Check for
updates

Geomagnetic Field Processes and Their Implications for Space Weather

Mioara Mandea[1] · Aude Chambodut[2]

Abstract

Understanding the magnetic environment of our planet and the geomagnetic field changes in time and space is a very important issue for assessing the Sun–Earth interactions. All changes in solar activity impact the delicate balance between influences of interplanetary magnetic field and of geomagnetic field. The most dynamic events eventually result in disturbances in the magnitude and direction of the Earth's magnetic field and therefore impact our planet and its magnetosphere as a whole. The dynamics of the ionosphere and thermosphere during magnetic storms and substorms involves the heating, expansion, and composition changes at high latitudes, but also the surface-level response in terms of geomagnetically induced currents and other geomagnetic and geoelectric disturbances. Here, we provide a short overview of the current knowledge of the Earth's magnetic field, its present shape and the way it responds to external forces. The main aim of the paper is not to present the complexity of the space weather processes, but rather to bring the attention of the geohazard community to the possible dramatic effects of space weather events. For this, the paper highlights some societal implications of space weather on our increasingly technology-dependent society, including some possible effects of geomagnetically induced currents, the disruption of satellite communications and navigation, and risks of radiation damage both in space and in aviation.

Keywords Geomagnetic field · Space weather · Geoeffectivity · Geomagnetic risks · Hazards

1 Introduction

A decade ago, the Eyjafjallajökull Icelandic volcano eruption (April 2010) and the resulting ash cloud demonstrated that the whole world can suffer as a consequence of natural events. One year after this event, the Tohoko Japanese earthquake and the related tsunami (March 2011) showed just how devastating a natural event could be. Another year later, a

✉ Mioara Mandea
mioara.mandea@cnes.fr

[1] CNES - Centre National d'Etudes Spatiales, 2 Place Maurice Quentin, 75039 Paris, France

[2] Institut de Physique du Globe de Strasbourg, UMR 7516, Université de Strasbourg/EOST, CNRS, 5 rue René Descartes, 67084 Strasbourg Cedex, France

solar active region gave rise to a powerful coronal mass ejection (July 2012), with an initial speed of some 2500 ± 500 km s^{-1} (Baker et al. 2013). The solar eruption was directed away from Earth, but what would have happened if this powerful event had been Earthward directed? To answer such a question we need first to better understand the Sun–Earth magnetic environment, but also the intrinsic structure and variations of the core magnetic field.

Space weather is a very complex concept and involves variations in the Sun, solar wind, magnetosphere, ionosphere, and thermosphere. Like the terrestrial weather, space weather is pervasive and its understanding is a challenge. Indeed, for space weather, as for weather-like variations, there are different types of variations: on some days, space weather is more severe than on others. Slight magnetic storms are rather common events; extremely large ones occur very rarely, perhaps once every century or two (Yokoyama and Kamide 1997; Riley 2012; Moriña et al. 2019). Moreover, space weather exhibits a climatology which varies over timescales ranging from a day to the 11-year solar cycle and even longer (Lockwood 2012).

To understand the Earth's complicated magnetic environment, the origins of the geomagnetic field need to be well known and well described. The Earth's magnetic field has its sources inside the Earth (internal contributions) and outside it (external contributions). The predominant internal source is the core field (also called "main field"), originating in the external fluid core, and the lithospheric field (also called "crustal field"), caused by magnetic minerals in the crust and, to a lesser extent, the upper mantle. The external sources originate in the ionosphere, the magnetosphere and also from electrical currents coupling the ionosphere and magnetosphere (named "field aligned currents", or FAC). These external sources induce secondary fields in the Earth.

An important player in the space weather is the core magnetic field, which acts like a shield to the solar wind that the Sun continually emits. However, currently the core field is changing dramatically (Mandea and Purucker 2018), and we are not yet able to deeply evaluate how these changes can increase or attenuate geoeffectivity, i.e. the ability to generate geomagnetic disturbances and more prolonged geomagnetic storms.

In recent decades, considerable progress has been made in solar physics and in understanding processes operating in the Earth's magnetosphere and ionosphere. The concept of space weather has developed as a scientific discipline and, increasingly, as a need to assess the vulnerabilities and to gauge the resilience of today's infrastructures built by humans on the ground and at satellite altitudes. A crucial requirement of space weather is to understand the magnetic terrestrial environment and to quantify the possibility of predictability of its variations.

To take into consideration these aspects, the remainder of this paper is organised as follows. Section 2 summarises the Earth's magnetic field contributions as measured on recent observational platforms. The following section highlights some particular features of their temporal variations. In Sect. 4, some aspects related to the geomagnetic risks and impacts are given, and finally Sect. 5 draws some conclusions and maps out future directions.

