its sign around 12 LT. The H component has a semidiurnal variation, which might be modulated by the semidiurnal tidal winds. On the other hand, the D component appear variation modulated by the Sq currents since the northward current of Sq currents changes southward around 12 LT

In right panel, the H component of KDU changes its sign around 12 LT. That might be modulated by the semidiurnal tidal winds. Also, the D component changes its sign around 09 LT and 15 LT. That might be modulated by the IHFACs and semidiurnal tidal winds. They have similar current structure; therefore, it is difficult to separate them from ground magnetic field data.

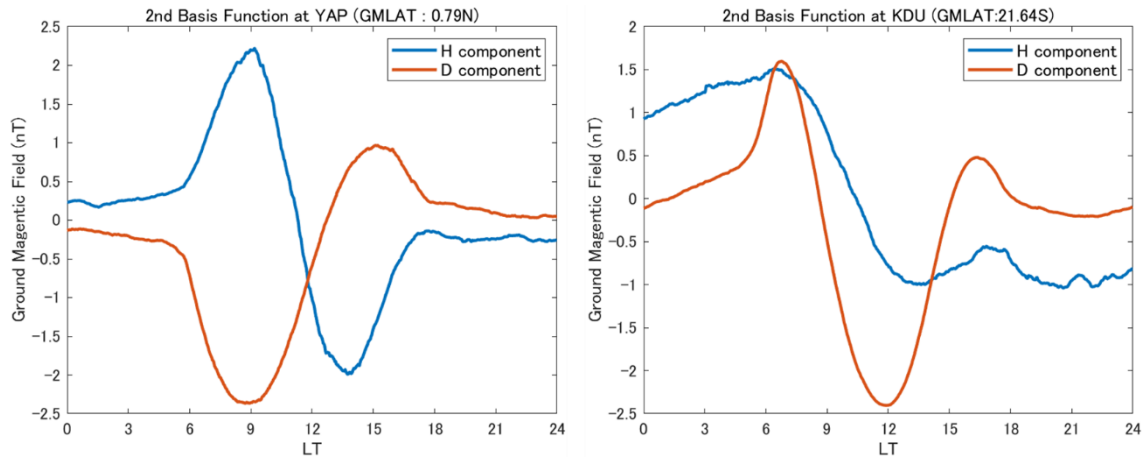


Figure 5.2. Same with Figure 5.1 except for the second basis function.

The first and second basis functions at all stations are shown in Table 5.1. The first and second basis functions of the H component at low- and middle-latitudes stations shows variation modulated by the Sq currents and semidiurnal variation in both hemispheres, respectively. Also, the first and second basis functions around the geomagnetic equator show the EEJ and semidiurnal variation. On the other hand, the first basis functions of the D component show the IHFACs and semidiurnal variation from the geomagnetic equator to middle latitudes and the Sq currents at middle latitudes in both hemispheres.

Table 5.1. Current type discriminated from the basis function (BF) of each station. Sq means Sq current system. Semidiurnal means semidiurnal variation.

Station	GMLAT(deg)	H 1st BF	H 2nd BF	D 1st BF	D 2nd BF
MSR	35.72	Sq	Semidiurnal	IHFACs + Semidiurnal	Sq
KNY	22.56	Sq	Semidiurnal	IHFACs + Semidiurnal	Sq
PHU	10.92	Sq	Semidiurnal	IHFACs + Semidiurnal	Sq
GUA	5.48	Sq	Semidiurnal	IHFACs + Semidiurnal	Sq
YAP	0.79	EEJ	Semidiurnal	IHFACs + Semidiurnal	Sq
DAV	-2.57	EEJ	Semidiurnal	IHFACs + Semidiurnal	Sq
KTB	-10.1	Sq	Semidiurnal	IHFACs + Semidiurnal	Sq
KDU	-21.64	Sq	Semidiurnal	Sq	IHFACs + Semidiurnal
ASP	-32.51	Sq	Semidiurnal	Sq	IHFACs + Semidiurnal

IHFACs are seen near the geomagnetic equator. At middle latitudes in both hemispheres, their meridional components become small and their vertical component become big as shown in Figure 5.3.

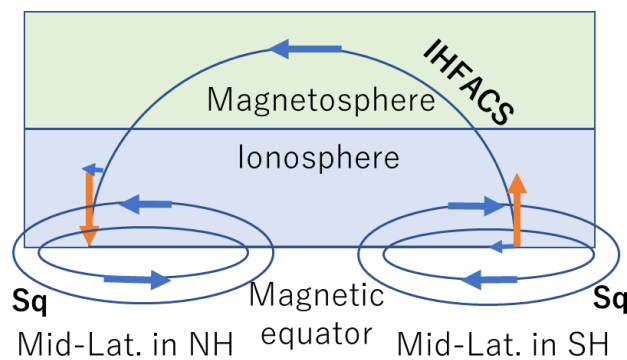


Figure 5.3. Relationship between the IHFACs and Sq currents. NH = northern hemisphere; SH = southern hemisphere.

5.2 Quasi-6-day variation in the Sq-EEJ current system (H and D component)

We investigate day-to-day variation of the amplitude of the principal components, which corresponds to the Sq-EEJ current system. Figure 5.4 shows day-to-day variations of the PC1 (PC2) amplitudes of the H (D) component at YAP and KDU. In the H component of right panel, the amplitude of YAP is bigger than the amplitude of KDU. The result shows the EEJ is stronger currents than the Sq currents. In the D component of left panel, the amplitude of YAP is smaller than the amplitude of KDU. The result shows the meridional Sq currents component is weaker around the geomagnetic equator.

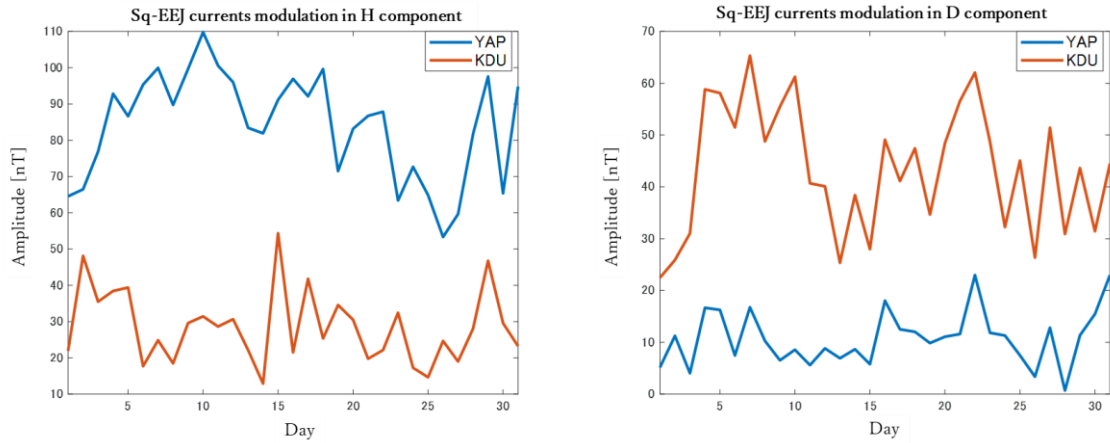


Figure 5.4. Amplitude of the sum of the principal components corresponding to the Sq-EEJ current system at YAP and KDU in (Right) PC1 of the H component and (Left) PC2 of the D component in January 2007.

