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Geomagnetic Field Variations during Solar Eclipses and the Geographic Location of Observing Sites

Jung-Hee Kim[1,2] and Heon-Young Chang[1,2]
[1]Department of Astronomy and Atmospheric Sciences, Kyungpook National University, Bukgu, Daegu 41566, Korea
[2]Research and Training Team for Future Creative Astrophysicists and Cosmologists (BK21 Plus Program), Korea
hyc@knu.ac.kr

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Abstract: We examine whether the solar eclipse effect is dependent on the geographic conditions under which the geomagnetic field variations are recorded. We concentrate our attention on the dependence of the solar eclipse effect on a number of factors, including, the magnitude of a solar eclipse (defined as the fraction of the angular diameter of the Sun being eclipsed), the magnetic latitude of the observatory, the duration of the observed solar eclipse at the given geomagnetic observatory, and the location of the geomagnetic observatory in the path of the Moon's shadow. We analyze an average of the 207 geomagnetic field variation data sets observed by 100 INTERMAGNET geomagnetic nodes, during the period from 1991 to 2016. As a result, it is demonstrated that (1) the solar eclipse effect on the geomagnetic field, i.e., an increase in the Y component and decreases in the X, Z and F componenets, becomes more distinct as the magnitude of solar eclipse increases, (2) the solar eclipse effect is most conspicuous when the modulus of the magnetic latitude is between 30° and 50°, (3) the more slowly Moon's shadow passes the geomagnetic observatory, the more clear the solar eclipse effect, (4) the geomagnetic observatory located in the latter half of the path of Moon's shadow with respect to the position of the greatest eclipse is likely to observe a more clear signal. Finally, we conclude by stressing the importance of our findings.

Key words: solar–terrestrial relations — eclipses — methods: data analysis

1. Introduction

When a solar eclipse occurs, the atmosphere of the Earth, at all altitudes from the surface to the upper ionosphere, is apt to experience transient changes within a shorter time-scale than the customary day-night period. The diminishing amount of solar radiation reaching the Earth due to Moon's silhouette results in a decline in the temperature of the Earth's surface layer. The pattern and precise amount of the decline is subject to many factors, including the time of day, local climate, and the meteorological properties of the observing site (Anderson 1999; Ahrens et al. 2001; Szalowski 2002; Eckermann et al. 2007; Gerasopoulos et al. 2008). It has also been established that the level of ionization in the Earth's ionosphere decreases due to the blocking of solar ionizing radiation, and the ionosphere subsequently reconfigures itself into night time-like state during the solar eclipse event (Cohen 1984; Tsai & Liu 1999; Afraimovich et al. 2002; Sridharan et al. 2002; Baran et al. 2003; Chandra et al. 2007; Jakowski et al. 2008; Sharma et al. 2010; Singh et al. 2011; Kumar & Singh 2012; Le et al. 2008, 2009; Ding et al. 2010; Yadav et al. 2013; Phanikumar et al. 2014; Pezzopane et al. 2015).

Disturbances in the geomagnetic field are subsequently expected, since the pattern of electric currents in the ionosphere is disrupted during the solar eclipse. This is because the conductivity in its region is abruptly modified. According to even a simple theory (Chapman & Bartels 1940), the perturbation in the lower ionospheric current system is detectable, as modification to the geomagnetic field at ground level in tens nT. Indeed, the effect of a solar eclipse upon the geomagnetic field has been detected, for example, as an increase in the Y component of the geomagnetic field, and a drop in the X component during the 11 August 1999 total solar eclipse (Malin et al. 2000; Strestik 2001; Özcan & Aydoğdu 2004; Curto et al. 2006). Generally speaking, the change in tendency and magnitude in the response of the geomagnetic field to an individual solar eclipse is diverse (Adushkin et al. 2007; Momani et al. 2010; Ates et al. 2011, 2015; Ladynin et al. 2011; Babakhanov et al. 2013; Onovughe 2013). This is not only because the regular geomagnetic daily variation shows large day-to-day variability depending on the solar cycle phase but also because disturbances in the ionospheric conditions, and geomagnetic field, depend on various geophysical or even geographic conditions, such as, time of the day, day of the year, and the relative location of observing site with respect to the position of the shadow (Baran et al. 2003; Afraimovich et al. 2007; Jakowski et al. 2008; Le et al. 2009; Ding et al. 2010; Wang et al. 2010; Vyas & Sunda 2012; Unnikrishnan & Richards 2014; Chen et al. 2015; Hoque et al. 2016).