2 The Geomagnetic Field Sources

2.1 Internal Sources

The Earth's magnetic field is a dynamic system and varies on a wide range of timescales from seconds to hundreds of millions of years.
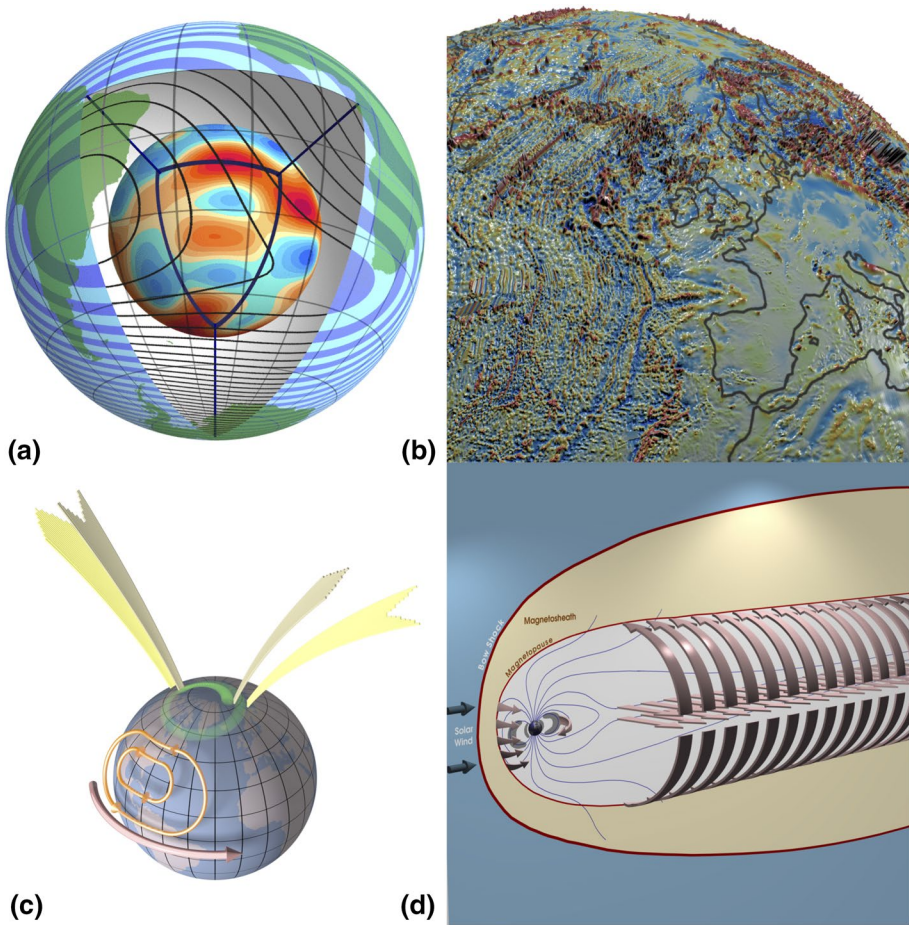
Fig. 1 Sketches of various sources of the geomagnetic field. **a** Contour lines of the dominating core field intensity at Earth's surface and downwards continued (radial field component) to the core-mantle boundary (CMB). The South Atlantic weak field anomaly is seen as a minimum in the intensity at the surface, caused by a large patch or reverse (blue) magnetic flux at the CMB. **b** The lithospheric field caused by magnetised rocks and tectonic structures from the World Digital Magnetic Anomaly Map. In the Atlantic region (left side of panel) the striped normal and reverse magnetic field pattern is seen. **c** The ionospheric Sq (orange) and equatorial electrojet (red) currents, with field aligned currents (yellow) linking high latitude ionospheric currents to the more distant magnetospheric current systems. **d** The magnetosphere shielding our planet against the solar wind, with Chapman-Ferraro currents on the dayside, tail current on the night side and the ring current circling the Earth at a few Earth's radii distance (all in pink). Magnetic field lines are stylised in blue. ©Korte and Mandea (2019)

The internal sources of the geomagnetic field include those originating in the core and lithosphere of the Earth (see Fig. 1a, b).

The core field (Hulot et al. 2015) is dominated by fields generated from a self-sustaining dynamo in the Earth's fluid outer core. This creates around 95% of the magnetic field strength at the Earth's surface. The measured magnetic field averages a strength on the order of 50 μT, varying however between some 20 and 60 μT. The strongest scalar magnetic fields originating from the Earth's core are found in the Earth's polar regions. The

area just offshore Antarctica, in the ocean between Australia and the Antarctic, possesses the largest scalar magnetic fields, averaging 66 µT. The core field exhibits large Earth-fixed spatial scales and varies on timescales of months to millennia (known as the secular variation), even millions of years when reversal processes are considered.

Another internal source is the lithospheric field (Purucker and Whaler 2015), generated in rocks containing minerals carrying the magnetisation and situated below the Curie temperature, generally in the upper 5–30 km of the Earth's surface. Globally, this contribution is much smaller at around 20 nT; however, locally it can be much larger. The lithospheric field covers a wide range of spatial scales that reflect the geological setting of the crust. It changes on timescales of millions of years except at sources such as active metamorphic processes, volcanic regions or along mid-ocean ridges.

2.2 External Sources

The external sources are created by solar-terrestrial interactions and include those originating in the ionosphere, those which couple the magnetosphere and ionosphere, and those associated with more distant regions of the magnetosphere, for example the ring current, the magnetotail and the magnetopause (see Fig. 1c, d). These fields are produced by electric current systems in the ionosphere and magnetosphere. Strong electric currents are also generated and flow down to the ionosphere in the auroral zones where intense east-west currents, named the auroral electrojets, are produced. The magnetic disturbances observed at high latitudes are due to the magnetic fields of these auroral electrojets.

The magnitude of these fields at the surface varies in local time (LT), in space, and in response to solar forcing. The external fields have magnitudes of a few pT to 100 nT on geomagnetically quiet days, but can change rapidly within minutes to thousands of nT, for example from the impact of an interplanetary coronal mass ejection (CME) upon the Earth.

2.3 Recent Observational Platforms

To understand these ranges of spatial and temporal variations, highly accurate and precise measurements of the near-Earth geomagnetic field from space are needed. They began with NASA's MAGSAT satellite which observed for 6 months from 1979 to 1980. This was followed in the first decade of the twenty-first century by the Ørsted[1], CHAMP[2] and SAC-C[3] magnetic field satellites.

Swarm[4], the 3-satellite ESA constellation, is the most recent and most advanced "geomagnetic observatory" in space (Fig. 2). The three satellites were launched on 22 November 2013, with a 4-year nominal mission, after a 3-month commissioning phase. In November 2017, the mission was granted a 4-year extension to 2021.

One of the novelties of the mission is not only the constellation concept, but also the new absolute scalar magnetometer: an optically pumped helium magnetometer which provides absolute scalar measurements of the magnetic field with high accuracy and stability for the calibration of the vector field magnetometer (Leger et al. 2009). The mission

---

[1] http://www.space.dtu.dk/english/Research/Projects/Project-descriptions/Oersted.

[2] http://www.gfz-potsdam.de/champ/.

[3] http://www.space.dtu.dk/english/Research/Scientific_data_and_models/Magnetic_Satellites.

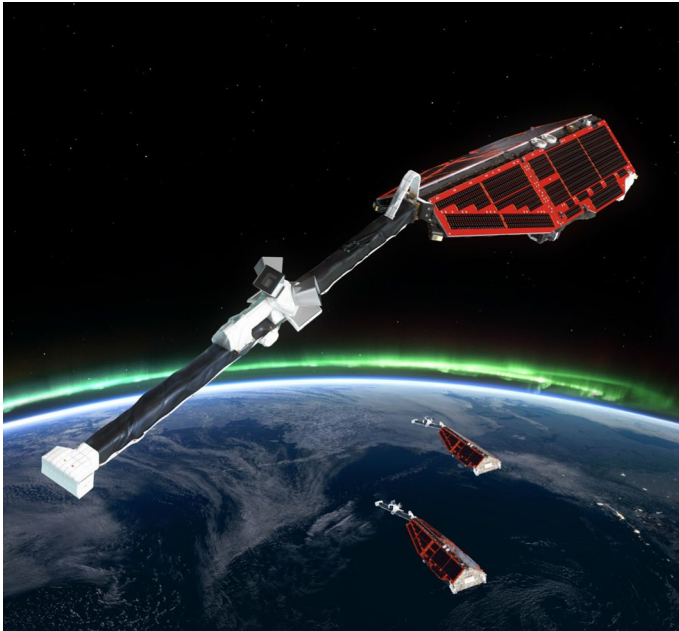[4] https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/swarm.

