Contribution of wind, conductivity, and geomagnetic main field to the variation in the geomagnetic *Sq* field

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[1] Long-term variation in the geomagnetic *Sq* field and the cause of the variation were examined. The amplitude of the geomagnetic Y component (*Sq*(Y)) in equinox was averaged for each year and adopted as a proxy of the *Sq* field. *Sq*(Y) was combined with the ionospheric conductivity estimated by the International Reference Ionosphere model to determine the dynamo electric field and neutral wind velocity by using the geomagnetic main field strength. It was found that the solar activity dependence of the *Sq* field could be almost completely attributed to the conductivity variation, and neutral winds tend to decrease when the solar activity increases. Although the long-term variation in the dynamo field differed among observatories, these differences were mostly attributed to the locality of the geomagnetic secular variation, whereas the variations in neutral wind amplitude were nearly the same in all regions. On the other hand, no clear long-term variation in neutral wind was detected other than that by solar activity.

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1. Introduction

[2] Solar quiet daily geomagnetic field variation (*Sq*) is primarily caused by ionospheric currents driven by the dynamo electric field ($\boldsymbol{V}_n \times \boldsymbol{B}$) generated by the interaction of neutral wind ($\boldsymbol{V}_n$) and geomagnetic main field ($\boldsymbol{B}$). The currents are subject to Ohm's law and thus determined by the product of the total (i.e., dynamo plus electrostatic) electric field and electrical conductivity ($\underline{\sigma}$), and thus, *Sq* amplitude is also determined by $\boldsymbol{B}$, $\boldsymbol{V}_n$, and $\underline{\sigma}$. Among these variables, the latter two are strongly controlled by solar radiation, and thus, most time variations in *Sq* are related to solar conditions. In fact, it is widely accepted that the amplitude of the *Sq* field is strongly controlled by solar activity [e.g., *Rastogi and Iyer*, 1976; *Takeda*, 2002a]. Moreover, *Briggs* [1984] showed that the day-to-day variation in the amplitude also well reflects that of the sunspot number (SSN).

[3] Many studies have examined the long-term variation in the *Sq* field and its relationship with factors such as geomagnetic main field, solar activity, and neutral wind. For example, *Glassmeier et al.* [2004] examined the effects of long-term geomagnetic variation on the magnetospheric and ionospheric physics and emphasized the importance of the geomagnetic main field in studying the physics. *Clilverd et al.* [2005] reported that a long-term increase in the solar coronal magnetic field strength causes the long trend of the *aa* index, and thus, the long trend of the *Sq* field can be at least partly due to solar activity.

[4] Although it may appear that a decrease of the main field strength should reduce the *Sq* field through the reduction of the dynamo field, such an effect is not so simple because electric conductivity is also affected by the field strength. That is, since the magnetic field generally prevents charged particles from moving across the field, a stronger magnetic field reduces perpendicular or Pedersen electric conductivity; however, Hall conductivity originates in a different drift motion of positive and negative charged particles and appears only if a magnetic field exists. Therefore, the dependence of the *Sq* field on the field strength is more complicated. In fact, *Takeda* [1996] simulated the effect of the geomagnetic main field strength and showed that a decrease of the main field surely reduces the electrostatic potential difference because of the smaller dynamo field and that height-integrated ionospheric currents are enhanced because the effect of the conductivity increase overcomes that of the reduction in the dynamo electric field. On the other hand, the main field does not decrease uniformly on the Earth's surface and may be constant or slightly increased in some areas as shown in Figure 1. Thus, the effect of the geomagnetic secular variation on the variation in ionospheric conductivity, dynamo electric field, and *Sq* field is expected to differ among observatories.

[5] In the present study, the *Sq* amplitude in the Y component (*Sq*(Y)) is first estimated, and the ionospheric conductivity and geomagnetic main field are calculated on the basis of these models. Next, the dynamo electric field and neutral wind are estimated from these values. Finally, the effects of solar activity and geomagnetic secular variation on the ionospheric dynamo are studied, and the long-term variation in the neutral wind in the ionosphere is discussed.

