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JOULE HEATING: HALLOWEEN STORM ON 29-31 OCTOBER 2003

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Abstract

Estimation and prediction of Joule heating is essential for studying the satellite drag, which causes a malfunctioning or complete loss of the satellite. This paper focuses on the production and enhancement of Joule heating and its dependence on the AE (Auroral electrojet) index during a Carrington-like event that occurred from 29th October to 31st October 2003. Simulated Joule heat from the global Magneto-Hydro-Dynamic model- Space Weather Modelling Framework (SWMF) is compared with Joule heating values obtained AE based empirical models. This analysis shows a similar spatial and temporal variation in both the Joule heating values and a similar magnitude with a moderate correlation. No other solar wind or plasma parameters show significant influence on Joule heating values during this extreme geomagnetic storm.

Introduction

Two processes deplete energy in the ionosphere: Joule heating due to the closure of field-aligned currents and the precipitation of magnetospheric electrons, which also induces auroral displays [*Palmroth et al.*, 2004]. Precipitating electrons heat thermalised electrons while Joule heating heats up ions. The global consequences of Joule heating are more significant even if the particle energy deposition rate can surpass the Joule heating rate as the electric fields span vast portions of the earth and have a long lifetime [*Vickrey et al.*, 1982]. Estimation and prediction of Joule heating rate is important because it has major space weather effects. Joule dissipation heats up and expands the ionosphere, which in turn increases the ion outflow and causes satellite drag. Therefore, it should be quantified.

Time variations of the Joule heat can be significantly different in an individual event because it depends on different solar wind parameters. Joule heating enhances and shows drastic time variations during major ionospheric disturbances such as geomagnetic storms and substorms. Joule heating in the ionosphere is expressed as $J \cdot E$, which represents the current and electric fields perpendicular to the magnetic field B [*Zhou et al.*, 2011]. Particles with lower energy generate ionisation at elevated altitudes when Pedersen conductivities surpass Hall conductivities, and Joule heating assumes increasing significance [*Galand and Richmond*, 2001; *Vasyliūnas and Song*, 2005].

Different studies report the variation of Joule heating during ionospheric disturbances; we focus on an extreme geomagnetic storm that happened from 29 to 31 October 2003 because it caused a blackout and temporarily disabled and saturated some space instruments [*Skoug et al.*, 2004]. This is evident as data gaps on the OMNIWeb data set of the interplanetary magnetic field vertical component (BZ), the solar wind velocity (VSW). This is due to the saturation of the Solar Wind Electron Proton Alpha monitor of the ACE satellite. This was a Carrington-like geomagnetic storm observed in the 21st century [*Cid et al.*, 2015], so studying this event may lead to an interpretation of the Joule heating on the 1859 Carrington event also.

An accurate estimation of Joule heating is not possible till now. Many studies have been carried out to estimate the rate of Joule heating by different methods [*Ahn et al.*, 1983; *Foster et al.*, 1983; *Baumjohann and Kamide*, 1984; *Richmond and Lu*, 2000]. We can estimate an average Joule heating rate either by AE-based empirical models or by using global Magneto-Hydro-Dynamic (MHD) simulations. In this paper, we use Joule heating from three AE-based empirical models and simulated Joule heating from one MHD model.

Data

Since there are big gaps in the OMNIWeb (https://omniweb.gsfc.nasa.gov/) data set of the interplanetary magnetic field components and plasma parameters, data from the Advanced Composition Explorer (ACE) satellite is used (http://www.srl.caltech.edu/ACE/). The data has a time lag of 40 min with respect to the OMNIWeb data. Sym-H data and AE index are also from the OMNIWeb database. Because of more coverage and the number of stations, we use the 1-minute SME index produced by SuperMag (https://supermag.jhuapl.edu/indices/) instead of the AE index for empirical calculations.

For an average estimation of Joule heating on 29 to 31 October 2003 (runnumber=Ewelina_Florczak_011421_2), we used the MHD simulation model Space Weather Modeling Framework (SWMF). Community Coordinated

Modeling Center (CCMC) gives us the simulated results from their database. The solar wind input for this simulation is provided by CDAWeb. We used the v20180525 version of SWMF.

AE-based empirical models are used in this study so that we can compare simulated Joule heating with Joule heating calculated from the observed AE index. We calculate the Joule heating using different empirical models that use the AE index. Models 1 and 2 are from other reported studies. Model 3 has an empirical model derived from our own studies of storm-time Joule heating during the autumn season. Model 1 gives empirical relation as U_{JH} (GW) = 0.32AE [*Baumjohann and Kamide*, 1984], and Model 2 gives U_{JH} (GW) = 0.28AE + 0.9 [*Østgaard et al.*, 2002a, b].