To investigate dominant periods of the Sq-EEJ current variation, a spectral analysis was performed (Figure 5.5). In the left panel, a distinct peak appears at a period of 6 day. Another peak appears at 4 and 10 days at YAP. In the right panel, a clear peak at 6 day is found at KDU, and weak peaks are found at 2.5, 4 and 6-7 days at YAP. Also, there is a peak at period of 10 days at YAP. That may be due to the quasi-10-day wave.

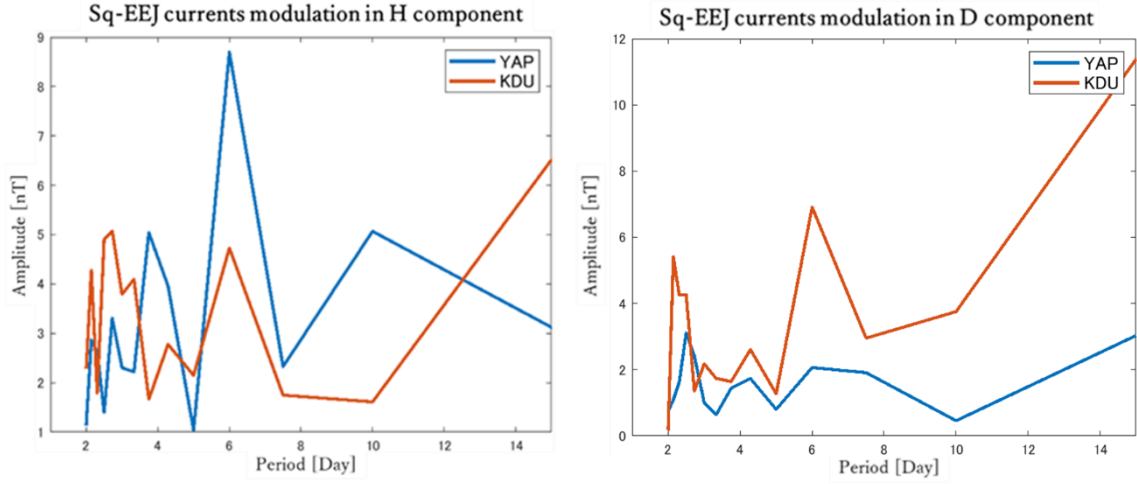


Figure 5.5. Power spectrum calculated from the amplitude of Figure 5.5 with the FFT. We limited them to 15 days to focus the oscillation with quasi-6-days period.

Figure 5.6 shows the amplitude of the quasi-6-day variation in the Sq-EEJ current system. In the top panel, the amplitude is larger at YAP than at KDU. This is due to the fact that the EEJ amplitude at the equator is much larger than the Sq-current amplitude at middle latitudes. In the bottom panel, the larger amplitude of KDU than YAP is likely due to the meridional component of the Sq current system at middle latitudes being larger than at the geomagnetic equator.

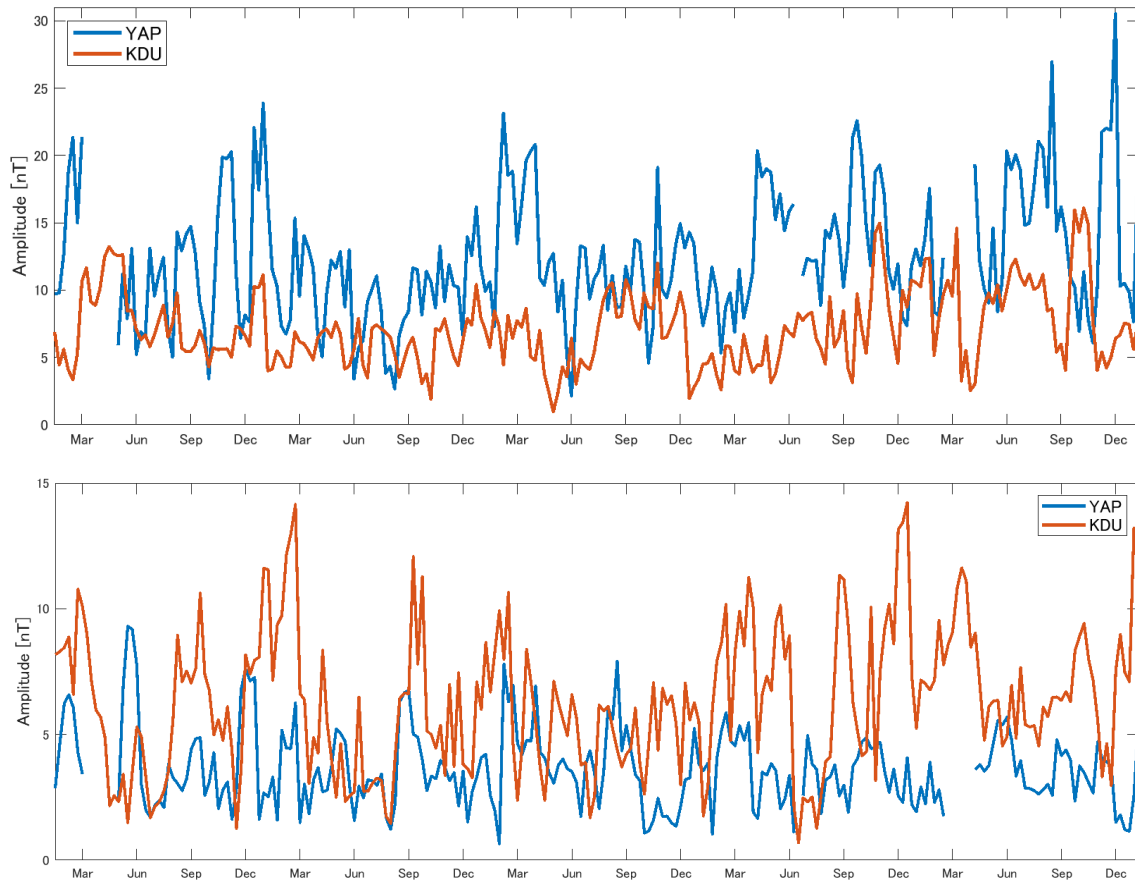


Figure 5.6. The amplitude of the quasi-6-day variation (with period of 4.5-7 days) in the PC1 of the H component as the Sq-EEJ current system (Top panel) and the PC2 of D component (Bottom panel). The horizontal axis indicates the beginning of each month.