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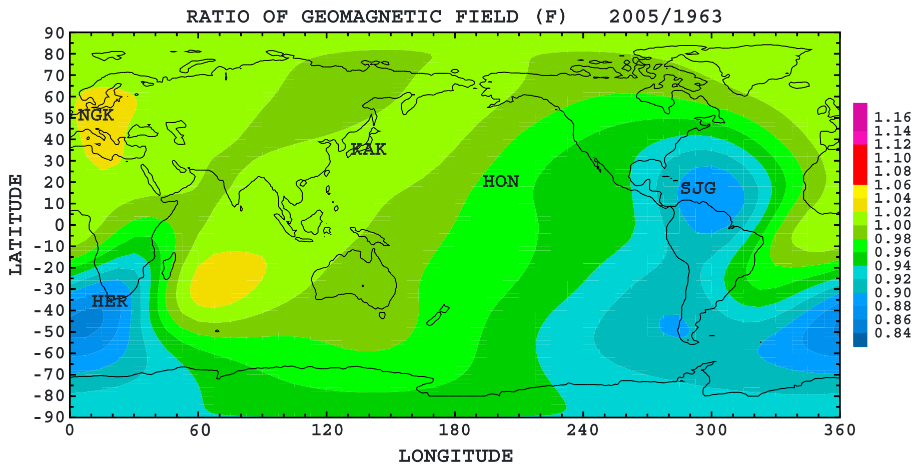

Figure 1. Global distribution of the ratio of geomagnetic main field strength from 1963 to 2005. The geomagnetic observatories mainly used in the present study are also shown.

2. Data Analysis

[6] In the present analysis, *Sq*(Y) at each observatory was considered, and the amplitude was determined by the same method as that in *Takeda* [2002b] and *Takeda et al*. [2003]. That is, *Sq*(Y) defined as the difference between the maximum and minimum values of the Y component in the daytime (06–18 LT) was adopted as the *Sq* amplitude that was used in the present study. The advantage of the Y component is that *Sq* is the clearest in the component in middle latitudes, where most observatories that provide long-term data are located, most clear in the component, and the Y component is less sensitive to disturbances in the geomagnetic field. Although the *Sq* field in the Z component is also prominent in middle latitudes, this component is sensitive to the relocation of the observatory [*Takeda*, 2013] and thus not appropriate for the examination of the long-term variation of the *Sq* field. In the present analysis, only days when the *Kp* index was less than 3+ in daytime were considered, and *Sq*(Y) on the days of equinoctial months (March, April, September, and October) were averaged and used as the annual *Sq*(Y).

[7] The geomagnetic observatories used in this analysis are Hermanus (HER), San Juan (SJG), Honolulu (HON), Kakioka (KAK), and Niemegk (NGK), the locations of which are shown in Figure 1. These observatories were selected because they are close to the latitudes where the center of the *Sq* current vortex passes, and their long-term