Recently, Kim & Chang (2018) have statistically confirmed that a solar eclipse event affects the *pattern* of the geomagnetic field variations, by investigating an

Corresponding author: H.-Y. Chang

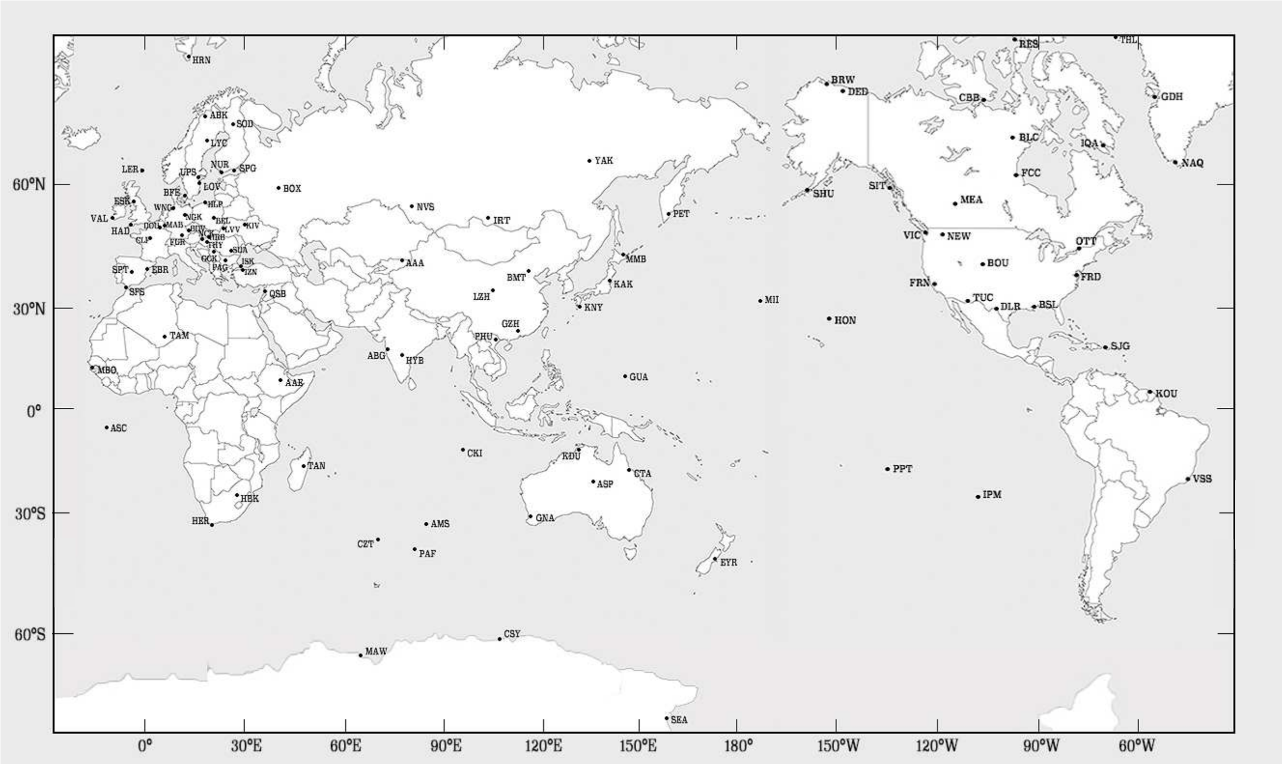

Figure 1. World map with locations of the INTERMAGNET geomagnetic observatories from which the geomagnetic data for the present analysis have been extracted.

average of 207 geomagnetic field variation data observed by 100 INTERMAGNET geomagnetic nodes. Theses measurements wee taken when the Moon's shadow proceeded over geomagnetic observatories on the day of the solar eclipse. The authors have carried out a thurther statistical analysis, by dividing the whole data set into subsets based on the geomagnetic field activity, solar activity, the gamma of the solar eclipse. This was done to see if the effect of a solar eclipse shows any dependence on various aspects of a solar eclipse event, such as, magnetic characteristics of the day when solar eclipses occur. When efforts are centered on a single solar eclipse, or on an individual observation of the geomagnetic field, such as in a case study, it is difficult to recognize the dependence of solar eclipse effects on various geographic conditions, and on solar-/geo-magnetic activities, which play their roles simultaneously. The uthors have demonstrated that the solar eclipse effect on the geomagnetic field is clearest when the day of solar eclipse is geomagnetically calm. That is, when the Ap index is approximately less than 7, an increase of the Y and a decrease in the X components and total strength of the geomagnetic field F can be observed. According to their findings, the effect of a solar eclipse on the observed geomagnetic field variation depends less sensitively on the level of solar activity and the phase of solar cycle than on the level of daily geomagnetic perturbations, even though the solar eclipse effect appears to have some smaller dependence on both the phase of the solar cycle, and on the level of solar activity. They have also found that the solar eclipse effect is apparent when $|\gamma| > 0.3$, where γ represents the distance from the center of the projected Earth as a fraction of the equatorial radius of the Earth, and characterizes how closely the shadow of the Moon passes over the center of the terrestrial globe.