5.3 Quasi-6-day variation in IHFACs (D component)

Figure 5.7 presents day-to-day variations of the amplitudes corresponding to the IHFACs. The amplitude of YAP and the amplitude of KDU are comparable. The IHFACs mainly appear in the D component at the geomagnetic equator, but the amplitude is not so big compared to the Sq currents since the IHFACs are generated from a portion of the Sq currents.

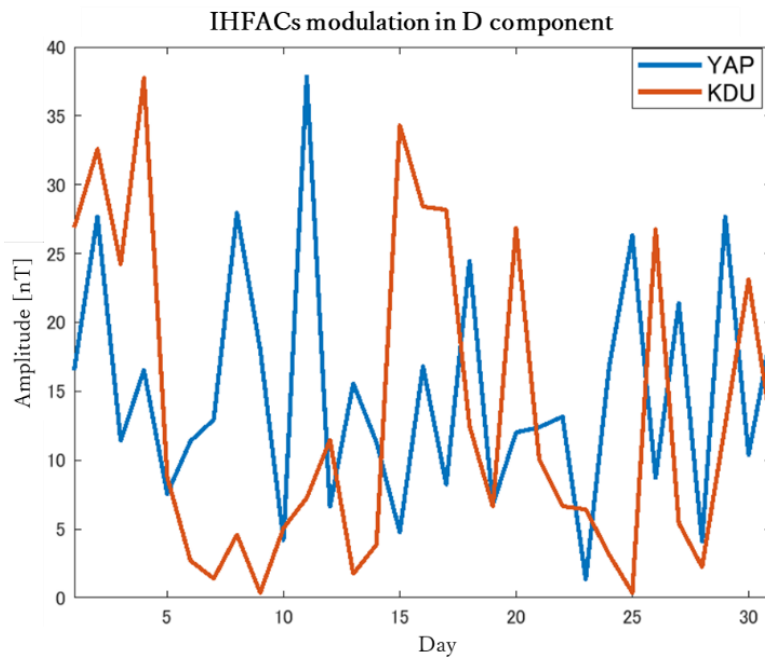


Figure 5.9. Variation amplitudes corresponding to the IHFACs at YAP and KDU in PC1 of the D component in January 2007.

Figure 5.10 presents the power spectrum of the amplitude of IHFACs. There are peaks in period of 4.5-7 days at KDU. On the other hand, large peaks were not seen in period of 4.5-7 days at YAP.

Figure 5.11 presents the amplitude of the quasi-6-day variation in the IHFACs. If the quasi-6-day variation are superimposed on the same IHFACs, the peaks of YAP and KDU should coincide, but they are different because of the effect of semidiurnal tidal variations.

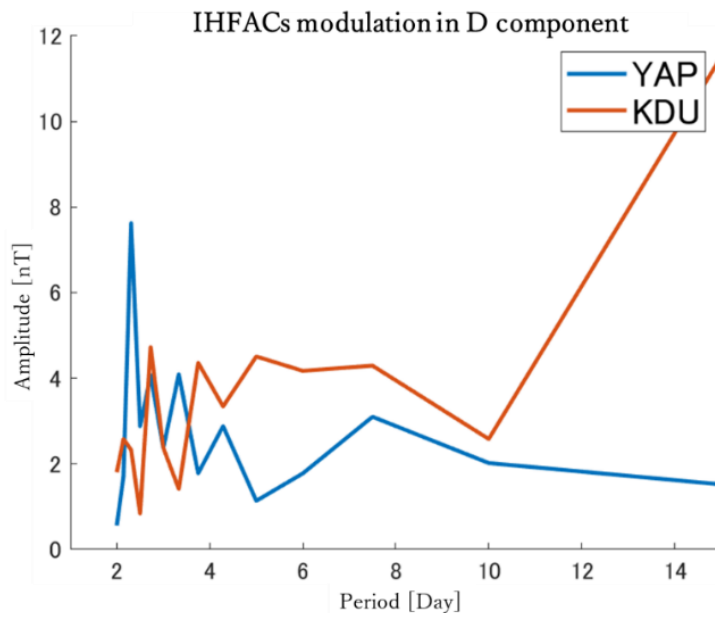


Figure 5.10. Same with Figure 5.7 except for Figure 5.9.

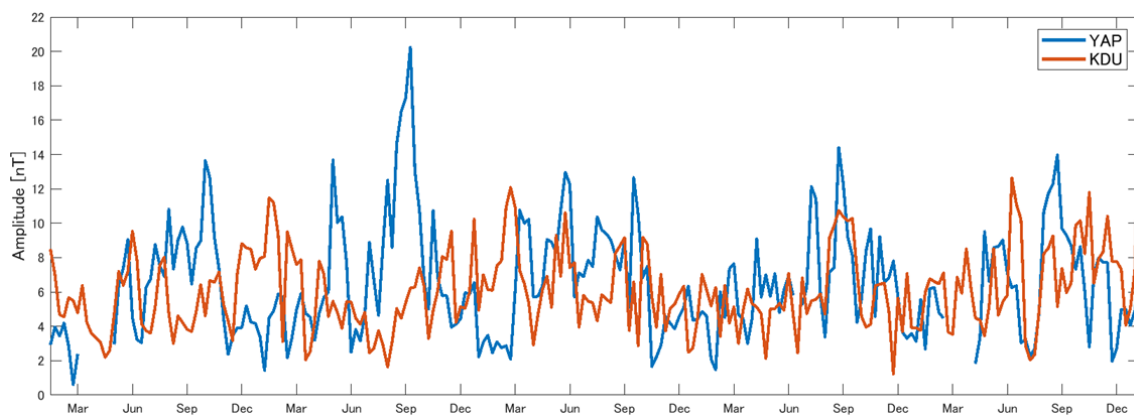


Figure 5.11. Same with Figure 5.8 except for PC1 of the D component associated with the IHFACs

5.4 Seasonal variation and longitudinal structure

Figure 5.12 presents the Q6DW amplitude in zonal and meridional wind averaged for 2007-2011. There are peaks during March-May, end-of-July-September, and December, which are included before and after equinoxes. We compare the seasonal variation and longitudinal structure of the Q6DW with the ones of the quasi-6-day variation in the Sq-EEJ currents and IHFACs.