Results and Discussion

Extreme geomagnetic storms occur during the October – November months and are often referred to as Halloween storms. One such extreme geomagnetic storm with a longer duration occurred from the 29th of October to the 31st of October 2003. According to *Bravo et al.* [2019]. this event was characterised by the presence of intense solar coronal mass ejections that followed the solar flares on 28 October at 11:10 UT and on 29 October at 20:49 UT. Figure 1. shows the variation of the Sym-H component (top panel) and the AE/SME index (bottom panel). The shock associated with solar flares on October 28 and 29 reaches satellite at 06:00 UT and the second shock at 16:00 UT on October 30, as shown in Figure 2. The southward turning of IMF Bz, which is essential for inducing variation in the AE index, is clearly seen. Corresponding sudden storm commencement (SSC) and variation in AE index are observed at 06:12 UT on October 29 and 16:20 UT on October 30 (Figure 1.). Drastic variations in the AE index denote that there is a chance of high dissipation of Joule heat.

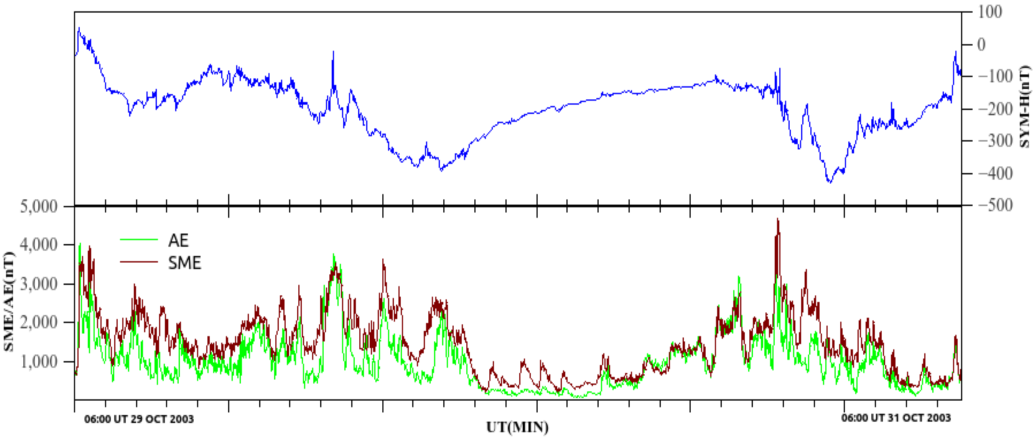

Figure 1. Variation of SYM-H component (top panel) and the AE/SME index (bottom panel) from 06:00 UT of 29th October to 31st October 2003.

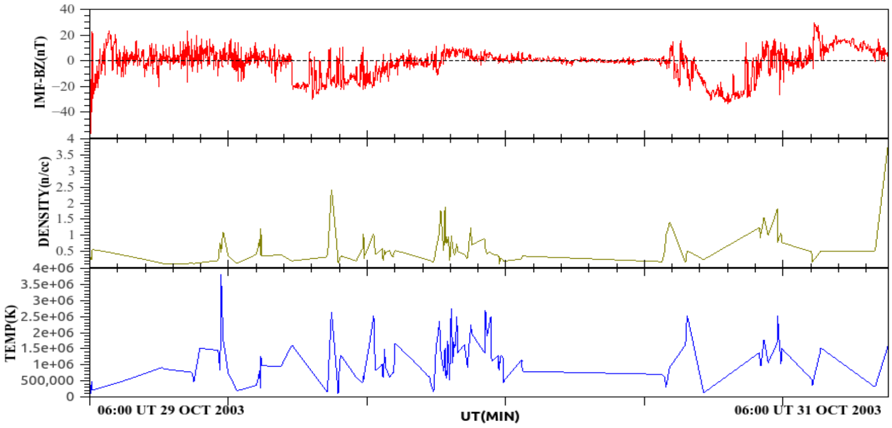

Figure 2. Solar wind input parameters used for simulation from CDA Web on 06:00 UT of 29th October to 31st October 2003.