Here, we further examine whether the observed geomagnetic field variation during a solar eclipse is affected by the geographic conditions of the observing site, in addition to the astronomical and/or geophysical circumstances under which a solar eclipse occurs. In this paper we focus on the geographic point of view, instead of the geophysical. In other words, unlike the earlier study Kim & Chang (2018), in which the solar eclipse effect is examined in terms of *when*, we focus our interest on attributes, such as, the distance from the path of totality to the observing site, the magnetic latitude of the observing site, the duration of the observed solar eclipse at the observatory, and the location of the geomagnetic observatory in the path of Moon's shadow with respect to the position of greatest eclipse. To achieve this goal we take a similar approach to Kim & Chang (2018) in which the effect of the solar eclipse on the pattern of the geomagnetic field variation is analyzed by comparing an average of subsets divided by the astronomical circumstances under which solar eclipses occur.

This paper is organized as follows. We briefly describe the procedures by which we have obtained the geomagnetic field data in Section 2. We present and

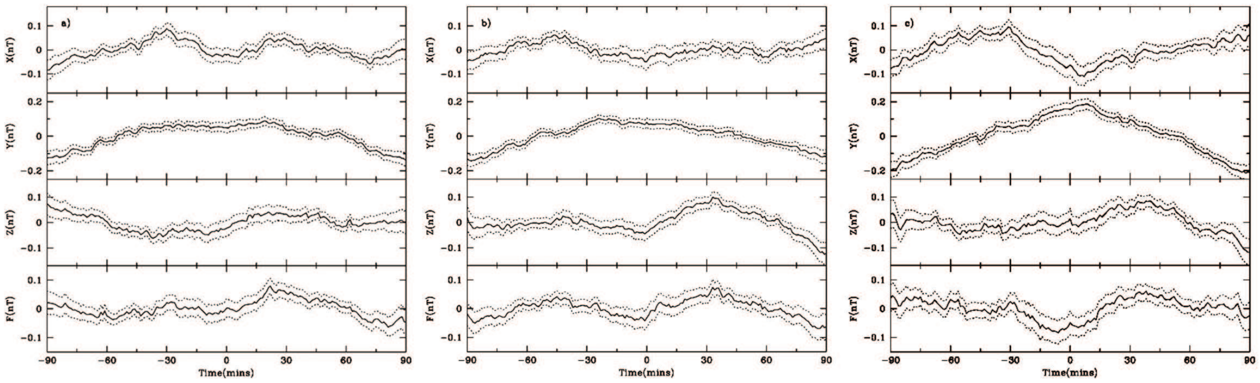

Figure 2. Variations of X, Y, Z components of the geomagnetic field, and the total strength of the geomagnetic field, F, are shown from top to bottom, respectively. The abscissa represents time in minutes, centered at the time of maximum eclipse. Continuous and dotted curves denote the average of 207 geomagnetic field variation data series, and the envelopes of $\pm$ 1 σ, respectively. Plots result from: (a) data sets where the magnitude of the solar eclipse is between 0.7 and 0.8, (b) data sets where the magnitude of the solar eclipse is between 0.8 and 0.9, (c) data sets whose solar eclipse magnitude is greater than 0.9. Note that magnitude of eclipse is given by the fraction of the angular diameter of the Sun being eclipsed. Three data sets contain 78, 78, and 51 geomagnetic field variation data, respectively.

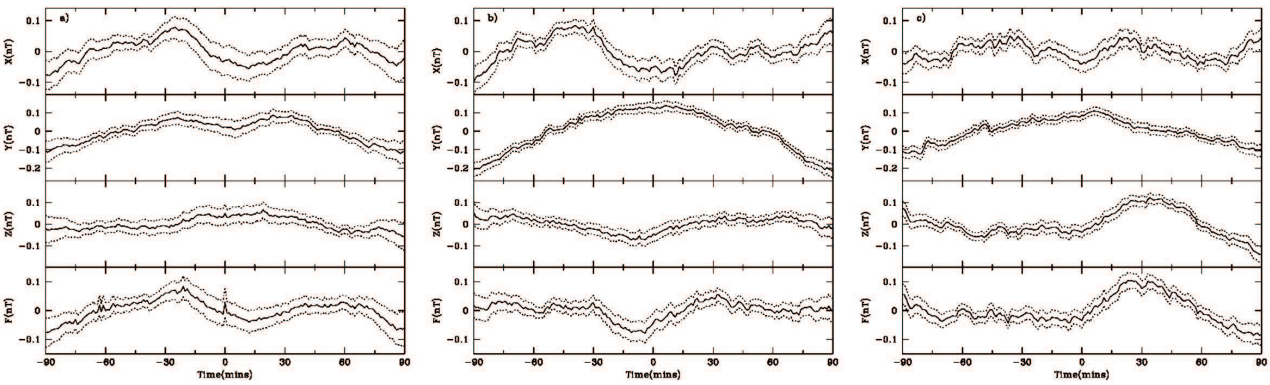

Figure 3. Similar results as in Figure 2. Plots result from: (a) data sets whose modulus of the magnetic latitude is between 0° and 30°, (b) data sets whose modulus of the magnetic latitude is between 30° and 50°, (c) data sets where the modulus of the magnetic latitude is between 50° and 90°. The geomagnetic longitude and latitude of the geomagnetic observatory is transformed from geographic coordinates using the website of the World Data Center for Geomagnetism. Three data sets contain 49, 76, and 82 geomagnetic field data, respectively.

discuss the results of analyzing the dependence of the solar eclipse effect on an observing site in Section 3. We finally summarize and conclude in Section 4.

