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Statistical analysis of geomagnetic field variations during solar eclipses

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Abstract

We investigate the geomagnetic field variations recorded by INTERMAGNET geomagnetic observatories, which are observed while the Moon's umbra or penumbra passed over them during a solar eclipse event. Though it is generally considered that the geomagnetic field can be modulated during solar eclipses, the effect of the solar eclipse on the observed geomagnetic field has proved subtle to be detected. Instead of exploring the geomagnetic field as a case study, we analyze 207 geomagnetic manifestations acquired by 100 geomagnetic observatories during 39 solar eclipses occurring from 1991 to 2016. As a result of examining a pattern of the geomagnetic field variation on average, we confirm that the effect can be seen over an interval of 180 min centered at the time of maximum eclipse on a site of a geomagnetic observatory. That is, demonstrate an increase in the Y component of the geomagnetic field and decreases in the X component and the total strength of the geomagnetic field. We also find that the effect can be overwhelmed, depending more sensitively on the level of daily geomagnetic events than on the level of solar activity and/or the phase of solar cycle. We have demonstrated it by dividing the whole data set into subsets based on parameters of the geomagnetic field, solar activity, and solar eclipses. It is suggested, therefore, that an evidence of the solar eclipse effect can be revealed even at the solar maximum, as long as the day of the solar eclipse is magnetically quiet.

Keywords: Solar eclipse; Geomagnetic field; Data analysis

1. Introduction

During the solar eclipse, solar radiation to the Earth is obscured by the Moon. The solar eclipse subsequently causes intricate changes in the atmosphere of the Earth, which occur at all heights from the surface layer to the upper ionosphere and even into the plasmasphere. For instance, it is well known that the loss of radiative energy due to the solar eclipse leads to a decline of air temperature in the Earth's surface layer (e.g., Anderson, 1999). Furthermore, the abatement in the solar ionizing radiation reaching the ionosphere of the Earth due to Moon's shadow results in diminished production of charged particles (e.g., Baran et al., 2003). In fact, since such phenomena provide insight into the nature of the ionosphere and of perturbation processes related to the solar influence, geophysical effects accompanying the solar eclipse have been a theme of extensive research on meteorological parameters (Anderson et al., 1972), boundary layer physics (Antonia et al., 1979), photochemistry (Srivastava et al., 1982; Zanis et al., 2007), total columnar ozone (Chakrabarty et al., 1997; Zerefos et al., 2000), gravity wave (Chimonas and Hines, 1970; Fritts and Luo, 1993; Altadill et al., 2001, 2004; Zerefos et al., 2007; Gerasopoulos et al., 2008; Manju et al., 2014; Chen et al., 2015), and ionospheric parameters (Chernogor, 2010a,b, 2012a,b, 2013a, b, 2016; Klobuchar and Whitney, 1965; Salah et al.,

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1986; Afraimovich et al., 1998, 2002; Tsai and Liu, 1999; Davis et al., 2001; Sridharan et al., 2002; Akimov et al., 2005; Farges et al., 2003; Grigorenko et al., 2003, 2008; Chandra et al., 2007; Jakowski et al., 2008; Krankowski et al., 2008; Le et al., 2008, 2009; Ding et al., 2010; Momani and Sulaiman, 2011; Singh et al., 2011; Kumar and Singh, 2012; Burmaka and Chernogor, 2013; Lyashenko and Chernogor, 2013; Domnin et al., 2013; Kumar et al., 2013; Yadav et al., 2013; Domnin et al., 2014; Chernogor and Garmash, 2017).