Using the MHD model SWMF, we got a simulated rate of Joule heating for the above-mentioned time period. These simulation results are available on the CCMC website (https://ccmc.gsfc.nasa.gov/results/viewrun.php?runnumber=Ewelina_Florczak_011421_). The simulated Joule heating rate is shown in Figure 3. When we compare the time variations of simulated Joule heating with SYM-H and AE/SME. There is a time lag between the two data sets because both are projected to two different regions [*Bagheri and Lopez*, 2023]. As we expected, there is an increased production of Joule heating during this extreme storm time. We studied the correlation of both quantities to check whether we can quantify the simulated Joule heating with the AE/SME index.

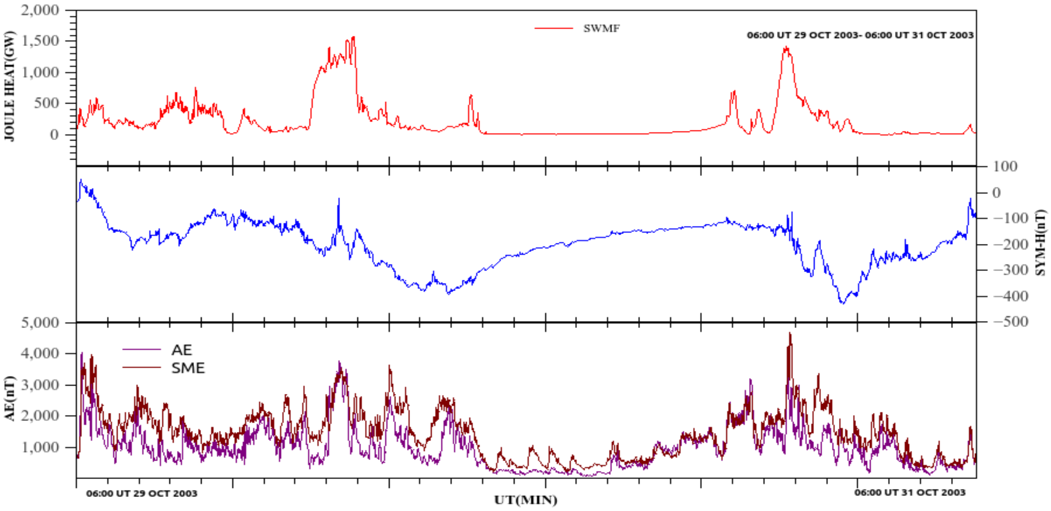

Figure 3. Simulated Joule heating from SWMF- CDA Web (top panel) and SYM-H and AE/SME index on 06:00 UT of 29th October to 31st October 2003.

We calculated the correlation coefficient between the simulated Joule heating obtained from SWMF and the observed SME index, which is represented in Figure 4. A moderate correlation coefficient of R = 0.53 is obtained.

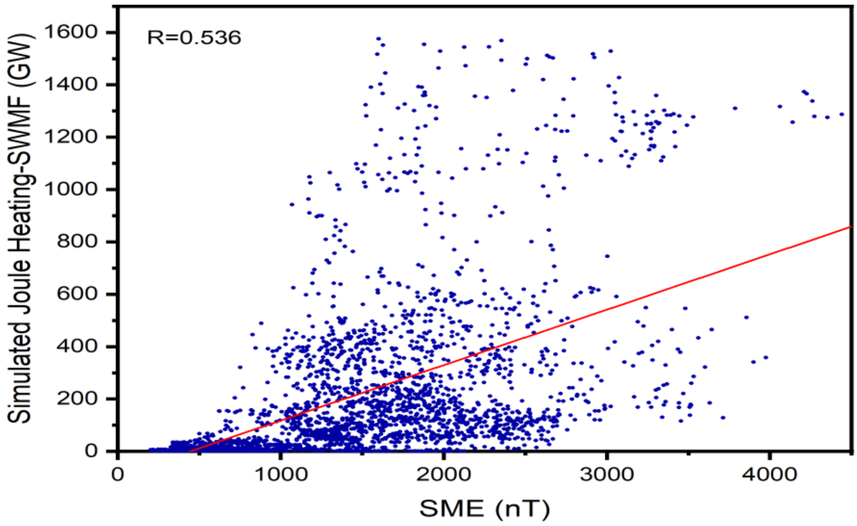

Figure 4. Simulated Joule heating from SWMF- CDA Web as a function of simulated SME index for the 06:00 UT of 29th October to 31st October 2003.

To know how much these simulated values agree with the values obtained from AE-based empirical models, we computed Joule heating using three AE-based empirical models mentioned above and plotted along with the simulated Joule heating obtained from SWMF as represented below (Figure 5).