2. Data

We have extracted observed geomagnetic field component data from the INTERMAGNET website[1], where the geographic details of 150 geomagnetic observatories from all the world can be found as well as corresponding geomagnetic field component data, in almost real time. The INTERMAGNET network was established to initiate a global network of digital geomagnetic observatories to satisfy the modern requirement for measuring and recording the terrestrial magnetic field. The first geomagnetic observatory (Geomagnetic Information Node, GIN) was founded in 1991, and has released data into the public domain ever since.

We assembled a catalog of the geographic coordidates of the location of 150 geomagnetic observatories from the INTERMAGNET website. After that, we compiled details of the local circumstances for all solar eclipses visible from those geomagnetic observatories from January in 1991 to September in 2016 using the JavaScript provided by the NASA website[2]. Theses data include the magnitude of the solar eclipse, the times of the first/fourth contacts, and of the maximum eclipse in universal time. Additionally, the greatest eclipse time in universal time is obtained from the NASA eclipse website[3]. In the end, for each geomag-

[1] http://www.intermagnet.org

[2] https://eclipse.gsfc.nasa.gov/JSEX/JSEX-NA.html

[3] https://eclipse.gsfc.nasa.gov/solar.html

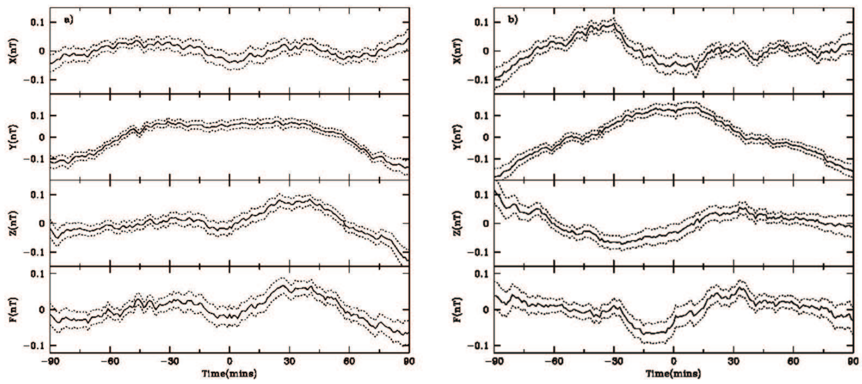

Figure 4. Similar results as in Figure 2. Plots result from: (a) data sets whose duration of a solar eclipse from the first contact to the fourth contact at an observing site is less than or equal to 8500 seconds, (b) data sets whose duration of a solar eclipse is longer than 8500 seconds. The two data sets include 112 and 95 geomagnetic field data, respectively.

netic observatory where solar eclipses with magnitude ≥ 0.7 can be observed, we collected, from the INTERMAGNET website, minute mean values of the 3 geomagnetic components (X, Y, Z), and F, from -90 minutes to +90 minutes, with respect to the universal time (UT) of maximum eclipse at the observatory (Ladynin et al. 2011). Note that the magnitude of solar eclipse is the fraction of the angular diameter of the Sun being eclipsed. Here, X, Y, Z are the X-, Y-, Z-components of the geomagnetic field, respectively, so that the total strength of the geomagnetic field F is computed by $F^2 = X^2 + Y^2 + Z^2$.

As a result, we have 207 geomagnetic time-series recorded by 100 INTERMAGNET geomagnetic nodes at events of the 39 solar eclipse events. These span from the maximum of the solar cycle 22 to the end of the solar cycle 24. In Figure 1, we show the world map with the locations of the 100 INTERMAGNET geomagnetic observatories the geomagnetic data for the present analysis have been extracted. Generally, the time interval of 180 minutes, over which we have analyzed for the current analysis, covers the entire solar eclipse event from the first contact to the fourth contact on an observing site. That is, only 14 out of 207 solar eclipse events last longer than the time interval for the present analysis.

3. Dependence on Geographic Conditions of Observing Site

To study the dependence of the solar eclipse effect upon the geographic conditions under which the geomagnetic field variations are recorded, we compare the *pattern* of the geomagnetic field variations grouped on the basis of various selections. To examine the pattern of the geomagnetic field variations caused by solar eclipses, we have averaged the time series of the geomagnetic field variation in subsets. Before averaging, we have carried out two preprocesses to avoid an instance where the averaged geomagnetic field variations is overwhelmed by one single large variation. First, we detrend slowly varying elements from each time-series of geomagnetic field variation data using a first order polynomial fit, before taking the average. Detrending is expected to remove elements which vary more slowly than those by a solar eclipse. Secondly, we normalize the detrended geomagnetic field variation curve such that the amplitude of the curve from the minimum to the maximum is equal to unity over each 180-minute-long data string. By doing these cumbersome operations, we are able to average the underlying shape of the geomagnetic field variation curve induced by solar eclipses. That is, if we assume that the observed geomagnetic field variations are due to random fluctuations, one would expect that if we take an average of the detrended curves all the crests and troughs would disappear and leave no features.