It is generally recognized that the geomagnetic field variations are induced by ionospheric disturbances during solar eclipses. It can be simply explained by a straightforward mathematical model (e.g., Chapman and Bartels, 1940; Parkinson, 1983; Campbell, 1989; Curto et al., 2006). Solar heating and ionization radiation shielded by the Moon could cause a reduction in electron content in the ionosphere and accordingly reduce the conductivity in its region affecting dynamical processes in layers of the ionosphere. This adjustment happens within a shorter range of time than the usual day-night period, i.e., about a couple of hours (Maji et al., 2017). It is thus expected that the current pattern in this region would be modified and that this might be detectable as disturbances to the geomagnetic field of tens nT at ground level. Interestingly, Strestík (2001) noted an increase of 10 nT in the Y component of the geomagnetic field and a decrease in the X component of 5 nT during the 11 August 1999 total solar eclipse. Ladynin et al. (2011) also reported some eclipse effects in the geomagnetic field at two places near totality path during the 1 August 2008 solar eclipse. On the other hand, such a report is not yet unanimously accepted. For instance, Özcan and Aydoğdu (2004) analyzed the 11 August 1999 total solar eclipse over Turkey and found a reduction of 20–40% in the ionospheric electron density and an increase in the Y component of the geomagnetic field, yet no significant effect in the X component of the geomagnetic field. Korte et al. (2001) even disclaimed any eclipse-related magnetic variation in Europe during the 11 August 1999 solar eclipse.

Contemplating the present state, therefore, it is fair to say that in practice the effect has proved very difficult to be detected by observation of a single event and that the problem of impacts on the geomagnetic field during solar eclipses still remains open. A reason for this current confusing situation, despite a number of studies concerning the influence of solar eclipses on the geomagnetic field, is partly because precise amount of effects of the solar eclipse on the geomagnetic field depend on various factors, such as, day of the year, time of the day, location of observing site, geophysical conditions, and et cetera (e.g., Baran et al., 2003; Kim and Chang, 2018). That is, the event itself is the outcome of complicated dependence which is hardly reproducible. Another reason is partly because it is very hard to incorporate a realistic model for the eclipse effect accommodating fairly various conditions of the solar eclipse mentioned just above. Though one might be tempted to naively think that eclipse conditions can be considered the same as night conditions, the decay rate of the ionosphere cannot be same since the Moon's umbra cast upon the Earth is very small compared with the dimension of the Earth. Hence, the compensating effect of the ionization coming from adjacent sunlit regions should be taken into account. Besides, the observed regular geomagnetic daily variation showing a large day-to-day variability even in magnetically undisturbed conditions is a sum of magnetic fields both internal and external over a larger area than the Moon's shadow, which tends to dilute any local effects due to the solar eclipse (Malin et al., 2000). The third, but not least, reason is partly because examining a cryptic signal out of noisy background cannot be settled with a case study but rather demands by nature a sort of statistical analysis. Until now, most of previous efforts are mainly focused on a certain observation of the geomagnetic field during a particular solar eclipse as a case study. A main drawback in this type of approach is that, as mentioned above, since an event of the solar eclipse is almost unique ensuing under different synoptic conditions an observed effect could be only a random realization of a possible underlying effect resulting from a fundamental process.

Here, we investigate as an ensemble average the geomagnetic field variations observed by INTERMAGNET geomagnetic observatories when the Moon's umbra or penumbra passed over them on a day of the solar eclipse. That is, we study the geomagnetic field modulations observed by geomagnetic observatories during the period from 1991 to 2016, resulting from the solar eclipses whose magnitude is greater than 0.7 at the site of geomagnetic observatories. The main goals of the present contribution are twofold. Firstly, unlike most of previous studies in which efforts are focused on an individual solar eclipse or on a single observation of the geomagnetic field as a case study, we analyze as a whole results acquired by 100 geomagnetic observatories. As a result, we can afford to statistically demonstrate that the solar eclipse does affect the geomagnetic field. Secondly, we also carry out probes by dividing the data set into 2 or 3 subsets on the basis of parameters of the geomagnetic field, solar activity, and solar eclipses to see whether the effect of the solar eclipse shows any dependence on circumstances under which solar eclipses occur. In this contribution, we concentrate our focus on the solar eclipse itself in that we select criteria for subsampling in terms of parameters representing the geomagnetic field and solar activity, and gamma value. Here, gamma of the solar eclipse γ is defined by the distance from the center as a fraction of the equatorial radius of the Earth describing how centrally the umbra of the Moon passes over the terrestrial globe. The positive (negative) sign of gamma value implies that the axis of the shadow passes north (south) of the center of the Earth. Effects of other attributes, for example, such as a location of the observing site, would be discussed in elsewhere (e.g., Kim and Chang, 2018).

This paper is organized as follows. We begin with brief descriptions of data analyzed for the present paper and

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