Nat. Hazards Earth Syst. Sci. Discuss., 2, 4463–4486, 2014
www.nat-hazards-earth-syst-sci-discuss.net/2/4463/2014/
doi:10.5194/nhessd-2-4463-2014

Natural Hazards
and Earth System
Sciences
Open Access
Discussions

How severe Space Weather can disrupt global supply chains

H. Schulte in den Bäumen[1], D. Moran[2], M. Lenzen[1], I. Cairns[1], and A. Steenge[3]

[1]School of Physics A28, University of Sydney, Sydney NSW 2006, Australia
[2]Programme for Industrial Ecology, Norwegian University of Science and Technology (NTNU), 7013 Trondheim, Norway
[3]The University of Groningen, Faculty of Economics and Business,
9700 AB Groningen, the Netherlands

Received: 5 June 2014 – Accepted: 9 June 2014 – Published: 24 June 2014

Correspondence to: H. Schulte in den Bäumen (hagen@physics.usyd.edu.au)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Coronal mass ejections (CMEs) strong enough to create electromagnetic effects at latitudes below the auroral oval are frequent events that could soon have substantial impacts on electrical grids. Modern society's heavy reliance on these domestic and international networks increases our susceptibility to such a severe space weather event. Using a new high-resolution model of the global economy we simulate the economic impact of strong CMEs for 3 different planetary orientations. We account for the economic impacts within the countries directly affected as well as the post-disaster economic shock in partner economies linked by international trade. For a 1989 Quebec-like event the global economic impacts would range from USD 2.4 to 3.4 trillion over a year. Of this total economic shock about 50 % would be felt in countries outside the zone of direct impact, leading to a loss in global GDP of 3.9 to 5.6 %. The global economic damages are of the same order as wars, extreme financial crisis and estimated for future climate change.

1 Introduction

We are now midway in the current solar cycle and so far we have not experienced a single extreme geomagnetic storm. The probability of such an event is highly increased due to a peak in solar storms when sunspot numbers are maximal (Ramesh, 2010). Solar storms consist of three major components: solar flares, solar proton events and coronal mass ejections (CMEs). All of these cause "space weather" that affect humanity's technological systems and society, as well as Earth's atmosphere, climate, and potentially the biosphere. Fast CMEs ($\approx$ 1000–2000 $\mathrm{km\,s^{-1}}$) are clouds of ejected plasma with embedded magnetic fields that can interact with Earth's magnetic field after an observed travel time as short as 15 h to create a geomagnetic storm (Cliver et al., 2004). Following this impact Earth's magnetic field can be disturbed worldwide for days (Bolduc, 2002), allowing more energetic solar and magnetospheric charged particles to find their way along the open magnetic field lines near the Earth's poles through the ionosphere and atmosphere to the surface. Many details of the associated physics are still unclear. However, currents and electric fields associated with enhanced particle precipitation can induce massive ground currents in electrical distribution networks which could result in large-scale power blackouts and permanent damage to electric transformers (Pirjola et al., 2000).

During a geomagnetic storm large time-varying currents are introduced in the ionosphere at auroral-like latitu These occur primarily on the night side where magnetic reconnection in the magnetotail accelerates particles along polar magnetic field lines. These time-varying auroral magnetic fields induce large sudden electric fields, voltage drops, and currents in power-lines and transformers, causing failures and possible reduction in electric power supply. Similar effects of geomagnetic storms due to sudden increased ionization on the dayside near the subpolar point due to a large X-ray flare from the Sun, or increased entry of energetic particles and interplanetary plasma due to magnetic reconnection on the dayside, are likely smaller and are ignored here. The strength of the AL and D_{st} indices, both due to variations in the magnetic field measurable on the ground due to space weather, depend strongly on the interplanetary event: when the interplanetary magnetic field B_z is directed southwards $AL = -v_{sw}^2 B_s$, where v_{sw} is the solar wind speed and B_s is a duration-weighted estimate of B_z (Muruyama et al., 1980).

The strength of the induced currents depends on a number of factors. They usually increase with geomagnetic latitude, transmission line length and voltage, but decrease with distance to the ocean and increased ground resistivity (Wei et al., 2013). Space weather events also cause auroras, usually in two small ovals around 65 (±5) degrees northern and southern latitude that vary in size, location and intensity during geomagnetic storms. The geographical distribution of the damage caused by a geomagnetic storm is very complex. Other observed consequences of geomagnetically induced currents (GICs) include damage to pipelines and telecommunication cables, accelerated corrosion, physical and electrical damage to satellites, and disruptions to radio navigation, which can particularly affect the transport and aviation sectors (Boteler et al., 1998).

In 1989 Earth experienced its largest space weather event in several decades: a geomagnetic storm that caused a power blackout in Quebec that left millions of people without electricity for hours. It permanently damaged transformers in Canada, the USA and the UK, and disconnected other power transmission devices from California to Sweden (Erinmez, 2002; Lakhina et al., 2005). This storm caused damage across about 120° of longitude and 5–10° latitude and lasted for more than 12 h. The Quebec power grid went from normal operations to complete shutdown in 90 s. Temporal changes in the geomagnetic field of $\mathrm{d}B/\mathrm{d}t = 1100\,\mathrm{nT\,min}^{-1}$ were experienced and the strength of the storm, in terms of the Disturbance storm index which measures how much Earth's magnetic field is weakened, was estimated to be $D_{st} = -640\,\mathrm{nT}$. Two other strong storms in the 20th century include a $\mathrm{d}B/\mathrm{d}t = 5000\,\mathrm{nT\,min}^{-1}$ storm in May 1921, the biggest geomagnetic event in the last century which lead to aurora borealis over Samoa, and a fast CME in October 2003 which despite its low strength of $D_{st} = -472\,\mathrm{nT}$ caused effects at latitudes as low as South Africa where it incapacitated several large electrical transformers (Lakhina et al., 2005). Regions with latitudes below 30° S were previously thought to stay free of damage.