Fig. 2 The Swarm constellation above polar aurora in progress ©ESA

was designed to derive the first global representation of the geomagnetic field variations on timescales from an hour to several years, addressing the crucial problem of source separation.

Swarm satellites remain at a low altitude, below 500 km, whereas other satellites are at much higher altitudes, up to several tens of Earth radii. These missions have a different scientific purpose as they have the capability of making highly precise and accurate magnetic field measurements directly within the magnetosphere or ionosphere, as Cluster, MMS and RBSP.

Cluster II[5] is an ESA mission launched in 2000 and consists of four satellites free flying in a tetrahedral formation around the Earth. The satellites provide information in three dimensions about how the solar wind affects the magnetosphere. Each satellite has the same set of instruments for measuring the plasma environment around the Earth, including magnetic and electric fields, ions and electrons. The relative positions and distances between satellites can be modified to answer various scientific goals.

As Cluster mission, the Magnetospheric Multiscale Mission (MMS)[6] is a NASA mission to study the Earth's magnetosphere, using four identical spacecraft flying in a tetrahedral formation. As for Cluster's case, by acquiring data simultaneously at multiple points in space, MMS allows scientists to differentiate between spatial variations and temporal evolution of the magnetospheric plasma processes.

The Radiation Belt Storm Probes (RBSP)[7] is a mission of NASA's Living With a Star program. The two spacecrafts are devoted to study the Van Allen radiation belts, providing

---

[5] http://sci.esa.int/cluster/.

[6] https://mms.gsfc.nasa.gov/.

[7] http://www.nasa.gov/mission_pages/rbsp/mission/.

insight into their physical dynamics and inputs to understand changes in this critical region of space.

Measuring the Earth's magnetic field at a wide range of altitudes represents a unique possibility to get a full picture of the field variations, by taking into account the complementary nature of these observational platforms.

3 Magnetic Field Variations

Here, we turn to an important part of this review, dedicated to the magnetic field variations and some of their specific features. The geomagnetic field is in a permanent state of change on timescales from seconds to hundreds of millions of years. The shortest timescales are linked to processes arising in the ionosphere and magnetosphere, and their coupling, and cover the scope of space weather. Temporal variations over timescales of months to decades mostly reflect changes in the Earth's core, and the very long ones, from centuries to millions of years reveal different aspects of core processes and space climate.

In the following, we list the main characteristics of the internal and external magnetic fields temporal variations and the need to consider them for space climate and space weather.

3.1 Core Field Variations

The geometry of the core field directly impacts the geoeffectivity. Moreover, from an operational point of view, some specific features of the secular variation may affect space weather tools and models, as the secular variation coefficients are incorporated as inputs (e.g., the geomagnetic coordinates are calculated from reference field models—such as the International Geomagnetic Reference Field (IGRF)[8]). We thus present in the following relevant internal magnetic field variations.

3.1.1 Dipole Moment Decay

The dipole moment has decreased by nearly 6% per century since intensity magnetic field measurements exist, and by about 30% over the past 2000 yrs according to archeomagnetic measurements and models. The magnetosphere, ionosphere and ground geomagnetic field perturbations respond as the geomagnetic dipole moment changes. The implications of this rapid change are critical, as a strongly reduced dipole moment allows access of solar protons into the Earth's atmosphere even at midlatitudes, with implications to the end users of space weather information.

Figure 3 shows the axial component of the dipole field as computed from the IGRF field model. The general decreasing rate is of some 16 nT yr^{-1}. However, at some epochs the field has very different rate fluctuations. For example around 1980, it diminished twice as fast as nowadays. If the same rate of decay is extrapolated in time, the axial dipole would reach zero values in less than 2000 yrs.

Aubert (2015) investigated the axial dipole decay and the place where the field is minimum at the Earth's surface, for the next 100 years. It appears that the South
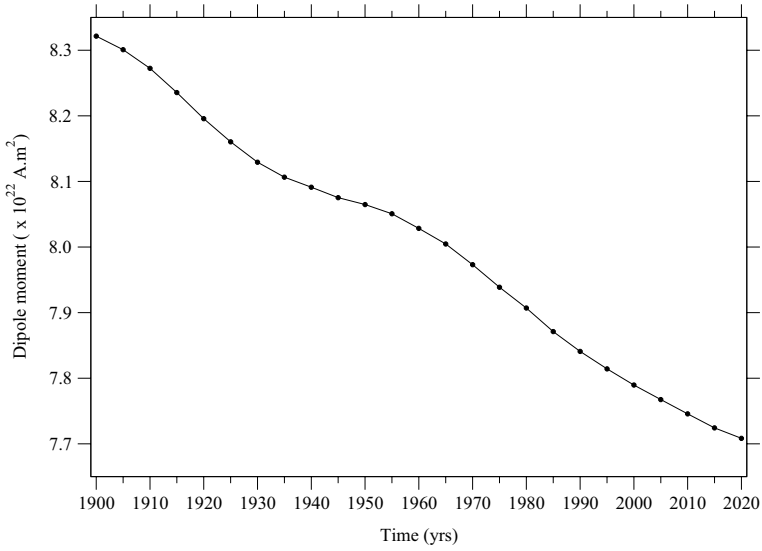
---

[8] https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html.

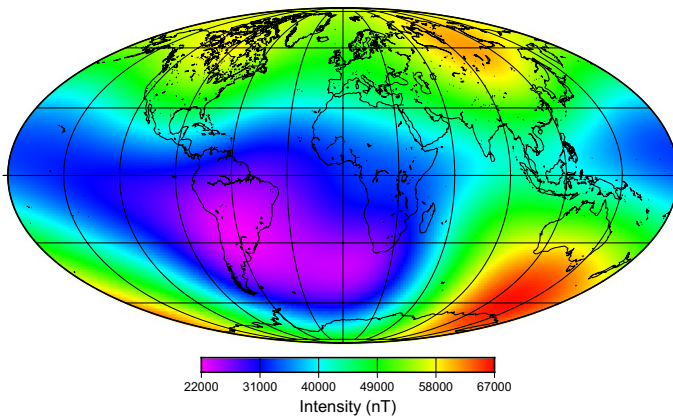**Fig. 3** Geomagnetic dipole moment as computed from the IGRF-13 model

Fig. 4 Magnetic field intensity at the Earth' surface calculated from the core field model IGRF-13 for epoch 2020.5

Atlantic/South America Anomaly (SAA, see Fig. 4) behaviour could be connected to the general decrease of the dipolar field and to the significant increase of the non-dipolar field in the Southern Atlantic region.