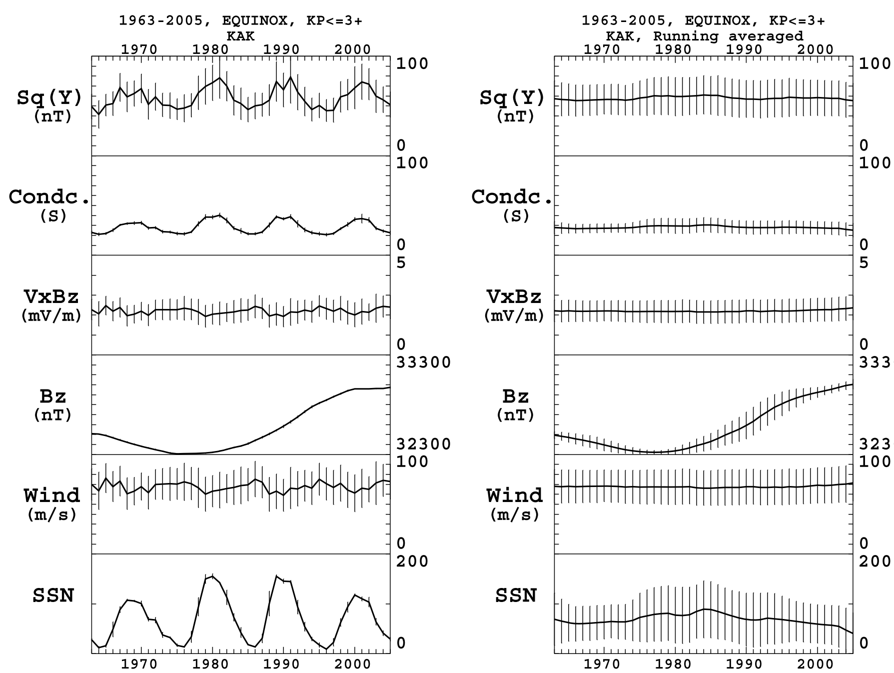

Figure 2. *Sq*(Y) amplitude, ionospheric conductivity, dynamo electric field, vertical geomagnetic main field, wind amplitude, and SSN at KAK from 1963 to 2005. (left) Yearly and (right) 11 year running averaged values. Error bars represent standard deviations.

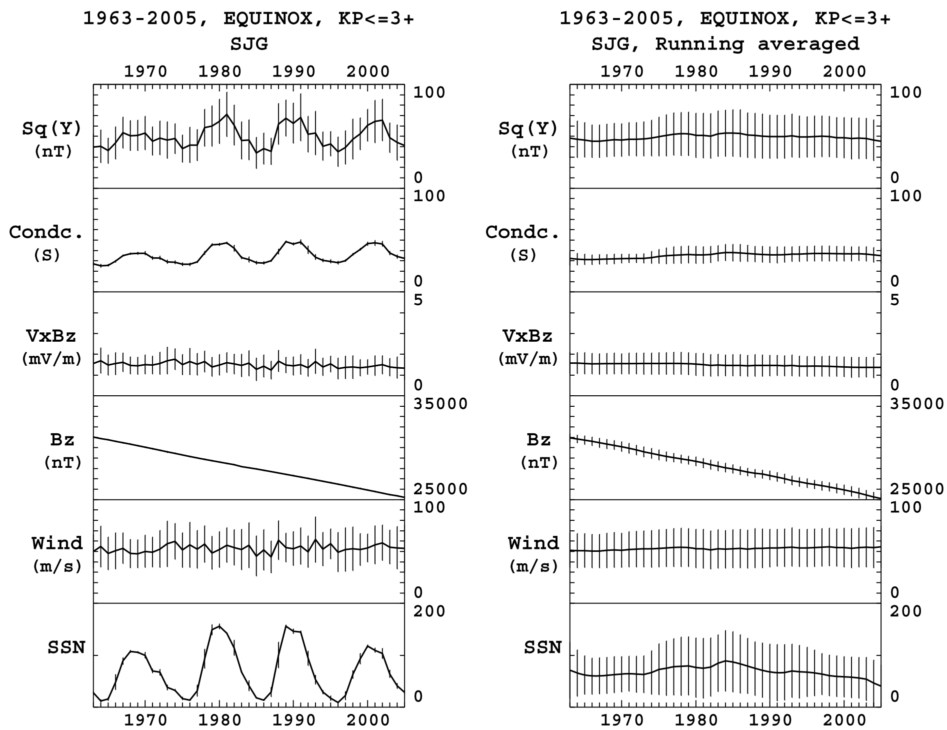

Figure 3. Same as Figure 2 but at SJG.

data are relatively continuous and of good quality. Figure 1 also shows the secular variation in the geomagnetic main field strength, and the observatories are classified according to the characteristics of the geomagnetic secular variation. That is, the strength clearly decreases at SJG and HER and slightly decreases or increases at HON, KAK, and NGK.