Polar ice studies and anecdotal evidence suggest the most severe space weather event in the last 450 years was the Carrington event of September 1859 (Shea et al., 2006). That storm caused auroras visible within 23° of the equator in both hemispheres, e.g. in Honolulu, Havana, and Rome (Tsurutani et al., 2003). In the United States and Europe fires were started by arcing from currents induced in telegraph wires (Green et al., 2006). The strength of this storm has been estimated to be $D_{st} = -1760\,\mathrm{nT}$ or three times stronger than the 1989 event and four times stronger than the October 2003 storm (Lakhina et al., 2005; Tsurutani et al., 2012). In August 2013 a CME of Carrington size missed the Earth by a week, or 90° in heliographic longitude.

Although a solar maximum period might have a higher frequency of intense solar storms, there is no evidence that this will affect the intensity of any single event

(Hapgood, 2012). Indeed, the 1859 event occurred outside solar maximum. The probability of a Carrington event (based on $D_{\mathrm{st}} < 850\,\mathrm{nT}$) per decade is estimated to be 12 %, or a once in a century event like a 9.0 earthquake (Riley, 2012; Love, 2012). It has been estimated (Thompson et al., 2011) that $\mathrm{d}B/\mathrm{d}t$ changes of 1000–4000 $\mathrm{nT\,min^{-1}}$ ($D_{\mathrm{st}} = 2000$–$5000\,\mathrm{nT}$) for a storm occur every 100 years and $\mathrm{d}B/\mathrm{d}t$ of 1000–6000 $\mathrm{nT\,min^{-1}}$ ($D_{\mathrm{st}} = 3000$–$6500\,\mathrm{nT}$) every 200 years. These frequencies are comparable to other severe natural disasters such as large earthquakes and volcanic eruptions. Power grids typically experience problems when the rate of change of the magnetic field exceeds a 100–200 $\mathrm{nT\,min^{-1}}$ (Wei et al., 2013). Occurring today, the Quebec 1989 event or the 1859 Carrington event would have profound impact on the daily lives of millions of people, both through direct effects and via the impacts to the globalized economic production system.

Little has been done on economic modeling of severe space weather so far and previous studies have mostly focused on the USA. It has been estimated in NAOS (2008); Showstack (2011) that a storm similar to that of 1859 or 1921 could cause damage of several trillion US dollars in the USA in the first year alone and that recovery could take years. The large transformers that could be vulnerable to a severe storm are produced infrequently, of order just 1–5 globally per year. The estimated damage to the power system in Quebec in 1989 is in the range of USD 2 billion, whilst the total damage is estimated to be around USD 13 billion (Kappenmann, 2010; Boteler, 1998). Another study estimates that the economic losses in North America and Europe for a power blackout for 5 months caused by a Carrington-like event would be between USD 0.5 and 2.6 trillion (Lloyds, 2013; Wei et al., 2013). It has also been estimated that a North American power grid blackout would result in a GDP loss in the USA of about USD 30 billion per day, accumulating to over USD 10 trillion per year (Lloyds, 2013). None of the cost estimates consider indirect effects on supply chains, including those of global trade.

The complex and interconnected network of today's globalized economy and infrastructure makes it difficult to predict the exact effects of a severe space weather event.

Therefore we focus on the most economically important impact from such an event: the interruption of electrical distribution grids and failure of electric power transmission systems. We combine a simple physical model for disruption of power grids with the most comprehensive and most highly resolved economic input–output framework of the world economy to estimate the direct and indirect economic costs of severe space weather events with sizes between the Quebec 1989 and Carrington 1859 events.

The reduction of production capacities of the electricity sector for each country is $\gamma_{\mathrm{el}} = R(S,C,\phi_0)$. Specifically,

$$\begin{aligned} R(S,C,\phi_0) &= F(S)A_C^{-1}\int \mathrm{d}A\,G(S,C,\phi_0) \\ &= F(S)A_C^{-1}\int \mathrm{d}A\,e^{\frac{-(\phi-\phi_0)^2}{2\sigma_\phi(S)^2}} \times \left[e^{\frac{-(\theta-\theta_0(S))^2}{2\sigma_\theta(S)^2}} + e^{\frac{-(\theta+\theta_0(S))^2}{2\sigma_\theta(S)^2}}\right]. \end{aligned} \tag{1}$$

The quantity $G(S,C,\phi_0)$ is the product of a Gaussian in longitude ϕ, centered at longitude ϕ_0 (which corresponds to the time when the event occurred) with event-dependent standard deviation $\sigma_\phi(S)$, that depends on the event size S, times the sum of Gaussians in latitude that model the event-dependent auroral ovals centered at $\pm\theta_0(S)$ with standard deviations $\sigma_\theta(S)$. Figure 1 illustrates the double-banded nature of the affected areas.

How should $\theta_0(S)$, $\sigma_\theta(S)$ and $\sigma_\phi(S)$ vary with S? Noting that the magnetic field $B(r)$ at radial distance r from a long axial current I varies as $B(r) = \mu_0 I/2\pi r$, where μ_0 is the permittivity of free space, it is clear that the distance r at which the same value of B is observable increases linearly with I. Thus as a first approximation $\sigma_\theta(S)$ and $\sigma_\phi(S)$ should vary linearly with I and so with S. Observations show that $\theta_0(S)$ decreases from nominal values near 65° geographical latitude as S increases, since the aurora moves equatorward as geomagnetic storms and the associated currents intensify and then moves poleward as the driving currents decrease and the system recovers (Baumjohann et al., 1980). Thus the geographical area in which a certain level of damage occurs should vary as S^2, but should move equatorward as S increases.

We assume $\sigma_\theta = 2^\circ \pm 1^\circ$ and $\sigma_\phi = 20^\circ \pm 5^\circ$ for a storm similar to the Quebec 1989 Space Weather event. This storm has a footprint of about 80° of longitude and about 8° of latitude in both the northern and Southern Hemisphere. Since the D_{st} and AL values for the Quebec 1989 and Carrington 1859 events are believed to have differed by a factor 3, the geographical footprint of the Carrington event is expected to be a factor of 9 larger and the values of σ_θ and σ_ϕ each a factor of 3 larger. From the physical model $\sigma_\theta = 6^\circ \pm 3^\circ$, and $\sigma_\phi = 60^\circ \pm 15^\circ$. During the Carrington event auroras were observed as far south as 20° latitude with the latitudinal spread observed to be 45°, and the longitudinal domain was close to 180° (Green et al., 2006). Accordingly, the model is consistent with observations.