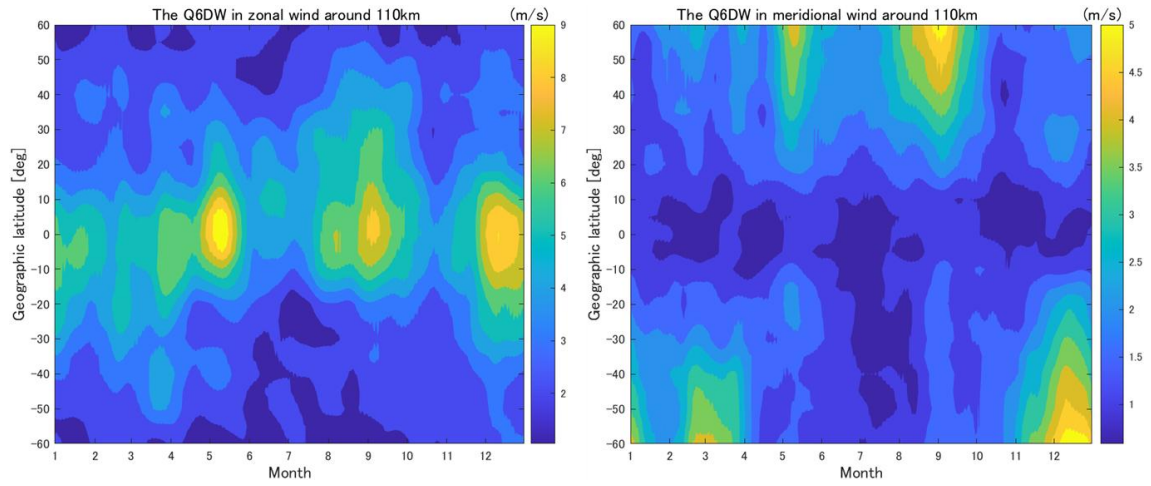


Figure 5.12. The averaged Q6DW amplitude in (Left panel) zonal wind and (Right panel) meridional wind for 2007-2011 around 110km simulated by GAIA

Figure 5.13 presents the quasi-6-day variation amplitude of the Sq-EEJ currents (PC1) in the H component averaged for 2007-2011. The PC1 has peaks from August to October, which is consistent with the seasonal variation in the Q6DW activity. Also, the quasi-6-day variation in the H component develops from the geomagnetic equator to low latitudes of 10.92°N and 21.64°S . That means the Q6DW affected the EEJ at magnetic equator and meridional component of the Sq currents at low latitudes.

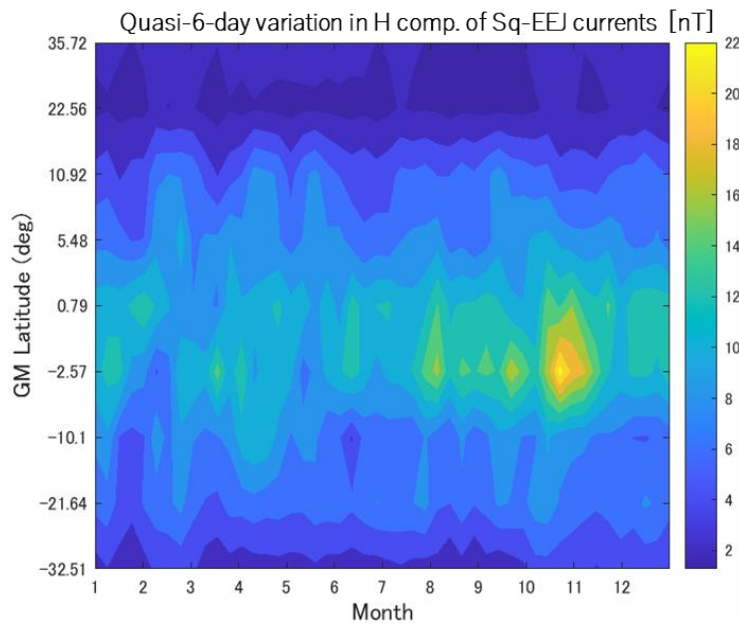


Figure 5.13. The 5-year averaged amplitude of the quasi-6-day variation of the Sq-EEJ currents in the H component.

Figure 5.14 presents the quasi-6-day variation amplitude of the Sq currents (PC2 except for PC1 at -21.64°S and -32.51°S) in the D component averaged for 2007-2011. The PC2 has peaks during April-May and end-of-July-August. The PC1 has peaks during December-January, March, August-September. These results are consistent with the seasonal variation in the Q6DW activity. While PC2's peaks are around the middle latitudes of 22.56°N and 2.57°S , PC1's peaks are around 32.51°S . That means the Q6DW affected the zonal component of the Sq currents at low-middle latitudes.

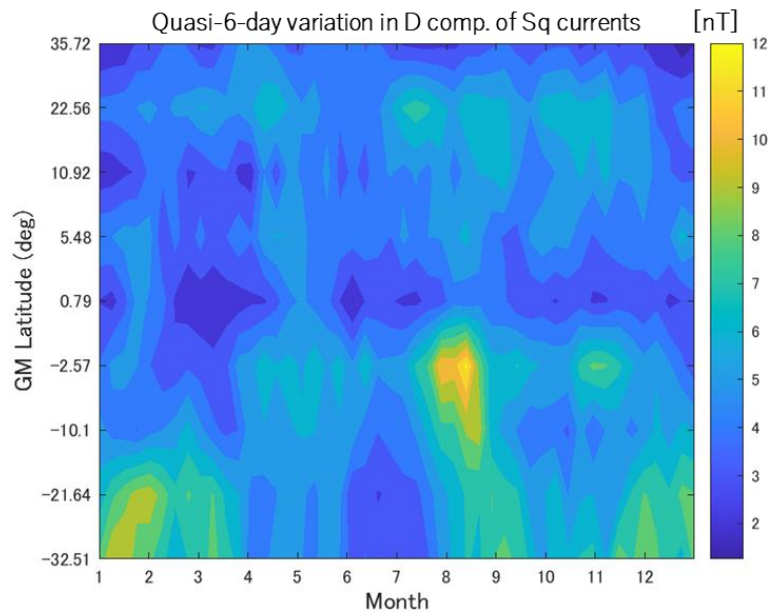


Figure 5.14. The 5-year averaged amplitude of the quasi-6-day variation of the Sq currents in the D component.

Figure 5.15 presents the quasi-6-day variation amplitude of the IHFACs averaged for 2007-2011. There are peaks in April-May, and end-of-July-September, which consistent with the seasonal variation of Q6DW activity. The quasi-6-day variation develops from the magnetic equator to middle latitudes in the northern hemisphere. That means the Q6DW affects the IHFACs. Also, there are minima at low latitudes in the southern hemisphere That was thought to be affected by semidiurnal tidal winds. This result aligns with the nonlinear interaction between the Q6DW and the migrating diurnal and semidiurnal tidal winds in the F region ionosphere (350 km altitude) by TIME-GCM mentioned in Gan et al. [2017].