[8] The ionospheric conductivity was estimated by the International Reference Ionosphere (IRI) models IRI2012 [*Bilitza et al.*, 2011] and IRI90 [*Bilitza*, 1990]. Since the amplitude of the geomagnetic field variation is nearly proportional to that of the height-integrated current, it was appropriate to use the height-integrated conductivity above the observatory for the present study. According to the generation mechanism of the *Sq* current system presented by *Fukushima* [1979], the *Sq* current pattern is essentially determined by the Pedersen current driven by the dynamo electric field and eastward electric field created by the polarization of the Pedersen currents by the dynamo field. That is, the formation of the *Sq* current system pattern does not require the Hall conductivity, and the existence of such conductivity only enhances the current intensity; this phenomenon was confirmed by simulations [*Takeda*, 1991]. Assuming that the geomagnetic field line is vertical, these height-integrated conductivities can be regarded as line-integrated conductivities. Thus, in the present analysis, the "extended Cowling conductivity (Σ_3)" was adopted in the present analysis. Σ_3 is defined as

$$\Sigma_3 = \Sigma_1 + \Sigma_2^2/\Sigma_1, \quad (1)$$

where Σ_1 and Σ_2 are the height-integrated Pedersen and Hall conductivities, respectively.

[9] The amplitudes of the dynamo electric field (E_d) and the zonal neutral wind (V) can be estimated from *Sq*(Y) as

$$V = 4Sq(Y)/(3\mu_0\Sigma_3 B_z), \quad (2)$$

where μ_0 is the permeability of the vacuum ($= 4\pi \times 10^{-7}$) and B_z is the vertical geomagnetic field strength. In this equation, some assumptions or simplifications are made, such as the contribution of the induced currents in the Earth is half of that of the external currents, and the *Sq* magnetic fields are assumed to be proportional to the zonal wind multiplied by the vertical magnetic field and the Cowling conductance. Of course, these simplifications are crude approximations, and not highly accurate representations, because many factors can affect the validity of these simplifications, e.g., the meridional winds, the height dependence of the zonal wind, nonlocal electric field generation, and contributions to the *Sq* fields from field-aligned currents above the ionosphere. However, the assumptions are based on the principal generation mechanism proposed by *Fukushima* [1979] and thus adequate to estimate the effects of wind, conductivity, and geomagnetic main field on the *Sq* field.

[10] In the present study, the conductivity at 15 h LT was adopted, because *Sq* variation in the Y component typically reaches maximum and minimum levels at 09 h LT and 15 h LT, respectively, and the conductivity is almost the same at both times because of the symmetry with local noon at least in the E region. The height-integrated Pedersen and Hall conductivities were calculated by integrating the conductivities at a 5 km height interval from 80 to 400 km, and then, the above mentioned Σ_3 was estimated by equation (1). B_z was estimated at an altitude of 150 km above the observatory. This height almost corresponds to that of ionospheric dynamo currents. Using the conductivity and vertical geomagnetic field strength,