For each country the total impact of the storm is the quantity R that integrates the storm's effects as a function of geomagnetic latitude and longitude over the country's area. The storm is modeled like a flash-like impact. Outside the area of impact the damage in the electricity sector is zero. Storms weaker than the Carrington 1859 event but stronger than the Quebec 1989 event could result in around 10–20 damaged transformers in the US alone (OECD, 2011; MITRE, 2011; UK House of Commence Defence Commitetee, 2012). Even the failure of a small number of transformers serving a highly populated area like the ones we choose in our scenario is enough to create prolonged power outage. We assume the storm causes damage which will last a year since the production and supply of a replacement transformer could take up to more than 12 months as could the restoration of a grid damaged over a huge area (Office of Energy Delivery & Electric Reliability, 2012).

In order to quantify the economic impacts of a severe Space Weather event we simulate the consequences [illegible]ajor disasters by utilizing Leontief's input–output (IO) theory (Steenge et al., 2007; Leontief, 1996). IO analysis has been used extensively for investigating the repercussions of changes in one part of an economy on other parts of the same economy (see the recent articles by Lenzen et al., 2011 and Wiedmann et al., 2013). Input–output databases are routinely published by more than 100 national statistical bureaus in the world. More recently, a number of teams have assembled large-scale, detailed global Multi-Regional Input–Output (MRIO) databases, which contain the same set of data but integrated for all world regions or countries (Tukker et al., 2013). MRIO tables can be used in the same analytical manner as national input–output tables, for investigating effects that ripple along global supply-chain networks (Leontief et al., 1963). In this study we utilize the most detailed [illegible]hese global MRIO database, distinguishing 187 countries with 25–400 sectors per country. The economic model captures more than 99.99 % of global trade.

2 The model

Most often, productive activity in modern economies is assumed to be demand-driven, and the so-called demand-pull model is evoked, where an initial change vector $\Delta \boldsymbol{y}$ in final demand $\boldsymbol{y}$ ($N \times 1$, for example decreased household consumption caused by reduced electricity supply) causes flow-on effects that ripple through a complex upstream supply-chain network, and ultimately leads to a change $\Delta \boldsymbol{x}$ in total output $\boldsymbol{x}$ ($N \times 1$) of an economy. The scalar N holds the number of sectors (industries and/or products) that are distinguished in the IO matrices. We distinguish $P = 15\,909$ country-sector pairs (Lenzen et al., 2013, 2014) using data from 2011. The flow-on effects can be enumerated using an $N \times N$ input–output transactions matrix $\mathbf{T}$, according to $\Delta \boldsymbol{x} = (\mathbf{I} - \mathbf{T}\hat{\boldsymbol{x}}^{-1})^{-1} \Delta \boldsymbol{y} = (\mathbf{I} - \mathbf{A})^{-1} \Delta \boldsymbol{y}$, where $\mathbf{I}$ denotes an $N \times N$ identity matrix, the hat symbol "ˆ" denotes matrix diagonalisation, and $\mathbf{A} = \mathbf{T}\hat{\boldsymbol{x}}^{-1}$ is the matrix of input coefficients. This relationship follows from the National Accounting Identity, which states that $\boldsymbol{x} = \mathbf{T}1 + \boldsymbol{y} = \mathbf{A}\boldsymbol{x} + \boldsymbol{y}$, where $1 = \{1, 1, \ldots, 1\}'$ is an $N \times 1$ summation operator. A transaction matrix $\mathbf{T}$ is essentially a square matrix with elements T_{ij} that represent the supply of products i for use in industry j. Matrices $\mathbf{T}$ and $\mathbf{A}$ thus include information on industrial interdependence and production structures in an economy, which can ultimately be used to trace flow-on effects of initial changes along supply chains that link all sectors in an economy.

Rather than following the effects of changes in final demand on levels of total output, we analyze a situation where the output of economies undergoes forced changes, and study the effects that these changes have on final demand or consumption possibilities. Such studies are generally known as disaster impact analysis (Li et al., 2013; Okuyama et al., 2007). Our approach to estimating the direct and indirect consequences of a severe space weather event affecting a specific set of countries $C = 1,\ldots,M$ and industries $i = 1,\ldots,N$ leads to an $N \times N$ diagonal matrix of fractions γ of production capacity lost due to the event:

$$\mathbf{\Gamma}(C,i) = \begin{bmatrix} \gamma_{C=1,i=1} & & \\ & \ddots & \\ & & \gamma_{C=R,i=N} \end{bmatrix}, \tag{2}$$

with $0 \leq \gamma \leq 1$. $\mathbf{\Gamma}$ has not only entries in the electricity sector(s), but also in the industrial sector(s) directly and indirectly affected by reduced electricity supply. Assume pre-disaster production is represented by total output $\boldsymbol{x}$. The post-disaster production possibilities are then $\tilde{\boldsymbol{x}} = (\mathbf{I} - \mathbf{\Gamma})\boldsymbol{x}$. This formulation is equivalent to the model in Eqs. (17) and (21)–(23) in Steenge et al. (2007). The result of a reduced industrial production $\tilde{\boldsymbol{x}}$ is a state of reduced post-disaster consumption, i.e. final demand $\tilde{\boldsymbol{y}}$. Since $\mathbf{A}\tilde{\boldsymbol{x}} + \boldsymbol{y} \neq \tilde{\boldsymbol{x}}$, the National Accounting Identity does not hold after the disaster, and the global economy is in imbalance. In particular, the reduced output is insufficient for satisfying final demand $\boldsymbol{y}$. Reduced post-disaster consumption possibilities are $\tilde{\boldsymbol{y}} = \tilde{\boldsymbol{x}} - \mathbf{A}\tilde{\boldsymbol{x}}$. Note that this formulation assumes that the post-disaster input coefficients $\mathbf{A}$, the production recipe, is the same as pre-disaster, meaning that at least in the short term (within a year), production processes in those industries affected cannot be altered (for example by substituting electricity with other energy carriers) in order to make up for lost capacities.