A question arises: What may be the future evolution and the implications of this significant dipole moment decay? To offer possible answers it is crucial to understand the physical process responsible for the dipole moment decay. Fluid motion in the outer core transports magnetic field lines, converting kinetic energy into magnetic energy. This ensures the maintenance of the magnetic field against Ohmic dissipation. Considering the free decay of the dipole, if the fluid motions ceased, estimates of some 55,000 yrs are needed to reach a zero level of the axial dipole magnitude. This time

interval is more than one order of magnitude larger that the value of 2000 yrs, based on recent observations. An explanation could be found in different scenarios for the fluid motions within the core proposed by Finlay et al. (2016).

3.1.2 South Atlantic Anomaly/South America Anomaly

One of the striking characteristics of the geomagnetic field was known as the South Atlantic Anomaly and now known as the South America Anomaly (SAA), where the total field intensity is unusually low and the fluxes of energetic protons and electrons trapped in the geomagnetic field are unusually high (see purple area on Fig. 4). In this area, the field intensity reaches less of 1/3 of the field strength at comparable latitudes. This regional weakening in field intensity allows energetic particles and cosmic rays to penetrate much deeper into the magnetosphere and even atmosphere than in other regions, resulting in significant space weather effects in space, such as satellite outages (Heirtzler et al. 2002; Willis et al. 2016) or even on the ground, to radio communications or induced currents in pipelines and transmission lines (Pulkkinen et al. 2012; Boteler and Pirjola 2014) (see next section).

The weakness of the field intensity in the SAA is caused by a patch of opposite magnetic flux compared to the dipole direction at the core-mantle boundary (stressing that the main contribution to the SAA is internal).

3.1.3 Magnetic Poles

The positions of the north and south magnetic poles gradually change. Considering the *gufm* model (Jackson et al. 2000) and more recent models, such as IGRF-13, locations and velocities for the two magnetic poles can be computed. Such computations indicate that both magnetic poles have changed their positions; however, the rate of movement for each pole is very different.

During the first half of the twentieth century the north and south magnetic poles velocities are comparable, around some 10 km yr^{-1}. Since 1970 (time of a well-documented geomagnetic jerk) the north magnetic pole has moved from Canada towards Siberia, with velocities reaching some 60 km yr^{-1} (Newitt et al. 2002; Olsen and Mandea 2007) and the south pole towards Australia, with a much lower velocity of around 5 km yr^{-1}.

Figure 5 shows the north and south magnetic and geomagnetic poles positions as obtained from IGRF-13 model. The north magnetic pole velocity has entered into a deceleration phase, decreasing from about 50 km yr^{-1} in 2015 to ∼ 45 km yr^{-1} in 2020.

The rapid change in the north magnetic pole positions can be thought as a signature of a sudden change in the behaviour of the field. However, in the other hemisphere the south magnetic pole has kept nearly the same velocity rate (Mandea and Dormy 2003). The location of the north magnetic pole appears to be governed by two large-scale patches of magnetic field, one beneath Canada and one beneath Siberia, and could be linked to a high-speed jet of liquid iron beneath Canada (Livermore et al. 2016). The fast accelerating/decelerating of the north magnetic field has a large significance for space weather, considering the dynamic polar processes.
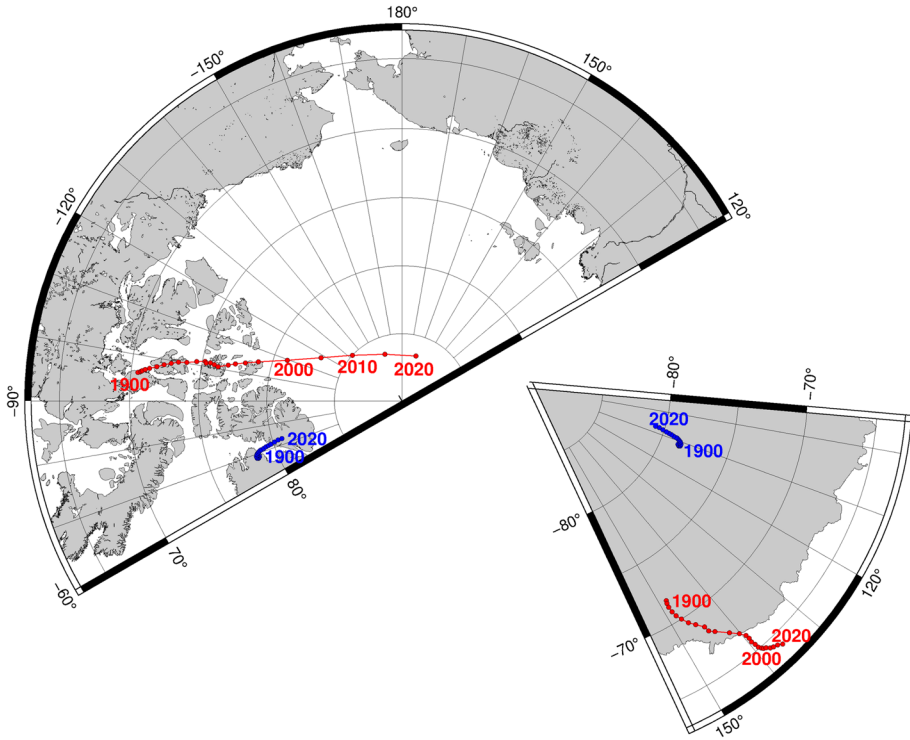
Fig. 5 North (left) and south (right) magnetic (red) and geomagnetic (blue) poles positions obtained from IGRF-13 model. All symbols are at 5-yr interval

3.2 Some Specific External Field Features

Processes originating from the Sun produce rapid variations, with periods from seconds to days. Electric currents within the ionosphere and magnetosphere produce magnetic fields, which are combined with the Earth's own magnetic field. An important role is played by the magnetosphere which acts as a shield against the solar wind coming from the Sun. Severe space weather events compress Earth's magnetic shield, releasing enough power to blind satellites, disrupt radio signals and impact human-made infrastructure on the Earth's surface plunging entire cities into electrical blackouts.