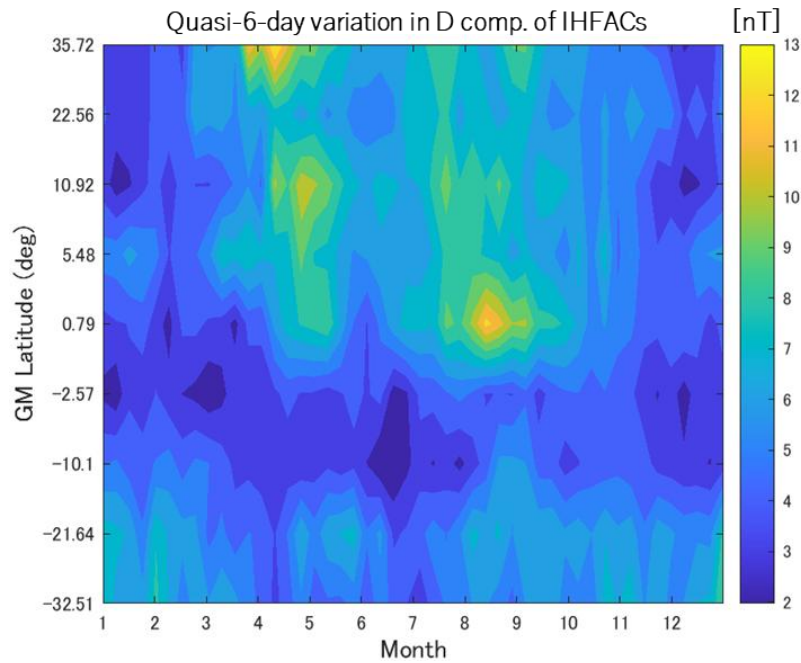


Figure 5.15. The 5-year averaged amplitude of the quasi-6-day variation of the IHFACs in the D component

5.5 Quasi-6-day variation in IHFACs and Sq currents around geomagnetic equator

IHFACs modulate the D component at geomagnetic equator. We focus on the D component by using YAP (GMLAT: 0.79°N) and GUA (GMLAT: 5.48°N) data observed during 2010-2011. The 2 years are magnetic quiet period with the average of F10.7 indices = 96.63. We compared the quasi-6day variation in the ionospheric currents with the Q6DW amplitude in the lower thermosphere reproduced by GAIA to clarify the effect of Q6DW.

We checked the structure of the BFs. Figure 5.16a and 5.16b shows the temporal variation of BF1 and BF2 at YAP and GUA obtained by PCA. BF1s at YAP and GUA change its sign around 0900 and 1500 LT, consistent with the variation expected from the previous observations of the IHFACs which flow from the summer hemisphere to the winter hemisphere during the morning and evening from the winter hemisphere to the summer hemisphere during the noon. BF2s at YAP and GUA change its sign around 1200 LT. This variation implies that BF2 corresponds to indicates the Sq currents since the meridional component of the Sq currents changes the direction at around 1200 LT. But Yap at geomagnetic equator should appear only the EEJ not Sq currents. Therefore, we think effects of the meridional currents getting into the EEJ around morning and going out it around evening. Although these currents have not yet been proven to exist and are debatable. Figure 1c and 1d shows eigenvalue spectrum at YAP and GUA. The sum of percentage of the first and second mode is higher than 80%. Also, the percentage of higher modes (BF3, BF4, ...) are less than 10%. Therefore, we focus only the first and second PCA modes in this study because they explain most of data.

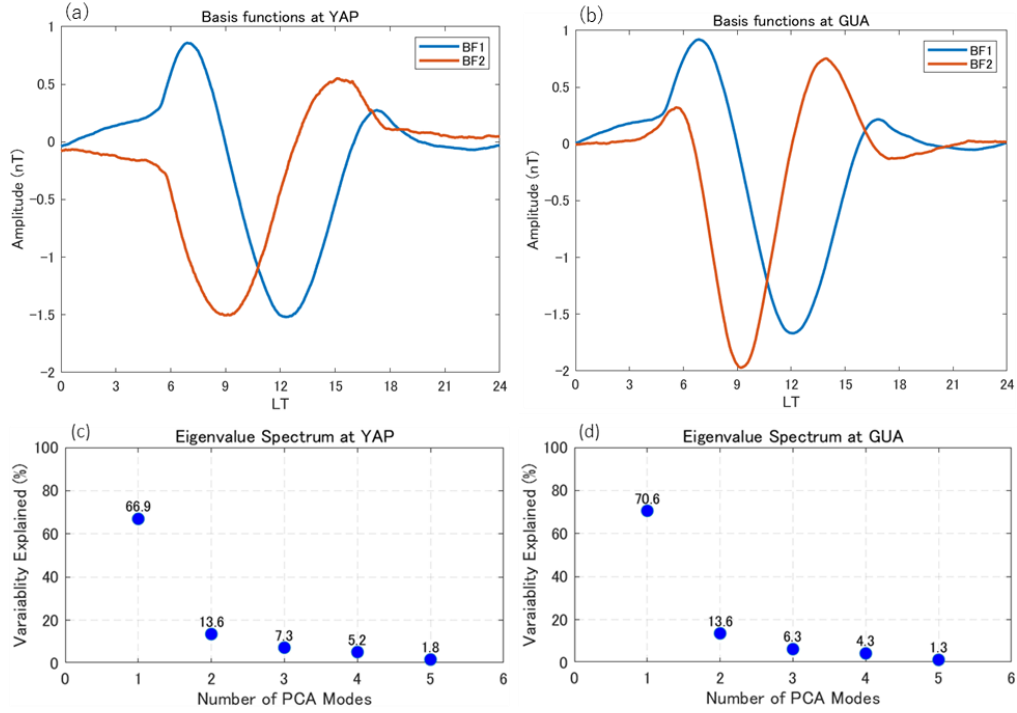


Figure 5.16. Temporal variation of the first and second basis functions (BF1 and BF2) at (a) YAP and (b) GUA. The relative percentage of the total variance captured by each PCA mode during the years 2010-2011 at (c) YAP and (d) GUA.

Next, we calculated the quasi-6-day variation of the daily score in each basis function using FFT. Then we compared the quasi-6-day variation in the two basis functions with the Q6DW amplitude in the lower thermosphere. Figure 5.17 shows the Q6DW amplitude in zonal and meridional wind around 110km and quasi-6-day variation in daily score of BF1 corresponding to the IHFACs at YAP and GUA. The correlation coefficients among them are shown in Table 5.1. From Table 5.1, Figure 5.17b and 5.17d are highly correlated. The maxima near 2010 August/December and 2011 May in Figure 5.17c and 5.17d almost coincide with the maxima of the Q6DW in Figure 5.17a and 5.17b. It is evident that the Q6DW in zonal and meridional wind affects the IHFACs around geomagnetic equator.