In a case where final demand is unable to shoulder the entire loss in production possibilities, we examine the Leontief inverse or total requirement matrix $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$. $\mathbf{L} = [l_{ij}]$ reveals how much gross output of each sector is required to meet final demand. We then see that the lost electricity supply is quite an important production input for

some sectors, but a very small input for others. If electricity is a very small input (we define a threshold for small) we decide that this sector is not hit by the global cascade, e.g. because this sector can substitute the small input with some other good. For those sectors where electricity is a significant input ($\mathbf{L}_{C,i} >$ threshold) we reduce the output of that sector as described above. The threshold is determined according to the global requirement of electricity supply from the electricity sectors directly damaged due to the geomagnetic storm (Fig. 2). In scenario 1 for example 1328 different sectors require two times 10^{-5} of the total supply from the damaged electricity sectors as a production input. If the total required production input of one these sectors is typically USD 2 billion, and electricity supply from the damaged sectors is 2×10^{-5} of it, USD 1000 worth of electricity are required as an production input. We argue that this sector can substitute USD 1000 worth of input of electricity with USD 1000 worth of, e.g. wood. Our threshold for this scenario is 2×10^{-5}.

3 Results

A large number of calculations run in which the storm size S, the damage factor $F(S)$, which describes the lost production capacity in the event-affected electricity sector(s), and the location ϕ_0 of the storm were varied. Considering direct effects only we simulated a complete grid shutdown in the USA, i.e. $F(S) = 1$. This scenario leads to direct economic damage in the USA of about USD 25 billion/day, which is similar to the USD 30 billion/day impact estimated (Lloyds, 2013). To simulate the economic damage of Quebec- and Carrington-like events, we use $F(S) = 0.1$, meaning that in areas of maximal storm intensity 10 % of the electricity supply is lost, in order to get similar damage as estimated in previous studies. Using this value for $F(S)$ while still considering direct effects only, a Quebec-like event occurring today centered over Quebec would cause daily economic damages in Canada of USD 165 million and USD 2.65 billion in the USA. This value is close to the estimates of USD 13 billion over 5 days for the event (Boteler et al., 1998). Similarly a Carrington event occurring today centered near New York (ϕ_0 = 40° N, θ_0 = 75° W) would lead to direct economic damage in the USA alone of about USD 1.2 trillion for 5 months. These results are in line with prior estimates of USD 0.5–2.6 trillion (Wei et al., 2013; Lloyds, 2013). Note that all economic impact studies conducted to date do not consider indirect effects due to disrupted intra- and international trade.

We run the model, still with $F(S) = 0.1$ but now considering direct and indirect effects, with Quebec-like scenarios for 6 different locations (Fig. 1): centered over America at ϕ_0 = ±45° N and θ_0 = 80° W (scenario 1), over Europe/Africa at ϕ_0 = ±50° N and θ_0 = 10° E (scenario 2), and over Asia/Australia at ϕ_0 = ± 35° N and θ_0 = 125° E (scenario 3). These targets were chosen as economically worst-case scenarios since they affect densely populated and highly industrialized regions.

In all scenarios we see economic damage not only in those countries directly affected by the storm, but also in further countries affected by disruptions in international trade and supply chains (red shading). This is because industries that rely on imports that in turn directly or indirectly depend on supplies from the damaged electricity sector(s), face input shortages, and hence have to scale back their production. However, we also find that some countries are faced with increases in consumption possibilities (green shading). This is because industries producing inputs that are directly or indirectly required by the damaged electricity sector(s) are not needed anymore since the electricity sector(s) operates at reduced capacity, and hence the output of the industries producing these inputs is available for additional domestic consumption. Whilst the latter situation provides in principle increased consumption possibilities, our model does not reveal whether adequate final demand will in fact be forthcoming to absorb the surplus production capacity. For the purpose of this study, we simply report on two types of economic imbalances, where (a) shortages of electricity inputs lead to production deficits and curtailed demand, and where (b) reduced demand for inputs by electricity sector(s) leads to surplus production that may remain unused.

For scenario 1 centered over the Americas we find (Fig. 3) that disruption of US power utilities would cause major losses in Canada (for example due to reduction in US vehicle supply), Germany (reduction in supply of US pharmaceutical products, industrial machinery and precision equipment), and China (electrical equipment, aircraft, plastic products). Economic loss for Canada in relative terms is even larger than for the USA, even though the USA is far more severely affected directly by the storm, because of Canada's smaller economy and strong dependence on key US exports. Countries featuring surplus production are those that specialize in exporting key resources into the USA, for example Russia (petroleum, aluminum, nickel, iron and chemicals), Saudi Arabia, Libya, Azerbaijan, Kazakhstan and Algeria (oil), South Africa and Gabon (precious minerals), France and Sweden (aircraft parts, power generating equipment), and Finland (paper). An examination of the UN Main Aggregates database (UNSD, 2011) shows that almost all of the countries characterized by increased consumption possibilities feature a consistent and significant trade surplus (Qatar, Libya, Gabon, Kuwait, Saudi-Arabia, Oman, Algeria, Azerbaijan, Russia, Angola, Myanmar, Iran, Kazakhstan).

Scenario 2 looks markedly different (Fig. 4). It appears that the world's dependence on European exports of all kind means that virtually all countries except for the USA are affected by GDP losses as a result of a severe space weather event over Europe. The USA registers net production surplus, because of key exports to Europe such as integrated circuits and other semiconductor products, pharmaceutical and chemical products, as well as vehicles and aircraft.