In Figure 2, we show the results from three datasets, divided in terms of the magnitude of the solar eclipse. That is, Figures 2a, b, and c result from datasets where the magnitude of the solar eclipse is between 0.7 and 0.8, 0.8 and 0.9, and greater than 0.9, respectively. Plots are due to the geomagnetic field variations recorded on the day of solar eclipse occurring from January in 1991 to September in 2016. In each of Figures 2a, b, and c, variations in the X, Y, Z components of the geomagnetic field and the total strength of the geomagnetic field F are presented from top to bottom, respectively. The abscissa represents time in minute, setting the time of maximum eclipse on the site of the geomagnetic observatory to zero. As mentioned in the last section, the time interval we are analyzing covers the duration of a solar eclipse from the first contact to the fourth contact at a given observing site. The continuous and dotted curves represent the average, which is obtained by the procedure we have described in the last paragraph, and envelopes of $\pm$ 1 σ, respectively. The three data sets contain 78, 78, and 51 geomagnetic field series, respectively. Decreases in X, Z and F, and an increase in Y, can be seen commonly regarded as the solar eclipse effect. In comparison, Figures 2a, b, and c obviously demonstrate that the pattern of the variations of X, Y and F due to solar eclipses becomes more distinct as the magnitude of solar eclipse increases, though that of Z appears rather insensitive. We checked

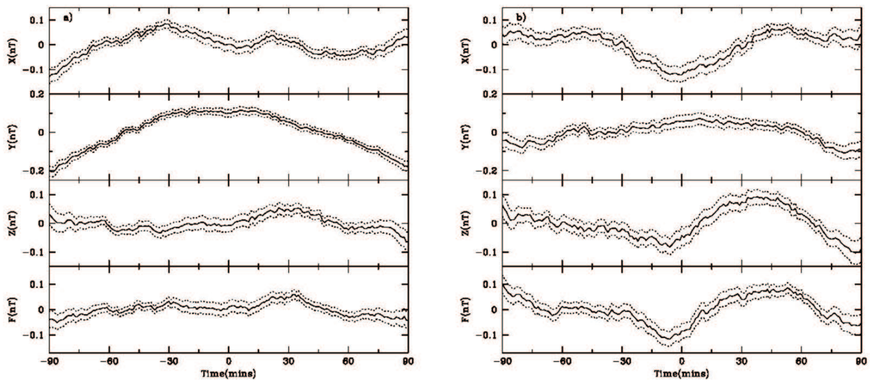

Figure 5. Similar results as in Figure 2. Plots result from: (a) data sets whose location of the geomagnetic observatory belongs to the first half (dawn side) of the path of shadow with respect to the position of the greatest eclipse, (b) data sets whose location of the geomagnetic observatory belongs to the second half (dusk side). Two data sets include 133 and 74 geomagnetic field data, respectively.

the mean values of the recorded Ap indices[4], to see if the observed dependence is due to the level of geomagnetic perturbations, since geomagnetic occurrences are suggested to override the solar eclipse effect (Kim & Chang 2018). It turns out that the mean values of the Ap indices, corresponding to the data sets resulting in Figures 2a, b, and c are 11.3, 12.7, and 10.7, respectively. This suggests that the level of disturbance in the geomagnetic field, on average, is more or less same for the three data sets. Hence, we conclude that the effect of solar eclipses is subject to the magnitude and that the obvious dependence of the solar eclipse effect is unlikely due to significant geomagnetic disturbances.

In Figure 3, we show plots similar to Figure 2. We divide the geomagnetic field variation data into three subsets based on the absolute value of the magnetic latitude. In other words, Figures 3a, b, and c result from data where the modulus of the magnetic latitude is between 0° and 30°, 30° and 50°, and 50° and 90°, respectively. We have transformed the geographic longitude and latitude of the geomagnetic observatory to the geomagnetic coordinate using the website[5] of the World Data Center for Geomagnetism (WDC) operated by Kyoto University. The three data sets contain 49, 76, and 82 geomagnetic field variation data series, respectively. Comparing Figures 3a, b, and c, the effect of solar eclipse on the geomagnetic field is the most clear in the case that the modulus of the magnetic latitude is between 30° and 50°. In this range of magnetic latitude, an increase in Y, and decreases in X, Z and F are clear. We conclude, therefore, that the dependence of the solar eclipse effect on the magnetic latitude is not monotonous. This could happen when two driving mechanisms work in opposite directions to compensate for each other as the magnetic latitude increases or decreases. Alternatively, this feature might be related to an electrojet system around the E region of the Earth's ionosphere. Two main electrojets travel near the northern and southern polar circles, which is called the Auroral electrojet, and a third liesat the magnetic dip equator, which are called the Equatorial electrojet. Since the electrojets result from the large conductivity and strong horizontal electric field in the ionosphere in particular latitudinal bands, one may suspect that the solar eclipse effect is enhanced where the conductivity is low and/or the horizontal electric field in the ionosphere is weak. Furthermore, the solar eclipse effect is depressed in higher and lower latitudes where the conductivity is high. To make sure that it is not due to geomagnetic activities, we checked again the mean values of the Ap indices corresponding to the data sets resulting in Figures 3a, b, and c, which are 11.2, 11.4, and 12.2, respectively. Again, the noticed dependence of the solar eclipse effect is very much unlikely due to significant geomagnetic disturbances.