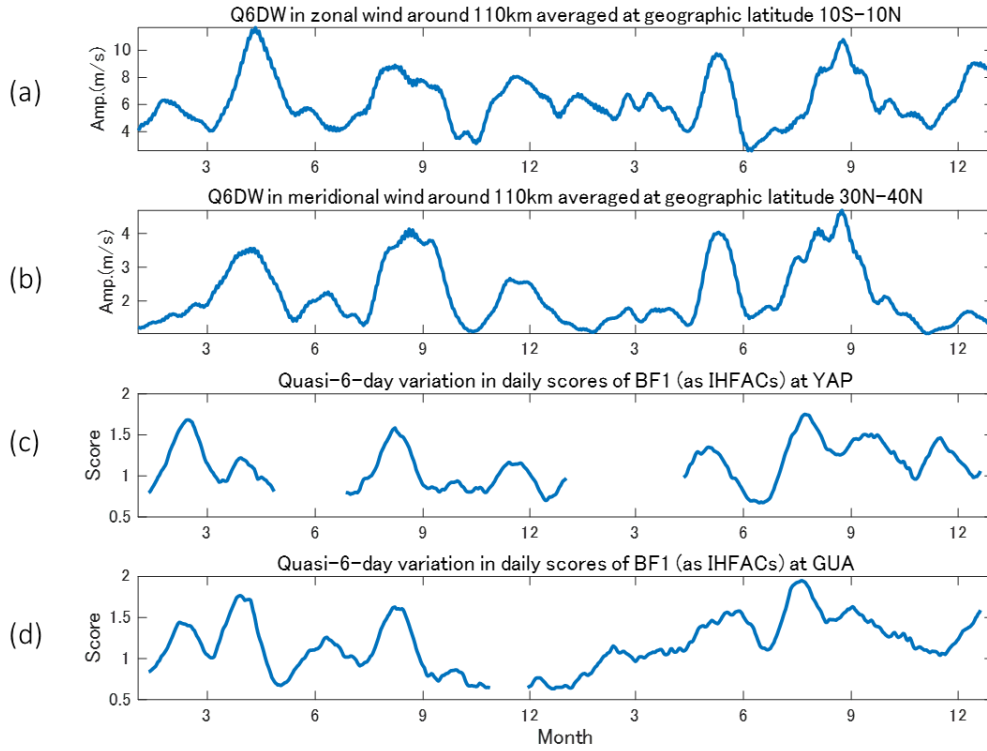


Figure 5.17. (a) The Q6DW amplitude in zonal wind around 110km averaged at geographic latitude 10°S - 10°N during 2010-2011. (b) The Q6DW amplitude in meridional wind around 110km averaged at geographic latitude 30°N - 40°N during 2010-2011. The quasi-6-day variation in the daily scores of BF1 corresponding to IHFACs at (c) YAP and (d) GUA.

Table 5.1 Correlation coefficient among temporal variations of Figure 5.17.

BF1	a	b
c	0.27	0.35
d	0.31	0.56

Figure 5.18 shows the Q6DW amplitude in zonal and meridional wind around 110km and quasi-6-day variation in daily score of BF2 corresponding to the meridional currents at YAP and the Sq current at GUA. The correlation coefficients among them as shown in Table 5.2. The maxima near 2010 August and April-May in Figure 5.18d almost coincide with Figure 5.18a and 5.18b. That could be said that the Q6DW in zonal and meridional wind affects the Sq currents. The quasi-6day variation of Figure 5.18c are different with Figure 5.18a and 5.18b. This result could be said that the Q6DW in zonal and meridional wind does not affect the meridional currents to the EEJ.

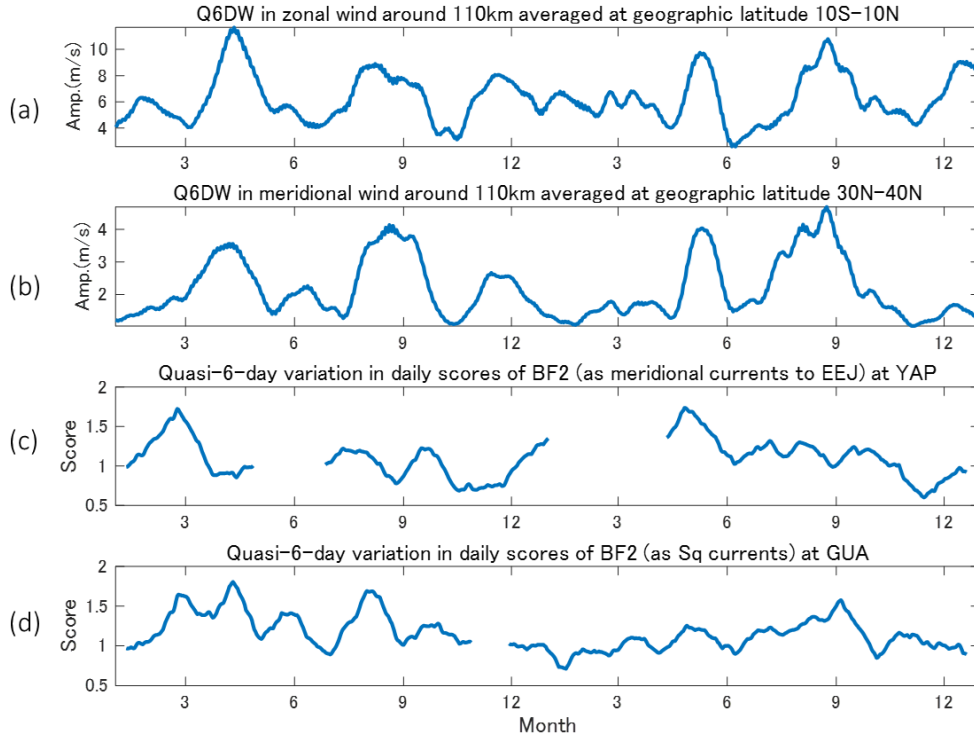


Figure 5.18. Same with Figure 5.17 except for daily scores of BF2 corresponding to meridional currents to the EEJ at YAP and the Sq currents at GUA.

Table 5.2 Correlation coefficient among temporal variations of Figure 5.18.

BF2	a	b
c	-0.09	0.14
d	0.43	0.57

These results suggest the possibility of inter-hemispheric propagation of the Q6DW modulation via dynamo process. Detailed propagation processes are discussed in Chapter 6.

Chapter 6

Discussion of propagating process of Q6DW

In this chapter, we discuss the mechanism for the quasi-6-day modulation of the ionospheric current caused by the Q6DW. At first, we will consider the influence of the zonal wind associated with the Q6DW on the Sq currents as shown in Figure 6.1. We assume that the Q6DW is symmetric to the geographic (GG) equator and the Sq currents is symmetric to the geomagnetic (GM) equator. Also, we assume that magnetic field lines have meridional and vertical component. The Q6DW in zonal wind $\mathbf{u}$ develops from the GG equator to low latitudes. The dynamo electric fields $\mathbf{E}$ have meridional and vertical components because of vertical and meridional magnetic field $\mathbf{B}$, respectively. Vertical dynamo currents $\mathbf{j}$ are not connected between the northern and southern hemispheres since the vertical electric field is antisymmetric to the GG equator. The meridional dynamo currents flow in the same direction of the polarization electric field to remove the bias in the electric charge. The meridional dynamo currents affect the Sq currents in both hemispheres. Therefore, the quasi-6-day variation appeared in the Sq currents.