3.2.1 Solar Cycles

Solar cycles are depicted by the number of sunspots on the Sun's surface. The present period, at the time of the edition of this article (mid-2020), is a solar minimum between the 24th and the 25th Solar Cycles. Solar Cycle 25 Prediction Panel experts coordinated by NOAA/NASA—preliminary forecast for Solar Cycle 25 (5 April 2019), considering that the Solar Cycle 25 may have a slow start, but is anticipated to peak with solar maximum
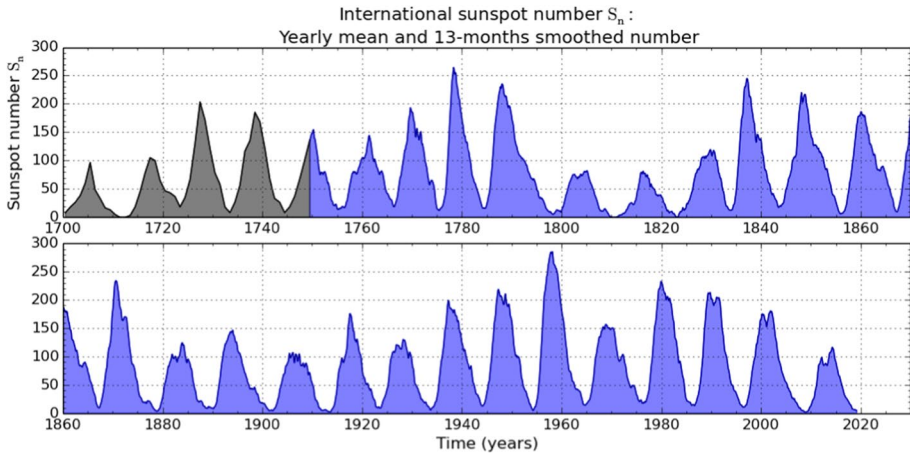
Fig. 6 Yearly mean sunspot number (black) until 1749 and monthly 13-month smoothed sunspot number (blue) from 1749 until nowadays. (Source: WDC SILSO-Sunspot Index and Long-term Solar Observations, Royal Observatory of Belgium, Brussels)

occurring between 2023 and 2026[9]. A low sunspot range of 95 to 130 (very similar in shape to Cycle 24) is also expected. Figure 6 shows the long-running international sunspot number (yearly values) as made available by the World Data Center SILSO (Sunspot Index and Long-term Solar Observations).[10]

Sunspot number is a dataset used in an increasing number of studies linked to Solar Activity and Global Change in the Earth's environment. This long-time series is a valuable complement to scattered historical magnetic measurements to infer space climate/space weather over a few centuries.

3.2.2 Quiet-Day Geomagnetic Variation

The variations are related to the Earth–Sun relation. The Sun illuminates and heats the dayside of the Earth, and Sun's radiations also affect the ionosphere causing convection. This convection implies a motion of the charged particles through the geomagnetic field creating a dynamo action. These daily or diurnal variations, commonly also named as "Solar Quiet" (*Sq*), are caused by electric currents of several µA m^{-2} flowing on the sunlit side of the E-region, at about 90–150 km heights. Recently, new advances in our understanding of the geomagnetic daily variations are provided by Yamazaki and Maute (2016), a basis for observations and existing theories to describe them.

3.2.3 Geomagnetic Storms and Substorms

The geomagnetic storms are caused by the interaction of the solar wind with the Earth's magnetic field. These phenomena can be driven by fast solar wind originating from the solar coronal holes (so-called co-rotating interactive regions, CIRs) or by coronal mass

---

[9] https://www.weather.gov/news/190504-sun-activity-in-solar-cycle.
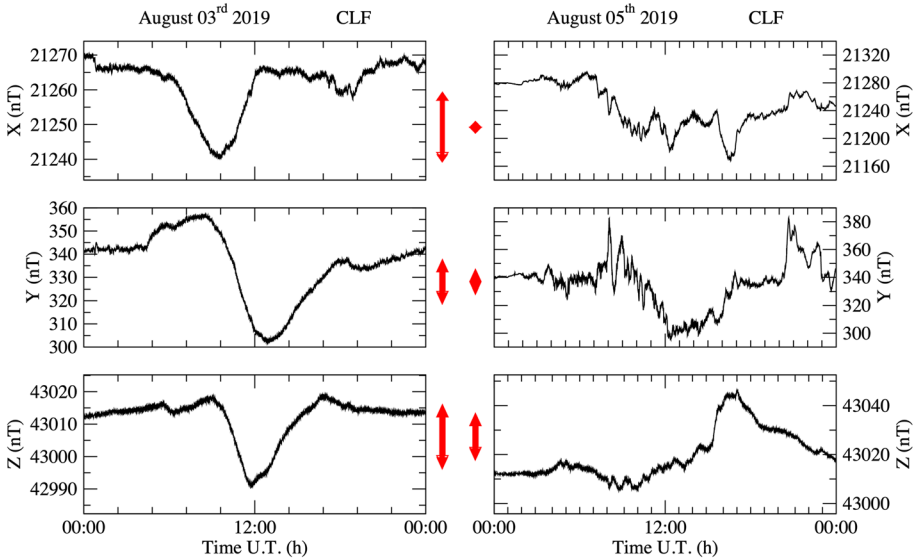[10] http://sidc.be/silso/home; http://doi.org/10.17616/R38322.

Fig. 7 Magnetograms for a quiet day (left, 03 August 2019) and a disturbed day (right, 05 August 2019), as recorded at Chambon la Forêt observatory (X—North component, Y—East component and Z—vertical component). Red arrows, representing 20 nT, allow an easier comparison of vertical axis

ejections (CMEs). The geoeffectiveness of a CME is related to the southward-pointing component of the interplanetary magnetic field (IMF). The continuing interaction between the solar wind and the magnetosphere increases the number of charged particles trapped within the magnetosphere. During disturbed times, charged particles are guided down the magnetic field lines into the upper atmosphere creating the polar aurora. A recent review on the geomagnetic storms from an historical perspective to the modern view is provided by Lakhina and Tsurutani (2016).

The substorms are related to the intensification of the ionospheric auroral electrojet current system and drive the field aligned currents (FAC) which connect the magnetosphere into the ionosphere at high latitude.

Geomagnetic storms are often characterised by an initial unexpected sharp increase in the northern (X) magnetic component of ground measurements at magnetic observatories, called a sudden storm commencement (SSC). The largest geomagnetic storms tend to occur near the maximum and during the declining phase of a solar cycle. The substorms occurrence is much more frequent than storms (about 1500 substorms occur per year).