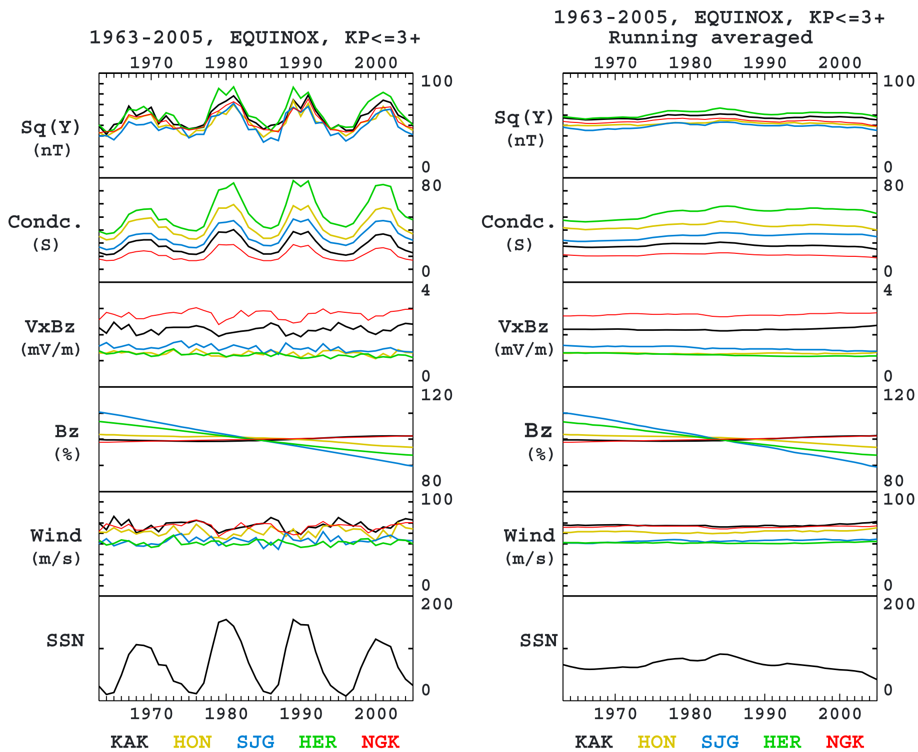

Figure 4. *Sq*(Y) amplitude, ionospheric conductivity, dynamo electric field, vertical geomagnetic main field relative to the mean values through this period, wind amplitude, and SSN from 1963 to 2005. (left) Yearly and (right) 11 year running averaged values. The black, yellow, blue, green, and red lines indicate values at KAK, HON, SJG, HER, and NGK, respectively.

V is estimated from *Sq*(Y). Since *Sq*(Y) is the amplitude of the Y component, V could be regarded as the difference in the zonal neutral wind velocity at 09 h LT and 15 h LT.

3. Result and Discussion

[11] Figures 2 and 3 show the *Sq*(Y) amplitude, ionospheric conductivity, dynamo electric field, vertical geomagnetic main field, wind amplitude, and SSN in 1963–2005 at KAK and SJG, respectively. The left and right panels represent annual and 11 year running averaged values, respectively, and the error bars indicate standard deviations. When the 11 year running averages are calculated, the original data are extended 5 years before and after the range of the plots in order to avoid the bias, which is the reason why the plotted period is limited to the period 1963–2005. It is evident that the *Sq* amplitude at both observatories is strongly controlled by the solar activity represented by SSN. As for long-term variation, the conductivity was shown to increase at SJG and HER because of the decrease in geomagnetic field strength at these observatories rather than at KAK.

[12] Figure 4 shows stack plots of *Sq*(Y) amplitude, ionospheric conductivity, dynamo electric field, vertical geomagnetic main field relative to the mean values through this period, wind amplitude, and SSN from 1963 to 2005 at KAK, HON, SJG, HER, and NGK. The left and right panels again represent annual and 11 year running averaged values, respectively. It is again clear that the solar activity predominantly affects *Sq* amplitude, and the characteristics of each solar cycle are reflected in the amplitude. This is not so surprising because *Sq* is driven by the solar diurnal tidal wind, and the ionospheric currents are proportional to conductivity, which is also controlled by solar radiation. The present study shows that the characteristics of each solar cycle are also reflected in the *Sq* amplitude. Thus, a simple running average spanning 11 years, which is one solar cycle length, cannot completely remove the solar activity effect.

[13] The most interesting point is that most of the solar activity effects on *Sq* are attributed to ionospheric conductivity, whereas the dynamo electric field does not practically contribute to solar activity dependence. Rather, it appears that the dynamo electric field slightly decreases when the solar activity is high. It may be unnatural that the neutral wind velocity is slower under higher solar activity condition, but in fact, it is not surprising because some observations [e.g., *Liu et al.*, 2004; *Sridharan et al.*, 2010] showed that the thermospheric tidal wind velocity is smaller during high solar activity period. This effect is likely attributed to the larger ion drag force owing to larger ion density. In fact, the dependence of the ionospheric electric field on the solar activity in the daytime during geomagnetically quiet periods, which is essentially the polarization field generated by the dynamo electric field, is not clear [e.g., *Fejer et al.*, 1991; *Berkey et al.*, 1990; *Buonsanto et al.*, 1993]. This supports the idea that neutral wind velocity is not the main contributor of solar variation in the geomagnetic *Sq* field.