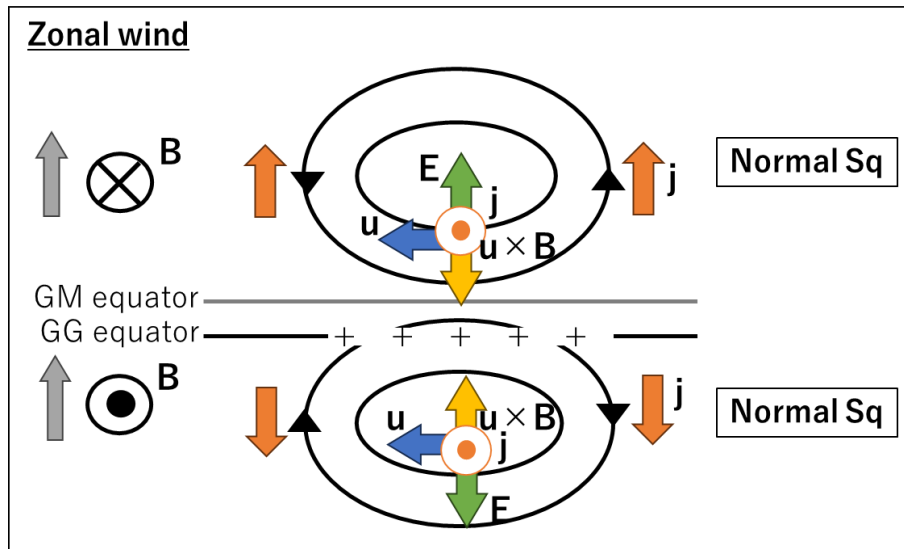


Figure 6.1. Connection between the Sq currents and dynamo currents made by zonal symmetric wind to the GG equator and magnetic field line.

Next, we examine the influence of the meridional wind associated with the Q6DW on the Sq currents and IHFACs as shown in Figure 6.2. Assumptions are the same as for zonal wind. The Q6DW in meridional wind $\mathbf{u}$ develops middle latitudes symmetrically to the GG equator. The polarization electric fields $\mathbf{E}$, which are made by the wind $\mathbf{u}$ and magnetic field $\mathbf{B}$, have zonal component. The zonal dynamo currents $\mathbf{j}$ flow in the same direction of the polarization electric field to remove the bias in the electric charge. The zonal dynamo currents affect the Sq currents in both hemispheres. While one Sq currents become strong, another Sq currents become weak. To compensate for the spatial non-uniformity of these Sq currents, dynamo currents connecting both hemispheres flow. Therefore, the quasi-6-day variation appeared in the Sq currents and IHFACs.

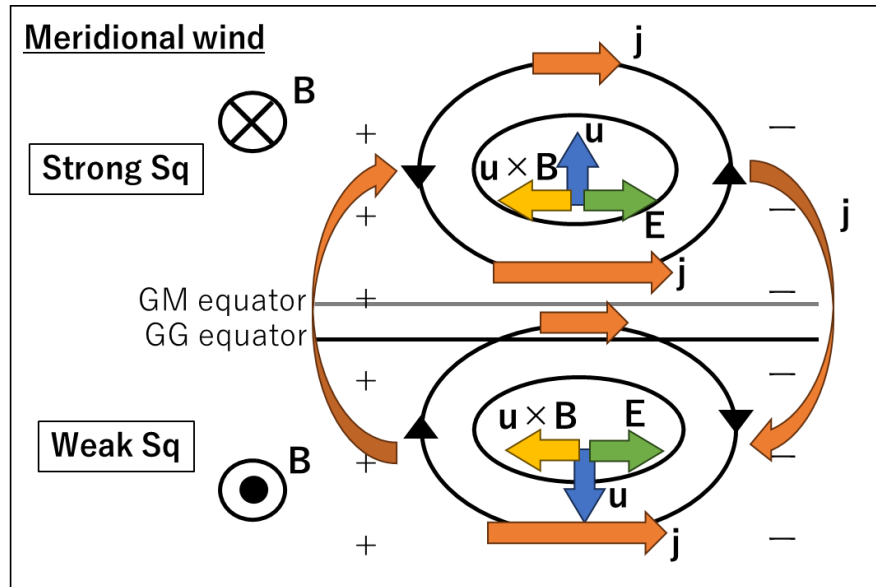


Figure 6.2. Connection among the Sq currents, IHFACs, and dynamo currents made by meridional symmetric wind to the GG equator and magnetic field line.

Next, we examine the influence of the zonal and meridional winds with anti-symmetry to the GG equator on the Sq currents and IHFACs as shown in Figure 6.3 and Figure 6.4, respectively. At first, we assume that the Q6DW is symmetric to the geographic (GG) equator. Therefore, these winds are some winds varying in a cycle of around 6 days not the Q6DW. Other assumptions are the same as for Figure 6.1 and 6.2. The zonal wind $\mathbf{u}$ develops from the GG equator to low latitudes anti-symmetrically. The polarization electric field $\mathbf{E}$ have meridional/vertical components because of zonal wind $\mathbf{u}$ and vertical/meridional magnetic fields $\mathbf{B}$, respectively. Vertical dynamo currents $\mathbf{j}$ connected between the northern and southern hemispheres since the vertical electric fields are symmetric to the GG equator. The meridional and vertical dynamo currents $\mathbf{j}$ flow in the same direction of the polarization electric field $\mathbf{E}$ to remove the bias in the electric charge. The meridional and vertical dynamo currents affect the Sq currents and IHFACs from GM equator to low latitudes, respectively. Therefore, the quasi-6-day variation appeared in the Sq currents and IHFACs.

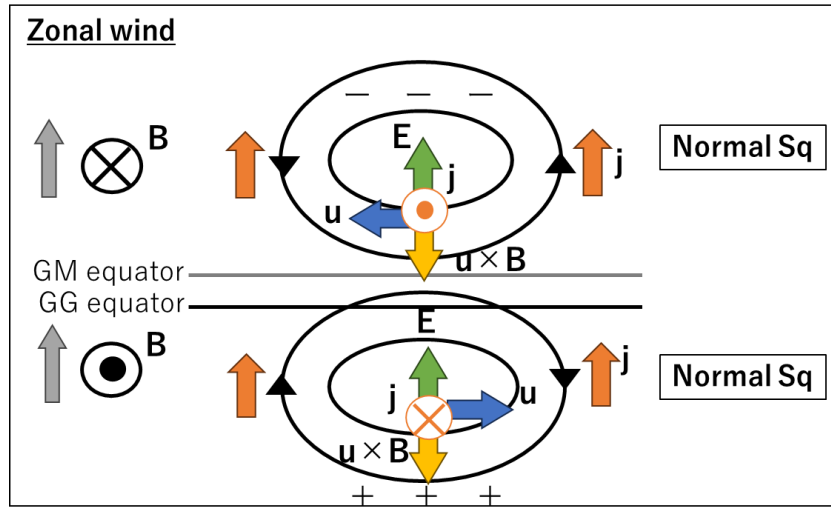


Figure 7.3. Connection among the Sq currents, IHFACs, and dynamo currents made by zonal antisymmetric wind to GG equator and magnetic field line.