In Figure 4, we show results from two subsets where the interval of a solar eclipse from the first contact to the fourth contact on an observing site is shorter than or equal to 8500 seconds, or longer than 8500 seconds. The two data sets contain 112 and 95 geomagnetic field variation data series, respectively. As we mentioned in the Data section, the time interval of 180 minutes covers the duration of most solar eclipses from the first contact to the fourth contact at an observing site. The median of the durations of the 207 solar eclipse events we are analyzed is roughly equal to 8500 seconds. These are to be physically justified in later investigations. An increase in Y and decreases in F can be seen in Figure 4a, although a hint of a decrease in X and Z may also be apparent. On the other hand, an increase in the Y component, and decreases in X, Z and F are obvious in Figure 4b, which results from the subset where the duration is longer than 8500 seconds. That is, the more slowly the Moon's shadow passes the geomagnetic observatory, the more clearly the solar eclipse effect can be seen. The mean values of the Ap indices corresponding to the data sets resulting in Figures 4a and b are 13.5 and 9.6, respectively. Hence, our final conclusion

[4] http://wdc.kugi.kyoto-u.ac.jp/kp/index.html
[5] http://wdc.kugi.kyoto-u.ac.jp/igrf/gggm/index.html

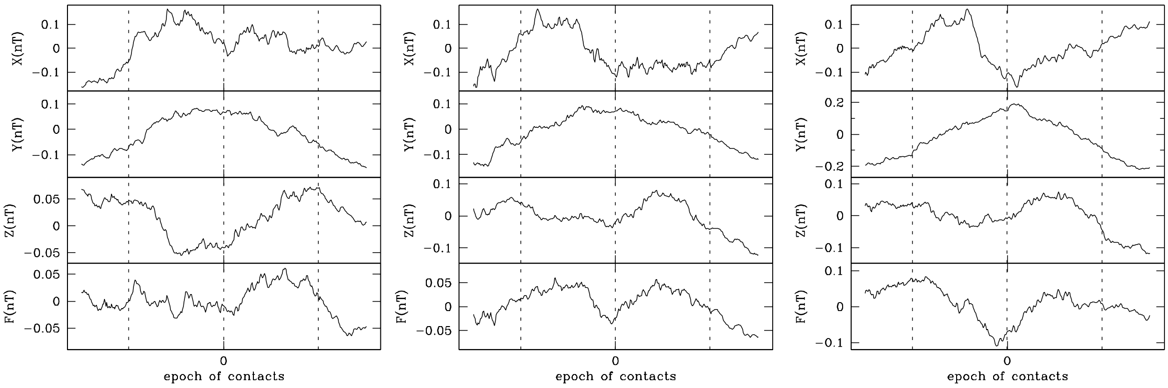

Figure 6. Similar to Figure 2, except that before averaging individual time-series of the observed geomagnetic field components the horizontal axis is stretched such that times of the first contact and the fourth contacts match up, respectively. Three vertical dashed lines denote times of the first contact, maximum eclipse and the fourth contact from the left, respectively.

on the effect of the duration of a solar eclipse should be drawn with due care.

It should be stressed that duration is not solely related to the the magnitude of the solar eclipses since a scatter plot of the duration and the magnitude of solar eclipses shows that they are totally uncorrelated in our data sample. The positions of the Earth or the Moon in their respective orbits are most crucial parameters, for determining the duration and magnitude of a solar eclipse, since the apparent angular size of the Sun and the Moon depends on the distance from the Earth (see, for details, Meeus (2003)). For example, when the Moon is at perigee, and the Earth is at aphelion, the angular diameters of the Moon and the Sun are largest and smallest, respectively. When these conditions are satisfied the duration become maximized. The position of the midpoint of a solar eclipse on the Earth surface is also important. That is, the duration can be different depending on whether the midpoint of a solar eclipse is close to the equator, and/or on whether the eclipse path proceeds diagonally or parallel to equator. Bearing this mechanism in mind, one may wish to figure out which solar eclipses would have been the most influential to the geomagnetic field change.