[14] Figure 4 shows that the dynamo electric field decreased at SJG and HER, and a slight decrease was recorded at HON. However, such decrease was not found at KAK and NGK. This difference can be attributed to the geomagnetic secular

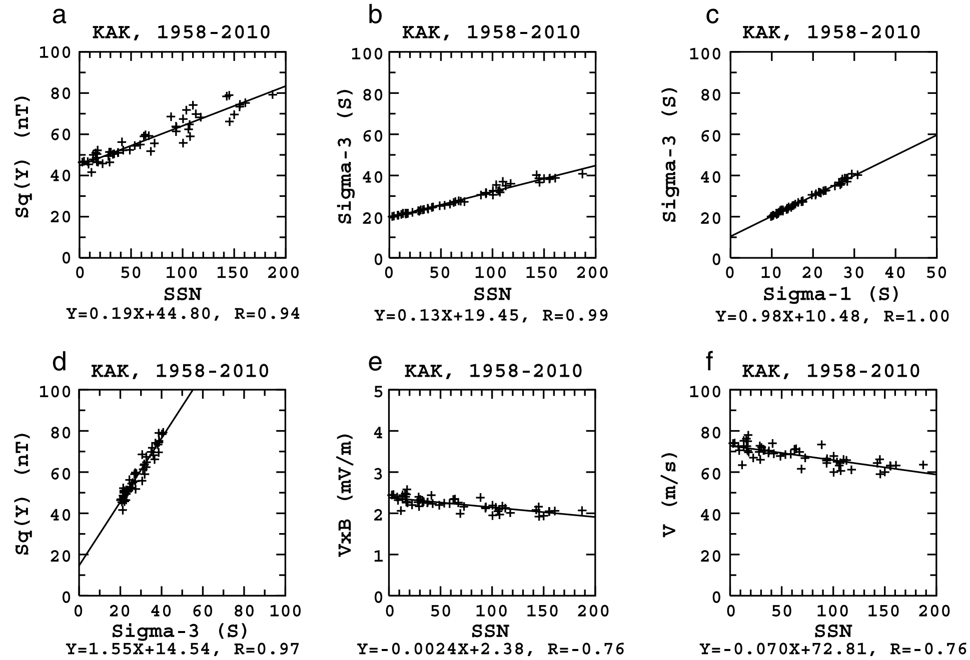

Figure 5. Correlation between (a) SSN and *Sq*(Y), (b) SSN and Σ_3, (c) Σ_1 and Σ_3, (d) Σ_3 and *Sq*(Y), (e) SSN and dynamo electric field (V × B), and (f) SSN and neutral wind velocity at KAK from 1963 to 2005. A linear regression line is drawn in each panel, and the linear regression equation and correlation coefficient are given at the bottom of each panel.

variation at each observatory. On the other hand, the obtained neutral wind velocity is almost the same for cases in which the main field clearly decreased, and the differences in each observatory are attributed to the main field rather than to the neutral wind. The obtained long-term variation in the neutral wind velocity is nearly the same at all observatories, and no clear long-term variation was detected other than that by solar activity.

[15] In order to check the relationship of conductivity, *Sq*(Y), neutral wind, and solar activity, Figure 5 represents correlation between SSN and *Sq*(Y), SSN and Σ_3, Σ_1 and Σ_3, Σ_3 and *Sq* (Y), SSN and dynamo electric field (V × B), and SSN and neutral wind velocity at KAK. A strong positive correlation is found between SSN and *Sq*(Y) and Σ_3 and *Sq*(Y), whereas a slightly negative correlation between dynamo V × B and