The daily magnetic field variation gives an important indication about the status of the day, i.e. a magnetically "quiet" or "disturbed" day. An example is given in Fig. 7, the choice being to show close days in August 2019, the 3rd, a quiet day, and the 5th, a moderate geomagnetic storm. This kind of information is important in distinguishing the status of the Earth's magnetic environment.

The Carrington solar event in 1859, the largest recorded solar magnetic event, has been associated with external field changes of more than −1500 nT at the Colaba Indian magnetic observatory (Cliver and Dietrich 2013). The solar cycle of this event (the solar cycle 10) was a weak cycle, typical of the nineteenth century. The cycle during which occurred the Carrington event was well below the nowadays average solar cycle. These specific conditions may allow such extreme events.

The geomagnetic storms and substorms are strongly dependent on local time (LT) and latitude, with high latitudes being particularly affected by the auroral electrojet current systems or magnetospheric waves. Due to simple geometric reasons (zonal currents), most of the above geomagnetic disturbances are observed in the geomagnetic component in the direction of the field lines.

3.2.4 Pulsations

Pulsations are wave trains with periods from fractions of a second to a few minutes. They are seen riding on the magnetic traces. These wave phenomena are faster magnetic variations and can be almost always observed during daytime. Pulsations are classified on a morphological basis dividing them into two classes: regular, continuous, sinusoid-like pulsations (Pc) and impulsive, irregular pulsations (Pi).

3.2.5 Geomagnetically Induced Currents (GIC)

GIC represent a large interest for the geomagnetic risks. GIC arise from the interaction of the disturbed geomagnetic field with the conductive ground. This phenomenon occurs with every geomagnetic storm, large and small. The induced electric fields depend on the local geological conditions (the electrical conductivity of the ground) and magnetic latitude, mainly.

The Earth's electrical conductivity is a complex parameter, as also is a geomagnetic storm, so the geoelectric field conditions are highly variable in time and space. Generally, the geoelectric field peaks appear during the largest fluctuations, such as at the beginning of a geomagnetic storm, but high-frequency components at later times during a storm can also lead to a large impact.

4 Which Magnetic Risks?

4.1 Hazard and Risk Factors

One of the largest solar storms ever seen struck the Earth in 1859 (see Sect. 2). It then spawned power surges that set the telegraphs on fire, while observers of the tropical islands were able to admire polar auroras, as in Cuba and Hawaii. What would be the consequences of a geomagnetic storm on our technology-dependent civilisation?

To understand the hazard and risk factors related to the geomagnetic field variations, it is crucial to consider the Earth's system as a whole (see Sect. 3). Let us consider a well-known example linked to the induced geoelectric field that represents the natural hazard for GIC. The important risk factors to be considered in this specific case are summarised in the following.

4.1.1 The Core Magnetic Field

The magnetic field produced in the Earth's core plays an important role in space weather hazard. Indeed, the core field strength and geometry impose the shape of the magnetosphere surrounding the Earth and act as a shield which protects our Planet against penetration of highly energetic cosmic and solar particles. For example, the evolution of the

SAA particle flux can be seen as the result of two main effects, on the one hand the secular variation of core magnetic field and on the other hand the modulation of the density of the inner radiation belts during a solar cycle. Domingos et al. (2017) analysis allows to well recover the westward drift rate, as well as the latitudinal and longitudinal solar cycle oscillations, important parameters to forecast the impact of the SAA on space weather.

4.1.2 The Magnetic Latitude

The magnetic latitude, defined as a function of the magnetic poles positions, plays an important role on the GIC hazard. In polar regions, the electric current systems are enhanced during geomagnetic storms and can expand southwards with effects at lower magnetic latitudes. The effects of large geomagnetic storm are reasonably well understood and modelled (Baker et al. 2019); however, it is still debated on how far from the pole these ionospheric current systems can move during the extreme events. Recently, Rogers et al. (2020) show how the likelihood estimates for the extreme horizontal geomagnetic field fluctuations depend on the magnetic latitude, besides some other parameters.

4.1.3 The Lithosphere Electrical Conductivity

The electrical conductivuty of the lithosphere has a large impact on GIC hazard. The variations of the electrical conductivity are important in coastal regions, due to the large difference in conductivity between continental and oceanic crusts, as well as in areas with complex geology of heterogeneous facies. GIC may reach very high values for several minutes ($> 1\ V\,km^{-1}$), at high latitudes, during disturbed conditions. When strong magnetic variations reach low resistance man-made structures, as most of fluid transport infrastructures (e.g., pipelines, power lines) or transport and communication frameworks (e.g., railways), they induce important DC currents that propagate into systems causing important damages.

4.2 Space Weather Impacts

Unlike some other natural hazards such as meteorological conditions, flooding or disease, space weather has no direct impact on humans. The early impacts of space weather (e.g., on the electric telegraph, on telephones and HF radio communications) affected systems used only occasionally in everyday life. The wider societal impact of space weather was limited until the latter part of the twentieth century. The increased susceptibility of technological society to extreme space weather events has driven research in this area.

O'Hare et al. (2019) shows that about 2610 years ago, a huge solar storm hit the Earth, detected by the analysis of ice cores in Greenland. Such an event, comparable to that which occurred in 774–775 AD, would cause a cataclysm in our modern civilisation, as suggested by the "Carrington" magnetic storm of 1859.