Scenario 3 (Fig. 5) shows that a space weather event affecting China, Japan, Korea and Australia causes GDP loss across most of Europe. Libya, Iran and Azerbaijan are exceptions because of their significant oil exports. The role of the USA requires closer examination. For example, whilst China received a net damage from a storm over the USA, the USA appears to be affected by surplus production as a result of a storm over China, even though China's exports to the USA far outstrip US exports to China. This is because whilst US exports to China (semiconductor components, soybeans, aircraft, and cars) are important inputs into further production, China's exports to the USA (digital disk drives, clothes, games, toys, furniture) are mostly destined for the final consumer, and hence have no damage-multiplying effect. Brazil is an equally interesting case here, because whilst being a net importer from the USA and most of Europe, it is a net exporter to China, Japan, Korea and Australia, and hence registers surplus production after a storm.

The economic model considers both direct impacts in international trade, such as the shared international power grids in Europe, and the indirect effects due to interrupted supply chains. In scenario 1, an American storm, indirect plus direct effects are calculated to reduce global consumption possibilities by 3.9 % or USD 2.4 trillion. In scenario 2 (the European storm) direct and indirect effects are calculated to reduce global consumption possibilities by 5.6 % or USD 3.4 trillion. In the Asia-centered storm of scenario 3 the storm is estimated to reduce global consumption possibilities by 5.0 %, or USD 3.1 trillion.

4 Discussion

In this paper we concentrated on the possible impact of severe Space Weather events [illegible] the electric distribution system. Damage in the telecommunication sector (not shown) can also result as a consequence of solar activity but is due to solar flares (accompanied by x-rays and density perturbations in the ionosphere) and are more distributed in time and locations than the damage caused by CMEs. Accordingly, a different physical model than the one we use here is needed to account for damages in the telecommunication sector. A space weather event is substantially different from other natural disasters on Earth. Whilst hurricanes, earthquakes and tsunamis could cause direct human losses, a solar storm is likely to cause material damage only. Although radiation risks for astronauts and airline passengers on polar routes are described in the literature, no human losses as a consequence of a solar storm have been recorded, and therefore are not considered in this work, for example as a loss of labor.

A severe Space Weather event could be the worst natural disaster in modern history with global costs estimated to be over 5 % of world GDP and impacts reaching

across every industry and every segment of society. Extreme space weather will impact severely on society's infrastructure – networks of trade, transport and production would need to adapt globally. In our modern globalized economy shocks to the production system in one country can cause large ripple effects in partner economies. Reduced inventories, increased shipping, the rise of just-in-time production and the acceleration of specialization and trade mean that the global economic production system, while more productive in total, is increasingly vulnerable to shocks. We have considered the possible impact of a century-scale space weather event on the global economy. The results indicate that total losses could be up to USD 3.4 trillion and impacts would affect sectors and populations well outside the direct area of impact. Changes in the intensity [illegible] timing of space weather event result in different global economic damage.

Global financial crises episodes lead to losses estimated between 2.95 and 4.54 % of world GDP (Kappy et al., 2012). Economic impacts from climate change have been estimated to cost USD 125 billion yr^{-1} (GHF, 2009). Our scenario estimates global GDP damage in between climate change and global financial crisis.

5 Conclusions

For the first time a physical and an economic model have been combined to analyze the global economic impacts of severe space weather events affecting major global industrial regions like the Northeastern USA, central Europe, and Southeast Asia. Macroeconomic models, such as the input-output model we are using in this study, have been used for impact analysis for some time. Such models can be used specifically to provide an estimate of the system-wide impact including those of international trade and global supply chains. We find that a severe Space Weather event could lead to global economic damages of the same order as wars, extreme financial crisis and estimated ~~for~~ future climate change. But some countries may even benefit from the disaster in terms of higher domestic consumption possibilities. A lot of details of the dependencies between solar activity, geomagnetic activity, and failure of electric distribution systems are still unclear. However, we provided a new physical model that relates the damages to the national power systems to the strength and size of a geomagnetic storm.

Appendix A: Disaster impact method

Assume a disaster analysis setting as in Steenge et al. (2007). In its original form, this method allowed only for changes in consumption possibilities, i.e. reductions in final demand, and excess production available for final demand. There is no provision for situations in which the production loss is larger than total final demand, i.e. where intermediate demand has to be affected by the disaster. In this study this circumstance is dealt with by introducing sharing parameters, dividing the total damage to a sector between its deliveries to intermediate and to final demand. This way, a situation where damages to final demand are larger than total final demand can always be avoided by setting the share parameter appropriately.

Reductions in the production of a damaged sector only affect those intermediate sectors that receive a significant enough input from the damaged sector. Intermediate sectors that receive only marginal inputs from a damaged sector are assumed to be able to substitute for the reduced input, or slightly alter their production recipe otherwise, so they can keep producing at pre-disaster levels. The distinction between marginal and significant inputs is controlled by manually setting a threshold.

Let $\mathbf{A}$ be an $N \times N$ input coefficients matrix, $\boldsymbol{y}$ ($N \times 1$) final demand, $\boldsymbol{x}$ ($N \times 1$) total output, and $\mathbf{I}$ a suitable identity matrix. Define $\{\tilde{\boldsymbol{x}}, \tilde{\boldsymbol{y}}\}$ as the post-disaster quantities of $\{\boldsymbol{x}, \boldsymbol{y}\}$. As in Steenge et al. (2007), we ask that the post-disaster economy $\{\tilde{\boldsymbol{x}}, \tilde{\boldsymbol{y}}\}$ is in balance:

$$\tilde{\boldsymbol{x}} = \mathbf{A}\tilde{\boldsymbol{x}} + \tilde{\boldsymbol{y}} \Leftrightarrow (\mathbf{I} - \mathbf{A})\tilde{\boldsymbol{x}} - \tilde{\boldsymbol{y}} = 0 \Leftrightarrow [\mathbf{I} - \mathbf{A} - \mathbf{I}] \left[\begin{array}{c} \tilde{\boldsymbol{x}} \\ \hline \tilde{\boldsymbol{y}} \end{array}\right] = 0.$$