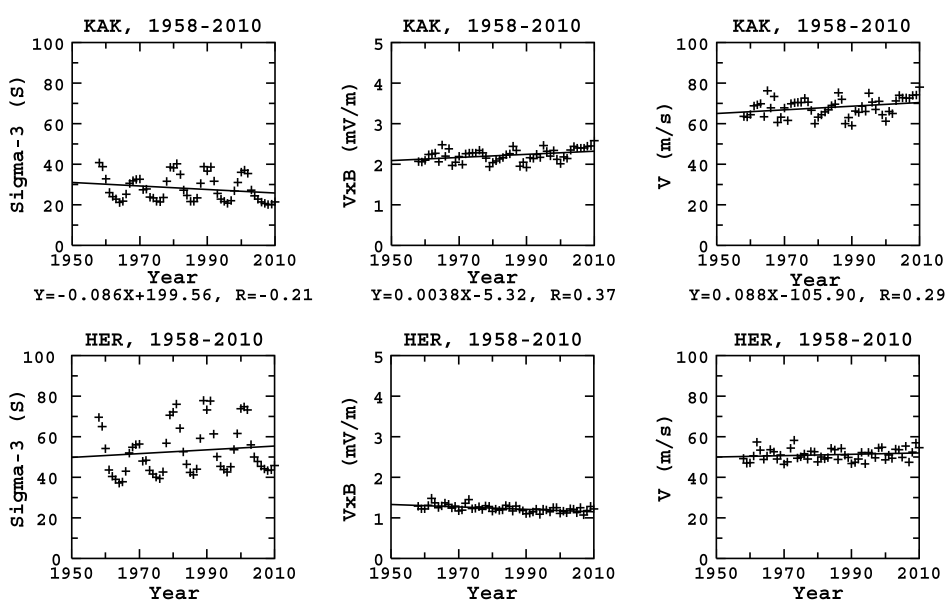

Figure 6. Correlation between (left) the running averaged Σ_3, (middle) V × B, and (right) V, and year at (top) KAK and (bottom) HER from 1963 to 2005. A linear regression line is drawn in each panel, and the linear regression equation and the correlation coefficient are given at the bottom of each panel.