Recently, Chapman et al. (2020) analysed a catalogue of geomagnetic field changes going back to 1868, using the *aa* index. They found that severe storms, with possible implications on our modern life, occurred in 42 of the last 150 years, while the most extreme storms, with possible significant damage and disruption occurred in 6 of those years, or once every 25 years. The top 10 years with the most severe geomagnetic activity from 1868 to nowadays are the following: 1921, 1938, 2003, 1946, 1989, 1882, 1941, 1909, 1960 and 1958 (in order of decreasing intensity of an event).
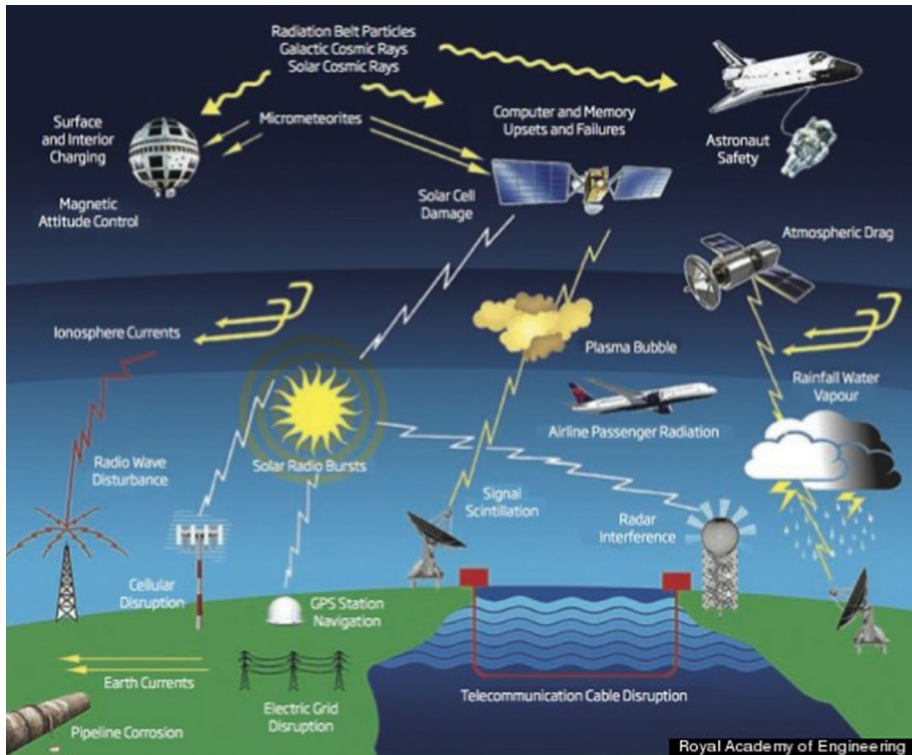
Fig. 8 Space weather impacts (©Royal Academy of Engineering)

The event recorded in May 1921, with disturbances on the US telegraph services, also brought northern and southern auroras, visible at far lower latitudes than usual, with one observatory claiming to detect the southern lights from the Samoa island. The August 1972 storm has detonated sea mines and the one of March 1989 produced huge perturbations of a Canadian power grid.

The severity of the Carrington magnetic storm is not uncommon. According to a report published by the National Academy of Sciences (2008), an exceptional solar event as it is recorded every hundred years could have an economic impact equal to the hurricane "Katrina" times 20! A solar storm of an intensity equivalent to those that have already occurred in the last 200 years could deprive entire regions of electricity for several months (Hapgood 2012). The author quotes a 2009 American study that estimates that a giant blackout could cost $ 2 trillion in the USA alone, because of repairs that would require 4 to 10 years of work.

Figure 8 summarises the space weather effects on different human facilities. Some of the main space weather impacts are summarised in the following. The interested reader is referred to Hapgood (2019) for more details.

4.2.1 Impacts on the Human-made Infrastructures at the Earth's Surface

All lines made of electrically conductive materials may be affected, such as pipelines, copper long distance communication cables, railways, etc. In particular for power grids, the risk of space weather disruption to electricity supplies is a consequence of additional electric currents that are injected into power transmission networks. The impact on power grids creates two primary risks: power outages and damage to grid systems. An example of a dramatic effect linked to a geomagnetic storms is the well-known collapse of Hydro-Quebec's electricity transmission system. Some six million people were left without power for 9 h. The geomagnetic storm causing this event on 13 March 1989 was a severe one, with extremely intense auroras seen as far south as Texas.

4.2.2 Impacts on the Satellite Mission Design, Lifetime, and Navigation Technology

During geomagnetic events, Low Earth Orbit satellites (< 1000 km altitude) may experience an increased air drag force that causes a reduction of satellite altitude. Such processes lead to disturbance of all nominal orbit parameters for constellation control, collision avoidance, re-entry prediction, attitude dynamics. The Global Navigation Satellite Systems (GNSS), at an altitude of about 20,000 km, give accurate measurements of position anywhere on Earth and also the current time with a high accuracy. A wide range of applications is based on GNSS information, from all forms of navigation to synchronisation of activities across networked infrastructures including communications, broadcasting and finance. The GNSS is vulnerable to space weather through the need to correct for the ionospheric delay of signals and through signal disruption by ionospheric scintillation.

4.2.3 Impacts on Spacecraft Physical Integrity

All spacecrafts are exposed to energetic particle radiation (electrons, protons and heavier ions). The fluxes of these particles vary considerably in time and space and lead to a range of effects. It is important also to note the radiation damage to the structure of materials, a major constraint on spacecraft lifetime via the needed power to keep all sub-systems in full running mode.

4.2.4 Impacts on Manned Air- and Spacecraft

During quiet space weather conditions, the radiations from space contribute at some 8% of the radiation observed at the surface, being the primordial contribution up to 3 km altitude. The aircraft cruising at some 10 km altitude flies in a radiation environment, not mentioning higher altitudes vehicles with the International Spatial Station and manned space flights. During severe solar events the contribution of radiation from space can be greatly enhanced.

Finally, let us note that the colossal coronal mass ejection of July 2012 missed Earth, but would have been of Carrington scale if we were in its path. So, devastating magnetic storms could be much more frequent than previously thought, and the new technological modern world needs to take this into account.

5 Conclusions and Future Directions

Continuous global observations of multiple parameters are needed to better understand and predict the closely coupled aspects of Earth's space weather system. An important message that emerges from this contribution is the need for a very strong interplay between the production and analysis of observational data, the development, validation and use of advanced models of the different types, to understand disturbances of the Sun–Earth's system propagating from above (classical space weather), from the coupled Earth's system (terrestrial and solar magnetic fields long-term variations and global electric circuit) and from below (seismic and volcano activity, injection of greenhouse gases into the atmosphere, atmospheric waves produced by solar heating and weather systems). Thus, different sources of hazard are complex, and to address all of them is out of the scope of this paper. Here, we mainly offer a tour of the Earth's magnetic field variations and how they are essential for space weather. We also point out some extreme events and their different consequences.

That relevant processes for the variability of the geomagnetic field need to be better described by a comprehensive separation and understanding of its internal and external sources. With respect of core field, two of its first-order features are of prime importance for space weather—the rapid decay of the dipole field, and the expansion and the decreasing intensity of the SAA—because they accentuate the impact of space weather events.