In Figure 5, we show results from two data sets divided by whether the observing site locates in the first half (dawn side) or in the second half (dusk side) of the path of Moon's umbra with respect to the position of greatest eclipse. Thus, in some sense, it reflects a dependence of the solar eclipse effect on the local time when solar eclipse is observed at a given geomagnetic observatory. The two data sets contain 133 and 74 geomagnetic field data, respectively. Though, an increase in Y is seen from Figure 5a, expected features in other components X, Z, F are ambiguous. However, decreases in the X, Z components, and F, are all evident in Figure 5b, while an increase in Y less distinct. It is noted that the mean values of the Ap indices are 11.9 and 11.3 for the data sets resulting in Figures 5a and b, respectively. Hence, based on this, one would expect that the solar eclipse effect would become stronger as Moon's shadow crosses the Earth's surface. We conclude that the geomagnetic observatory located in the latter half of the path of Moon's umbra with respect to the position of the greatest eclipse, or at the dusk side, is likely to observe a more clear signal.

In some published papers the geomagnetic field variation is plotted in time with marks for the first contact and so on. Particularly, when the total solar eclipse, where some of observed geomagnetic fields appear to vary with the phase of the solar eclipse event, times of contacts may provide a guideline to see a clearer trend as they play a role of phase in some sense. On the other hand, studies of partial solar eclipses do not provide contact times, since the first and fourth contacts are the only ones defined among the 4 contact times by definition of a partial solar eclipse. Also, the times of contact are asymmetrical with respect to the time of maximum eclipse, since a solar eclipse occurs on a surface of the sphere. In other words, although one fixes the second and third contact times and stretches the time axis like a rubber band, the remaining contact times, and the time of maximum eclipse, cannot be automatically set. For instance, the times of the first and second contacts are not exactly same with third and fourth contacts in most of cases, nor is the time between the second contact and the time of maximum eclipse the same as the time between the third contact and the time of maximum eclipse. In this sense, strictly speaking, the times of the different contacts cannot be used as a *phase*. Notwithstanding, we attempt to find an average by dividing the time-series of the observed geomagnetic field variation curves into 3 intervals and interpolate the curves interval by interval, so that the curve is quasi-uniform. For comparison, we provide Figures 6 to 9, which correspond to Figures 2 to 5, respectively. It should be noted that before averaging individual time-series of the observed geomagnetic field components the horizontal time axis is stretched such that the times of the first contact and the fourth contacts match up. In Figures 6 to 9, the three vertical dashed lines denote times of the first contact, maximum eclipse and the fourth contact from left to right. The results are similar to what we originally obtained.

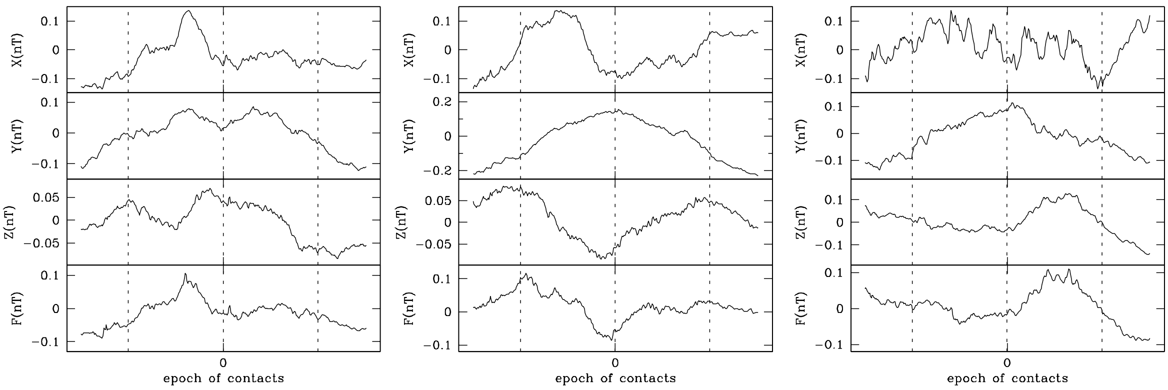

Figure 7. Similar to Figure 3, except that plots are generated in a same manner as in Figure 6.

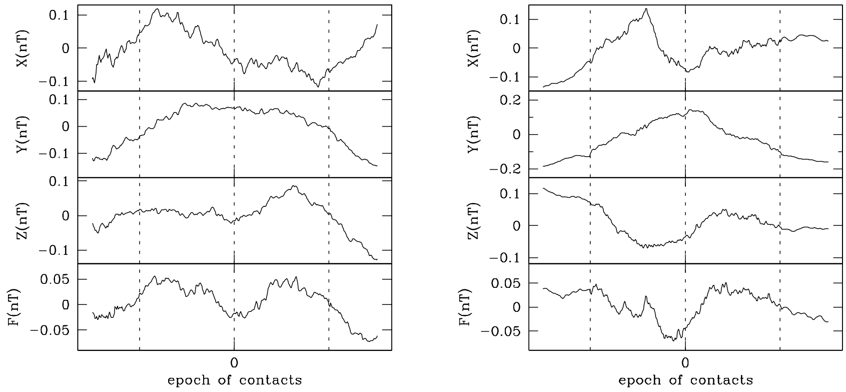

Figure 8. Similar to Figure 4, except that plots are generated in a same manner explained as in Figure 6.