Introduce damage parameters Γ so that $\tilde{x}_i = (1 - \Gamma_i)x_i$. Γ_i is the relative production loss of sector i. $1 - \Gamma_i$ is the relative remaining capacity of sector i. The following approach

let part of the production loss affect intermediate demand, so that the loss affecting final demand is never larger than total final demand itself: $y_i - \tilde{y}_i = \lambda_i(x_i - \tilde{x}_i) = \lambda_i\Gamma_i x_i \Leftrightarrow \tilde{y}_i = y_i - \lambda_i\Gamma_i x_i$. λ_i is the factor that splits the production loss $x_i - \tilde{x}_i$ into a fraction $y_i - \tilde{y}_i$ imposed on final demand, and the remainder on intermediate demand. Assuming a constant production recipe $\mathbf{A} = \text{const.}$, a reduction in only one intermediate input T_{ij} from a damaged sector i means that the entire production of sector j must go down in the same proportion as the reduced input i. Here the production of those sectors j is reduced, where input i formed a significant contribution of sector j's production recipe. Where this is not the case, sectors j are allowed to operate at pre-disaster levels of output.

The loss of production of the electricity sector(s) is represented by $\Delta x_{\text{el}} = \gamma_{\text{el}} \cdot x_{\text{el}}$. This loss affects power supply to households and to other industrial, non-electricity sectors, and is distributed according to $D_{\text{el}} = y_{\text{el}}/x_{\text{el}} = \Delta y_{\text{el}}/\Delta x_{\text{el}}$. We assume the fraction of production capacity lost in non-electricity sectors to be $\gamma_{i \neq el} = \Delta y_{\text{el}}/y_{\text{el}} = \Delta T/T_{\text{el}}$. We generally find

$$\frac{\Delta T}{T} = \frac{\Delta x - \Delta y}{x - y} = \frac{\frac{\Delta y}{D} - \Delta y}{y/D - y} = \frac{\Delta y\left(\frac{1}{D} - 1\right)}{y\left(\frac{1}{D} - 1\right)} = \frac{\Delta y}{y}.$$

Thereafter final and intermediate demand is relative (not necessarily absolute) curtailed equally. If $\Delta x = \Delta y$, i.e. $\Delta T = 0$, one would minimize total economic damage, because the indirect impacts on supply chains and international trade are missing from the assessment of the damage caused by the geomagnetic storm.

Acknowledgements. Author contributions: H. Schulte in den Bäumen, D. Moran, M. Lenzen and A. Steenge designed research, H. Schulte in den Bäumen and M. Lenzen performed research and analyzed data; and H. Schulte in den Bäumen, M. Lenzen and I. Cairns wrote the paper. Competing financial interests: the author(s) declare no competing financial interests.

The Supplement related to this article is available online at doi:10.5194/nhessd-2-4463-2014-supplement.

References

Baumjohann, W., Untiedt, J., and Greenwald, R. A.: Joint two-dimensional observations of ground magnetic and ionospheric electric fields associated with auroral zone currents: 1. Three-dimensional current flows associated with a substorm-intensified eastward electrojet, J. Geophys. Res., 85, 1963–1978, 1980.

Bolduc, L.: GIC observations and studies in the Hydro-Québec power system, J. Atmos. Sol.-Terr. Phy., 64, 1793–1802, 2002.

Boteler, D. H., Pirjola, R. J., and Nevanlinna, H.: The effects of geomagnetic disturbances on electrical systems at the Earth's surface, Adv. Space Res., 22, 17–27, 1998.

Cliver, E. W. and Svalgaard, L.: The 1859 solar-terrestrial disturbance and the current limits of extreme space weather activity, Sol. Phys., 224, 407–422, 2004.

Erinmez, I. A.: Management of the geomagnetically induced current risks on the national grid company's electric power transmission systems, J. Atmos. Sol.-Terr. Phy., 64, 743–756, 2002.

Green, J., Boardsen, S., and Odenwald, S.: Eyewitness accounts of the 1859 superstorm, Adv. Space Res., 38, 145–154, 2006.

Hapgood, M.: Prepare for the coming space weather storm, Nature, 484, 311–313, doi:10.1038/484311a, 2012.

Kappenman, J.: Geomagnetic Storms and their Impacts on the U.S. Power Grid, Metatech Corporation, 358 S. Fairview Ave., Suite E, Goleta, CA 93117, available at: www.ornl.gov/sci/ees/etsd/pes/pubs/ferc_Meta-R-319.pdf (last access: 4 June 2014), 2010.

Kappy, D. and Vegaz, M.: Real Output Costs of Financial Crises: A Loss Distribution Approach, available at: http://mpra.ub.uni-muenchen.de/38988/ (last access: 4 June 2014), 2012.

Lakhina, G. S., Alex, S., Tsurutani, B. T., and Gonzalez, W. D.: Research on historical records of geomagnetic storms, Coronal and Stellar Mass Ejections, IAU Symposium Proceedings of the International Astronomical Union 226, Held 13–17 September, Beijing, edited by: Dere, K., Wang, J., and Yan, Y., Cambridge: Cambridge University Press, 3–15, 2005

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., and Geschke, A.: International trade drives biodiversity threats in developing nations, Nature, 486, 109–112, 2011.

Lenzen, M., Kanemoto, K., Moran, D., and Geschke, A.: Mapping the structure of the world economy, Environ. Sci. Technol., 46, 8374–8381, 2012.

Lenzen, M., Moran, D., Kanemoto, K., and Geschke, A.: Building Eora: a global multi-region input–output database at high country and sector resolution, Econom. Syst. Res., 25, 20–49, 2013.

Leontief, W.: Input–Output Economics, Oxford University Press, New York, NY, USA, 1966.

Leontief, W. and Strout, A.: Multi-Regional Input-Output. Analysis, in: Structural Interdependence and Economic. Development, edited by: Barna, T., Macmillan, London, UK, 119–149, 1963.

Li, J., Crawford-Brown, F., Syddall, M., and Guan, D.: Modeling imbalanced economic recovery following a natural disaster using input–output analysis, Risk Anal., 33, 1908–1923, 2013.