In the framework of studying space weather impacts on man-made infrastructure a special attention needs to be paid to fast and sometimes violent dynamic changes in any of the magnetospheric and ionospheric current systems. A better knowledge of phenomena in these regions will improve space weather forecasts, with immediate applications, as the correction of GNSS signals in real time. It is clear that the impact of a severe space weather event on the modern technology requests vigilance and new mitigation strategies. The information about conditions in near-Earth's space together with a full understanding of Earth's deep interior is important to make progress towards a complete understanding of Solar-Terrestrial coupling and its effects on humankind and human societies.

References

Aubert J (2015) Geomagnetic forecasts driven by thermal wind dynamics in the earth's core. Geophys J Int. https://doi.org/10.1093/gji/ggv394

Baker DN, Li X, Pulkkinen A, Ngwira CM, Mays ML, Galvin AB, Simunac KDC (2013) A major solar eruptive event in July 2012: defining extreme space weather scenarios. Space Weather. https://doi.org/10.1002/swe.20097

Baker DN, Balogh A, Gombosi TI, Koskinen HEJ, Veronig A, von Steiger R (2019) The scientific foundation of space weather. Space sciences series of ISSI. Springer, Dordrecht

Boteler DH, Pirjola RJ (2014) Comparison of methods for modelling geomagnetically induced currents. Ann Geophys. https://doi.org/10.5194/angeo-32-1177-2014

Chapman SC, Horne RB, Watkins NW (2020) Using the aa index over the last 14 solar cycles to characterize extreme geomagnetic activity. Geophys Res Lett. https://doi.org/10.1029/2019GL086524

Cliver EW, Dietrich WF (2013) The 1859 space weather event revisited: limits of extreme activity. J Space Weather Space Clim 3:31. https://doi.org/10.1051/swsc/2013053

Domingos J, Jault D, Pais MA, Mandea M (2017) The south atlantic anomaly throughout the solar cycle. Earth Planet Sci Lett 473:154–163. https://doi.org/10.1016/j.epsl.2017.06.004

Finlay CC, Aubert J, Gillet N (2016) Gyre-driven decay of the Earth's magnetic dipole. Nat Commun 7:10422. https://doi.org/10.1038/ncomms10422

Hapgood M (2012) Prepare for the coming space weather storm. Nature. https://doi.org/10.1038/484311a

Hapgood M (2019) Technological impacts of space weather. In: Mandea M, Korte M, Yau A, Petrovsky E (eds) Geomagnetism, aeronomy and space weather: a journey from the earth's core to the sun

Heirtzler JR, Allen JH, Wilkinson DC (2002) Ever-present South Atlantic Anomaly damages spacecraft. EOS Trans Am Geophys Union 83(15):165–172

Hulot G, Olsen N, Sabaka TJ, Fournier A (2015) The present and future geomagnetic field. In: Schubert G (ed) Treatise on geophysics (2nd edn), pp 33–78. https://doi.org/10.1016/B978-0-444-53802-4.00096-8

Jackson A, Jonkers ART, Walker MR (2000) Four centuries of geomagnetic secular variation from historical records. Philos Trans R Soc Lond A 358:957–990

Korte M, Mandea M (2019) Geomagnetism: from alexander von humboldt to current challenges. Geochem Geophys Geosyst 20(8):3801–3820. https://doi.org/10.1029/2019GC008324

Lakhina GS, Tsurutani BT (2016) Geomagnetic storms: historical perspective to modern view. Geosci Lett. https://doi.org/10.1186/s40562-016-0037-4

Leger JM, Bertrand F, Jager T, Le Prado M, Fratter I, Lalaurie JC (2009) Swarm absolute scalar and vector magnetometer based on helium 4 optical pumping. In: Proceedings of the Eurosensors XXIII conference, pp 634–637. https://doi.org/10.1016/j.proche.2009.07.158

Livermore P, Finlay C, Hollerbach R (2016) An accelerating high-latitude jet in Earth's core. In: SEDI meeting abstracts

Lockwood M (2012) Solar influence on global and regional climates. Surv Geophys. https://doi.org/10.1007/s10712-012-9181-3

Mandea M, Dormy E (2003) Asymmetric behaviour of magnetic dip poles. Earth Planets Space 55:153–157

Mandea M, Purucker M (2018) The varying core magnetic field from a space weather perspective. Space Sci Rev 214:11. https://doi.org/10.1007/s11214-017-0443-8

Moriña D, Serra I, Puig P, Corral Á (2019) Probability estimation of a carrington-like geomagnetic storm. Sci Rep 9(1):2393

Newitt LR, Mandea M, McKee LA, Orgeval J-J (2002) Recent acceleration of the North Magnetic Pole linked to magnetic jerks. EOS Trans Am Geophys Union 83(35):381–389

O'Hare P, Mekhaldi F, Adolphi F, Raisbeck G, Aldahan A, Anderberg E, Beer J, Christl M, Fahrni S, Synal H-A, Park J, Possnert G, Southon J, Bard E (2019) ASTER Team, R. Muscheler, Multiradionuclide evidence for an extreme solar proton event around 2,610 b.p. (660 bc). Proc. Natl. Acad. Sci. USA, pp 5961–5966 . https://doi.org/10.1073/pnas.1815725116

Olsen N, Mandea M (2007) Will the magnetic north pole wind up in Siberia? EOS Transactions American Geophysical Union

Pulkkinen A, Bernabeu E, Eichner J, Beggan C, Thomson AWP (2012) Generation of 100-year geomagnetically induced current scenarios. Space Weather. https://doi.org/10.1029/2011SW000750

Purucker M, Whaler K (2015) Crustal magnetism. In: Schubert G (ed) Treatise on geophysics, 2nd ed, pp 185–218

Riley P (2012) On the probability of occurrence of extreme space weather events. Space Weather 10(2):1–12

Rogers Neil C, Wild James A, Eastoe Emma F, Gjerloev Jesper W, Thomson Alan WP (2020) A global climatological model of extreme geomagnetic field fluctuations. J Space Weather Space Clim. https://doi.org/10.1051/swsc/2020008

Willis P, Heflin MB, Haines BJ, Bar-Sever YE, Bertiger WI, Mandea M (2016) Is the jason-2 doris oscillator also affected by the South Atlantic anomaly? Adv Space Res. https://doi.org/10.1016/j.asr.2016.09.015

Yamazaki Y, Maute A (2016) Sq and eej—a review on the daily variation of the geomagnetic field caused by ionospheric dynamo currents. Space Sci Rev. https://doi.org/10.1007/s11214-016-0282-z

Yokoyama N, Kamide Y (1997) Statistical nature of geomagnetic storms. J Geophys Res Space Phys 102(A7):14215–14222