On the other hand, the meridional wind $\mathbf{u}$ develops from the GG equator to low latitudes anti-symmetrically. The polarization electric fields $\mathbf{E}$ have zonal component because of meridional wind $\mathbf{u}$ and vertical magnetic field $\mathbf{B}$. Zonal dynamo currents $\mathbf{j}$ flow in the same direction of the polarization electric field $\mathbf{E}$ to remove the bias in the electric charge. These currents make the Sq currents strong in both hemispheres. If dynamo currents are not same intensity in both hemisphere because of difference conductivities or wind strength, the vertical dynamo currents affect the IHFACs. Therefore, the quasi-6-day variation appeared in the Sq currents and IHFACs.

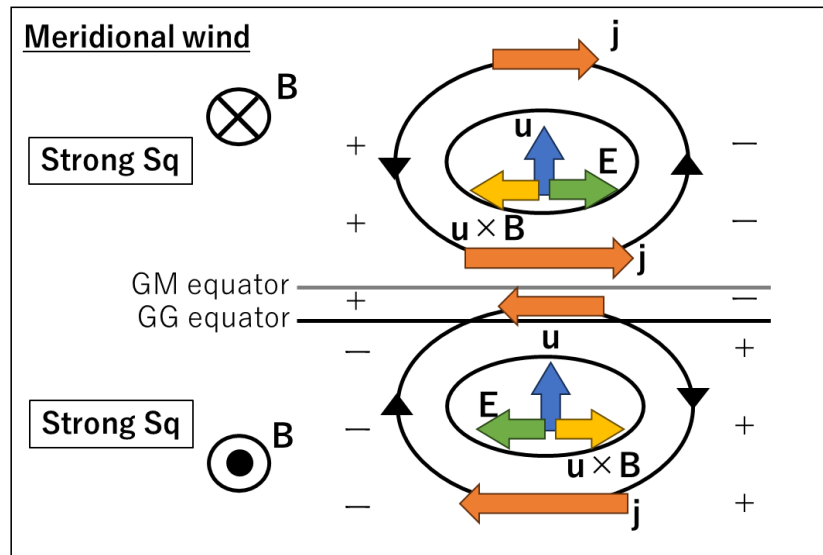


Figure 6.2. Connection between the Sq currents and dynamo currents made by meridional antisymmetric wind to the GG equator and magnetic field line.

Chapter 7

Conclusions and future perspective

7.1 Conclusions

In this study, we analyzed ground magnetic field data obtained from several magnetometers during 2007-2011 to clarify characteristics of quasi-6-day variation in ionospheric currents and investigated what mechanism mainly causes spatiotemporal variations in the atmosphere-ionosphere-magnetosphere coupling region by comparing with GAIA data. As main method, using PCA, we could extract the ionospheric currents variation modulated by Sq-EEJ current system, IHFACs, and atmospheric tidal winds by applying PCA to the H and D components of the ground magnetic field. Then we calculate the quasi-6-day variation amplitude on these currents with FFT.

First, we investigated spatiotemporal variations of each principal component during quiet days from 65°S to 65°N in GMLAT of Japan sector. First components form the Sq-EEJ current system, and both of second/third components form two vortices in one hemisphere modulated by semidiurnal tidal winds.

Second, we simulated the amplitude of the Q6DW in zonal wind, quasi-6-day variation in current density with zonal wave number 1 at the E region of the ionosphere and integrated magnetic field to clarify the propagation process of the Q6DW. The Q6DW in zonal and meridional wind develops strongly before and after equinoxes as described in previous studies. Also, the Q6DW in zonal wind generated around the equator might modulate the quasi-6-day variation in vertical electric field/current there by dynamo theory, then quasi-6-day variation in the H and D components of ground magnetic field around the equator might be modulated. On the other hand, the Q6DW in meridional wind generated around middle latitudes in the northern and southern hemispheres might modulate the quasi-6-day variation in zonal electric field/current there by dynamo theory, then the D component of the ground magnetic field around middle latitude might be modulated. Therefore, comparing the quasi-6-day variation in the simulated magnetic field with the quasi-6-day variation in observed ground magnetic field, they have similar seasonal variation.

Third, we applied PCA to the H and D components of ground magnetic field at 9 stations and distinguished each which basis function were modulated by which current. The first basis functions (BF1s) of the H component were modulated by

the Sq current in low-middle latitudes and the EEJ around the geomagnetic equator. BF2s of the H component show semidiurnal variations. On the other hand, BF1s of the D component were modulated by the IHFACs from low latitude in the southern hemisphere to middle latitude in the northern hemisphere and the Sq currents in middle latitude in southern hemisphere. BF2s of the D component were mainly modulated by the Sq currents. Then we calculate quasi-6-day variation on each variation amplitude. Since the quasi-6-day variation increases in proportion to magnitude of the Sq-EEJ current system and IHFACs, the quasi-6-day variations might be influenced by the Q6DW.

Fourth, we investigated whether the quasi-6-day variations are modulated by the Q6DW by comparing the quasi-6-day variation amplitude at YAP (GMLAT: 0.79°N) and GUA (GMLAT: 5.48°N) with the Q6DW amplitude in lower thermosphere observed at 40°N from the Microwave Limb Sounder on the Aura satellite from Yamazaki (2018) during 2010-2011. From these results, we can say that the quasi-6-day variation on the IHFACs and Sq currents around geomagnetic equator were modulated by the Q6DW. On the other hand, the quasi-6-day variation on the meridional currents to the EEJ at geomagnetic equator is low correlation with the Q6DW amplitude in lower thermosphere.

Finally, we considered that the possibility of propagation process that the Q6DW intensifies the Sq currents in one hemisphere and weakens the Sq currents in another hemisphere, then modulates the quasi-6-day variation on the IHFACs.

7.2 Future perspective

In chapter 5.5, further observational data analysis of ground magnetic field around middle latitudes in northern and southern hemispheres and in other longitudinal regions can elucidate the global and three-dimensional structures of the Q6DW modulation of ionospheric currents. Also, the quasi-6-day variation on semidiurnal variation were also modulated by the Q6DW. These results suggest the possibility of interactions between the Q6DW and some of atmospheric tidal winds. To clarify the interactions, we need further simulated data analysis of their winds by GAIA.

In addition, we can use same methods to other planetary waves with zonal wavenumber 1 such as quasi-2-day, 10-day, and 16-day waves. It must be noted that the longitudinal structures of their waves are different with the Q6DW as known from Hough functions. The overarching objective of future studies in this field is to elucidate the complex atmospheric-ionospheric-magnetospheric coupling occurring in the near-Earth environment.

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