4. Summary and Conclusion

The observed effects of a solar eclipse on the geomagnetic field components at ground levels depend on various geophysical conditions. For instance, Kim & Chang (2018) demonstrated that effect of a solar effect on the geomagnetic field is evident when the day of solar eclipse is geomagnetically calm. They further showed that the solar eclipse effect on the observed geomagnetic field variation depends less sensitively on the solar activity, and the phase of solar cycle, than on the level of daily geomagnetic events.

In this paper we have examined whether the solar eclipse effect shows any dependence on the geographic environment under which the geomagnetic field variations during solar eclipse are recorded. We have, in particular, focused our interest on attributes, such as, the magnitude of solar eclipse, the magnetic latitude of the observing site, the interval of the observed solar eclipse at a given geomagnetic observatory, and the location of the geomagnetic observatory in the path of Moon's umbra with respect to the greatest eclipse. After detrending and normalizing, we have averaged the geomagnetic field variations grouped on the basis of selection criteria, and compared underlying patterns. For the current analysis, 207 geomagnetic field variation series recorded by 100 INTERMAGNET geomagnetic nodes for the 39 solar eclipse events during the period from January in 1991 to September in 2016 are examined.

Our findings are as follows:

(1) According to the comparison of the patterns of the variation of X, Y, Z and F due to the solar eclipses, solar eclipse effect, namely, an increase in Y and decreases in X, Z and F, becomes more distinct as the magnitude of solar eclipse increases.

(2) Comparing results from the three data sets divided on the basis of magnetic latitude, the solar eclipse effect on the geomagnetic field is most evident in the case where the modulus of the magnetic latitude is between 30° and 50°. That is, the dependence of the effect of a solar eclipse upon the magnetic latitude is unlikely to be monotonous, which results from two driving mechanisms that work in opposite directions and act against each other.

(3) It is also found that the more slowly the Moon's shadow passes the geomagnetic observatory, the more conspicuously the solar eclipse effect can be observed. According to the mean values of the Ap indices corresponding to our data sets, however, our final conclusion should be drawn with due care.

(4) As a result of analyzing the two data sets divided by whether the observing site is located in the first half (dawn side) or in the second half(dusk side) of the path of Moon's umbra with respect to the position of the greatest eclipse, we have found that the geomagnetic observatory located in the dusk side, is likely to observe a clearer signal.

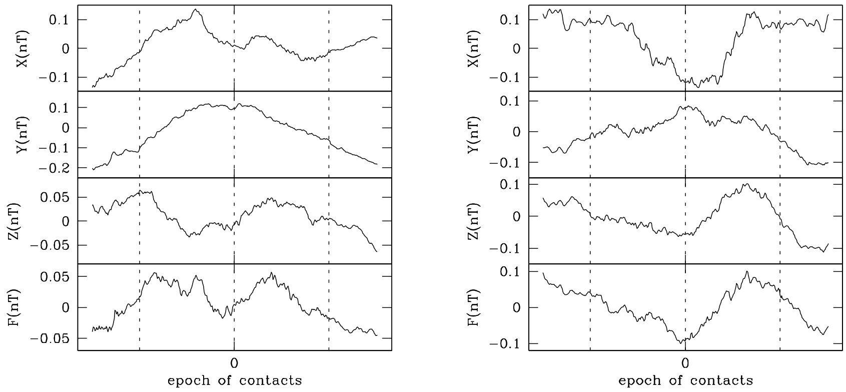

Figure 9. Similar to Figure 5, except that plots are generated in a same manner explained as in Figure 6.

We conclude by briefly discussing the importance of what we have found. The blocking of solar ionizing radiation by the Moon causes drops in the electron density in E and F1 layers of the ionosphere. This decrease may subsequently cause deformations in the current systems in the region. The resulting variations in the geomagnetic field can be obtained via model calculations (Malin et al. 2000; Hvoždara & Prigancová 2002; Özcan & Aydoğdu 2004), which agree with the observed features, i.e., an increase in Y, the decreases in the X and Z and total strength F of the geomagnetic field. However, further exploration is required because the exact pattern and amount of anomaly are dependent upon many factors, yet to be included in a theoretical calculation. In this regard, one would like to identify the most critical factors in reproducing the recorded geomagnetic field variation curve. By a similar approach to the analysis presented in this paper, one may single out crucial factors affecting the solar eclipse impact on the geomagnetic field. It is admitted, of course, that the averaging process employed here should be expanded upond by utilizing a proper weight function. Our findings evidently provide a first step in figuring out which parameters need to be incorporated into a weight function unlike most of previous studies in which efforts are concentrated on a single solar eclipse or on an individual observation of the geomagnetic field.

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