Lloyd's: Solar Storm risk to the North American grid, available at: www.lloyds.com (last access: 4 June 2014), 2013.

Love, J. J.: Credible occurrence probabilities for extreme geophysical events: earthquakes, volcanic eruptions, magnetic storms, Geophys. Res. Lett., 39, L10301, doi:10.1029/2012GL051431, 2012.

Muruyama, T. and Nakai, H.: Empirical formula to relate the auroral electrojet intensity with interplanetary parameters, Planet. Space Sci., 28, 803–813, 1980.

OECD/IFP Futures Project on Future Global Shocks, US Department of Homeland Security, Office of Energy Delivery & Electric Reliability: "Large Power Transformers and the U.S. Electric Grid", Report, available at: http://energy.gov/oe/downloads/large-power-transformers-and-us-electric-grid-report-june-2012, 2012.

Office of Risk Management and Analysis: "Geomagnetic Storms", available at: www.oecd.org/dataoecd/57/25/46891645.pdf (last access: 4 June 2014), 2011.

Okuyama, Y.: Economic modeling for disaster impact analysis: past, present, and future, Econom. Syst. Res., 19, 115–124, 2007.

Pirjola, R. J., Viljanen, A., Pulkkinen, A., and Amm, O.: Space weather risk in power systems and pipelines, Phys. Chem. Earth Pt. C, 25, 333–337, 2000.

Ramesh, B.: Coronal mass ejections and sunspots – solar cycle perspective, Astrophys. J. Lett., 712, L77–L80, 2010.

Riley, P.: On the probability of occurrence of extreme space weather events, Pete Riley, Space Weather, 10, S02012, doi:10.1029/2011SW000734, 2012.

Steenge, A. E. and Boèkarjova, M.: Thinking about imbalances in post-catastrophe economies: an input–output based proposition, Econom. Syst. Res., 19, 205–217, 2007.

Shea, M. A., Smart, D. F., McCracken, K. G., Dreschhoff, G. A. M., and Spence, H. E.: Solar proton events for 450 years: the Carrington event in perspective, Adv. Space Res., 38, 232–238, 2006.

Showstack, R.: Threat of severe space weather to the U.S. electrical grid explored at conference, EOS T. Am. Geophys. Un., 92, 374–375, 2011.

The human impact report on climate change: The anatomy of a silent crisis, Geneva, available at: http://www.ghf-ge.org/human-impact-report.pdf (last access: 4 June 2014), 2009.

The MITRE Corporation: JASON Report, “Impacts of Severe Space Weather on the Electric Grid”, The MITRE Corporation JASON Program Office, 7515 Colshire Drive McLean, Virginia 22102, USA, 2011.

Thomson, A. W. P., Dawson, E. B., and Reay, S. J.: Quantifying extreme behavior in geomagnetic activity, Space Weather, 9, S10001, doi:10.1029/2011SW000696, 2011.

Tsurutani, B. T., Gonzalez, W. D., Lakhina, G. S., and Alex, S.: The extreme magnetic storm of 1–2 September 1859, J. Geophysics. Res., 108, 1268, doi:10.1029/2002JA009504, 2003.

Tsurutani, B. T., Verkhoglyadova, O. P., Mannucci, A. J., Lakhina, G. S., and Huba, L. D.: Extreme changes in the dayside ionosphere during a Carrington-type magnetic storm, Space Weather Space Clim., 5, A05, doi:10.1051/swsc/201 2004, 2012.

Tukker, A. and Dietzenbacher, E.: Global multiregional input–output frameworks: an introduction and outlook, Econom. Syst. Res., 25, 1–19, 2013.

UK House of Commons Defence Committee, Developing Threats: Electro-Magnetic Pulses (EMP), JASON Report, available at: http://go.nature.com/edi8qf (last access: 4 June 2014), 2012.

UNSD: National Accounts Main Aggregates Database, New York, USA, United Nations Statistics Division, available at: http://unstats.un.org/unsd/snaama/Introduction.asp (last access: 4 June 2014), 2011.

US National Academy of Sciences, Severe Space weather Events – Understanding Societal and Economic Impacts, a workshop report, Washington, DC: The National Academies Press, 2008.

Wei, L. H., Homeier, N., and Gannon, J. L.: Surface electric fields for North America during historical geomagnetic storms, Adv. Space Res., 11, 451–462, 2013.

Wiedmann, T. O., ~~Wiedmann, T. O.,~~ Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., and Kanemoto, K.: The material footprint of nations, P. Natl. Acad. Sci. USA, doi:10.1073/pnas.1220362110, in press, 2013.

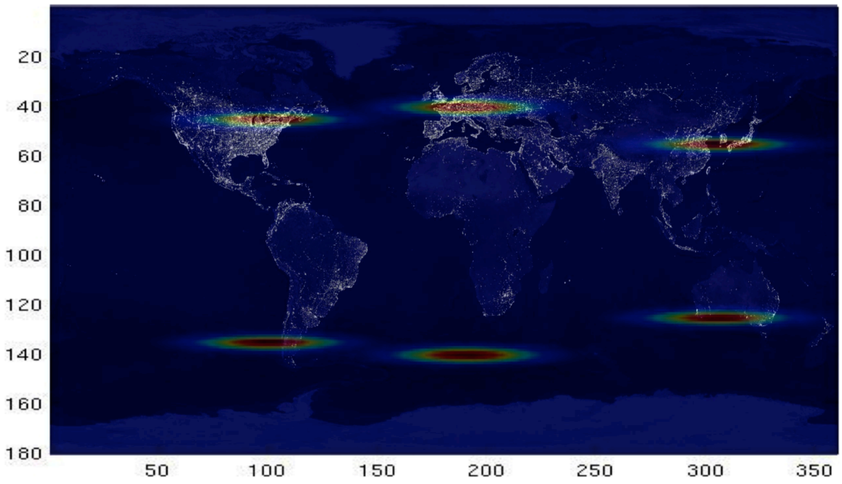

Figure 1. Earth at night ~~with~~ Quebec-like events over the Americas (scenario 1), Europe and the southern ocean (scenario 2), and East Asia and Australia (scenario 3). The red area has the highest storm intensity normalized to 1. The storm’s intensity has a Gaussian falloff.