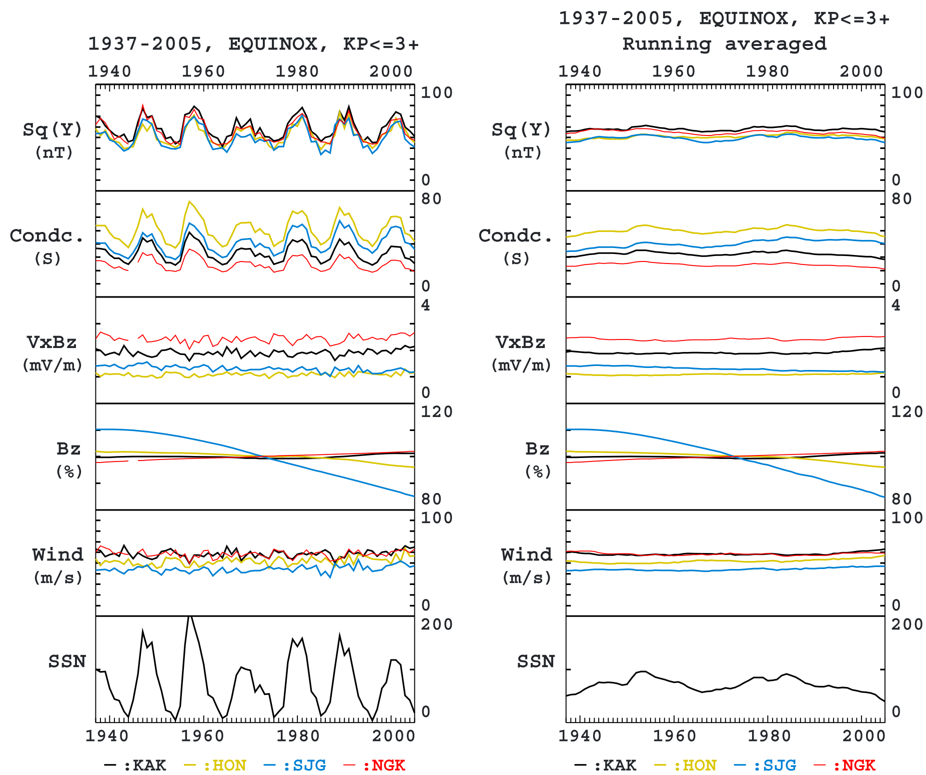

Figure 7. *Sq*(Y) amplitude, ionospheric conductivity, dynamo electric field, vertical geomagnetic main field relative to the mean values through this period, wind amplitude, and SSN from 1937 to 2005. The black, yellow, blue, and red lines indicate values at KAK, HON, SJG, and NGK, respectively. Conductivity was estimated by the IRI90 model.

SSN, and neutral wind velocity and SSN. This supports the above mentioned idea that the solar activity dependence of *Sq*(Y) is mostly attributed to the conductivity. This figure shows that Σ_3 approximately equals Σ_1 plus 10 S. Σ_3 and Σ_1 are highly correlated, but they are not proportional: Σ_1 changes by about a factor of 3 over the solar cycle, while Σ_3 changes only by about a factor of 2. Therefore, if the study had used Σ_1 instead of Σ_3 as a measure of conductance variability, it would have found a larger percentage change of conductance over the solar cycle, and therefore a larger reduction of V × B and V as solar activity increases.

[16] Figure 6 shows the correlation between 11 year running averaged conductivity, dynamo electric field, and neutral wind velocity, and year at KAK and HER from 1963 to 2005. The running averaging cannot completely remove the effect of solar activity variation as was mentioned above, and thus, some ripples remain at both observatories. If these ripples are ignored, there is no clear secular variation in all parameters at KAK. On the other hand, at HER, the conductivity increases because of the decrease in the geomagnetic main field strength, and the dynamo field increases, but the neutral wind does not show clear secular variation.

[17] For longer-term variations, Figure 7 shows similar plots as those in Figure 4; however, only the 1937–2005 period records at KAK, HON, SJG, and NGK are listed. Plots for HER are not shown in this figure because geomagnetic data at that observatory are available only after 1941. The conductivities were estimated by the IRI90 model because the IRI2012 model is not available before 1957. This figure shows that the previously mentioned features in the long-term variation were essentially the same in the longer period. Since the IRI90 model tends to give larger conductivity values than the IRI2012 model, the resultant dynamo field and neutral wind velocity were smaller at all observatories.

[18] It is interesting to note that *Sq*(Y) does not significantly increase at the observatories where the main field intensity decreases. Such a result seems to contradict the previous simulation results that the *Sq* field is enhanced by the decrease of the geomagnetic field. One of the probable reasons for this difference is that the *Sq* current system is determined by the global dynamo field, and thus, the local main field effect can be little. In fact, *Sq*(Y) is almost the same at NGK and KAK in 1937 and tended to be smaller at NGK than at KAK with year, although the geomagnetic field was almost constant at both observatories. This suggests that attempts to explain geomagnetic variations in terms of local field changes instead of global dynamo effects are not fully adequate.

4. Conclusion

[19] The contribution of wind, conductivity, and geomagnetic main field to the variation in the geomagnetic *Sq* field was examined by using *Sq*(Y) and an IRI model. The main results are summarized as follows.

[20] 1. *Sq*(Y) is strongly controlled by solar activity and reflects the characteristics of each solar cycle.

[21] 2. The solar activity dependence is caused almost completely by the solar activity control of the ionospheric conductivity, and the dynamo electric fields and neutral winds tend to decrease when the solar activity increases.

[22] 3. The dynamo electric field decreased at observatories where the main field clearly decreased. However, the variation is due to the main field rather than the neutral wind.

[23] 4. On the other hand, *Sq*(Y) did not increase significantly at observatories where the main field intensity decreased.

[24] 5. No clear long-term variation in neutral wind was detected other than that by solar activity.

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