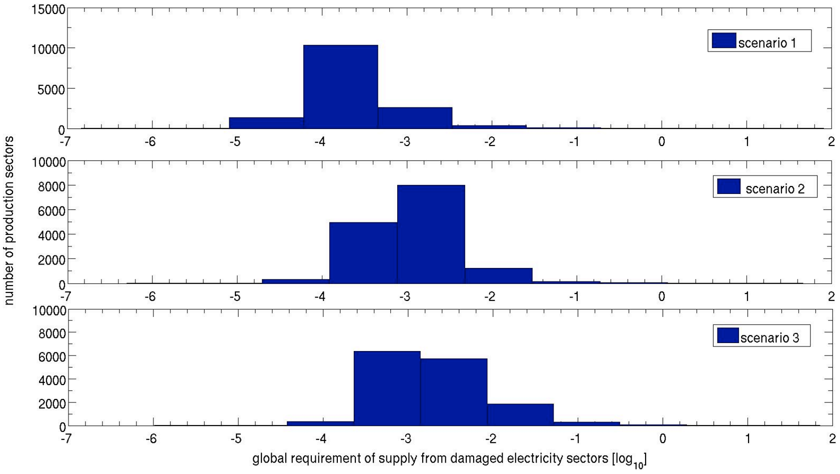

Figure 2. Global production requirement o ply from damaged electriciy sectors. The treshold for scenario 1 is 2×10^{-5}, for scenario 2 5 $\times 10^{-5}$, and for scenario 3 10^{-6}.

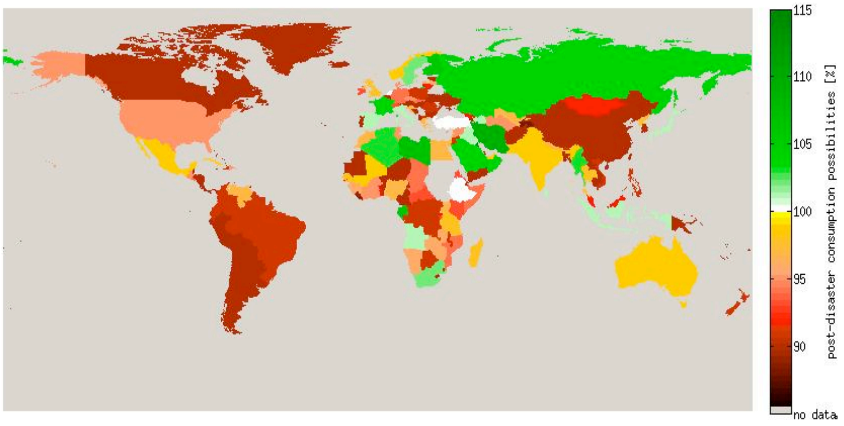

Figure 3. Effects of scenario 1, a Quebec 1989-like event centered over the Americas. Globally, the storm would reduce total consumption possibilities by 3.9 % though the effect is uneven: it is most severe in countries directly affected and their economic partners, while other countries (e.g. Russia, Saudi Arabia, France, and Egypt) may gain consumption possibilities in the post-disaster economy.

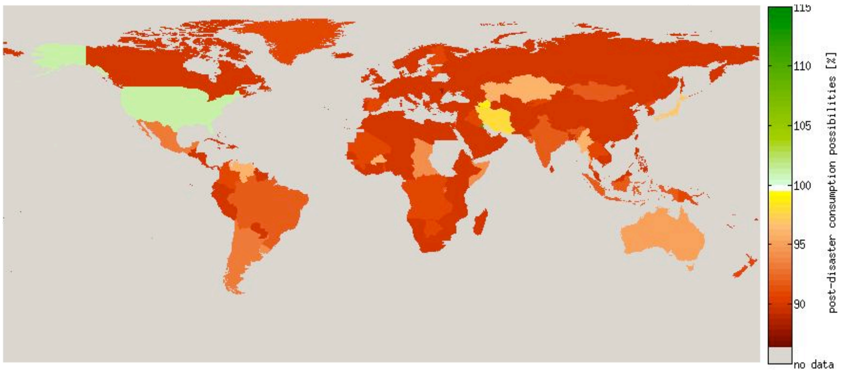

Figure 4. Storm scenario 2, a Quebec-like event centered over Europe. Due to Europe's participation in many global supply chains, a disaster in Europe would be felt not just in the continent itself but in nearly all other countries in the world as well. The US is a notable exception: that economy could experience a slight increase in consumption possibilities in the post-disaster economy.

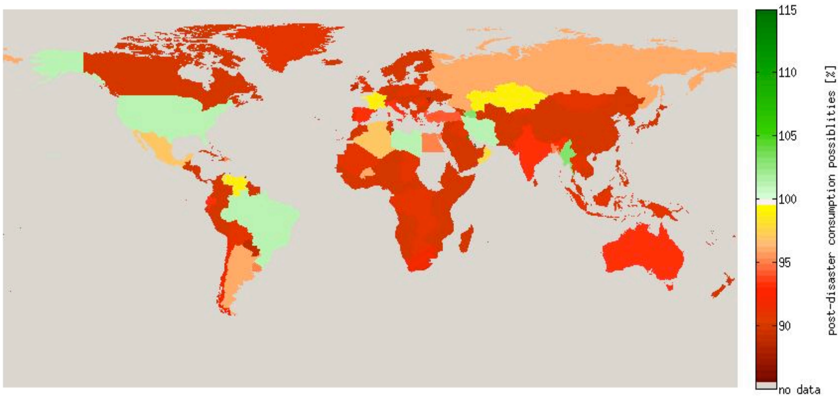

Figure 5. In scenario 3, an Australasian storm, the effects again are seen most strongly in the directly impacted countries and their trade partners.