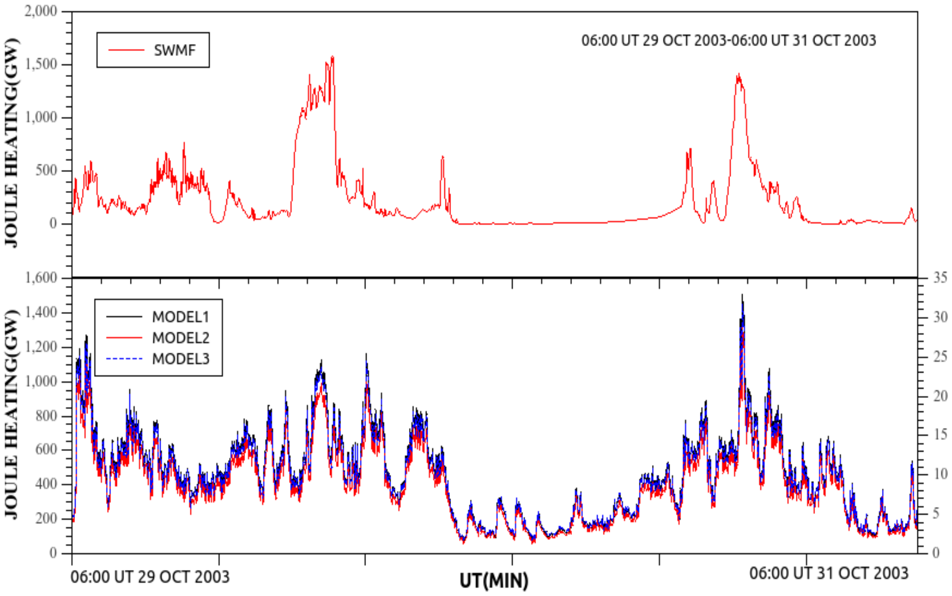

Figure 5. Simulated Joule heating from SWMF- CDA Web (top panel) and Joule Heating obtained from AE-based empirical models on 06:00 UT of 29th October to 31st October 2003.

The observations from all three models are moderately consistent with the spatial and temporal variations. Figure 5 clearly shows the variation of the AE index prior to the enhancement of Joule heating. This suggests an increase in auroral currents and, consequently, in Pedersen conductivity, which raises the rate of Joule heating production. The magnitude of Joule heating is comparable to that predicted by Models 1 and 2; however, Model 3 underestimates the magnitude of Joule heating. Correlation investigations between these AE/SME-based models and simulated Joule heating yielded a correlation coefficient of 0.536, as depicted in Figure 6. All three empirical models have identical correlation coefficients to 14 decimal places. When compared to the aforementioned results as empirical models simulated Joule heating shows a fair dependency on AE/SME index.

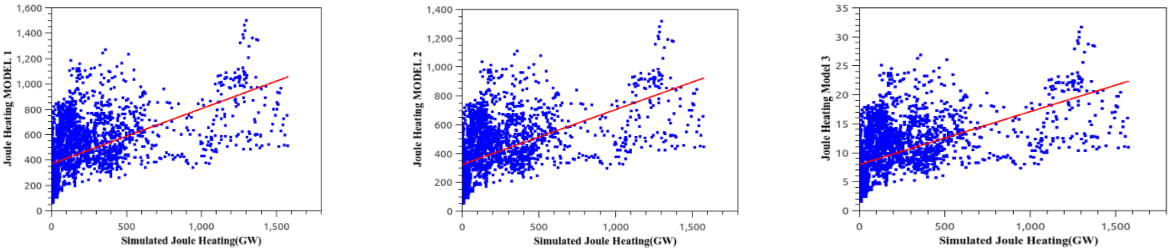

Figure 6. Simulated Joule heating from SWMF - CDA Web as a function of Joule Heating obtained from AE-based empirical models on 06:00 UT of 29th October to 31st October 2003.

Inference

The Carrington event was the greatest known magnetic storm in Earth's history, and it took place on September 1 and 2, 1859 [*Tsurutani et al.*, 2003]. According to *Tsurutani et al.* [2003], the main phase decrease of the H component of the magnetic field was -1600 nT. A superstorm of that magnitude now would have disastrous effects on the ground and space technology systems that modern society depends on. The rapid expansion of the ionosphere caused by the energy released in the atmosphere during strong magnetic storms causes additional drag on low-Earth orbiting satellites, which can shorten their lives or even cause them to explode. Moreover, data loss, satellite communication failure, navigational problems, significant inaccuracies in GPS measurements, and potential threats for both astronauts and passengers on aeroplanes because it causes malfunctions or even irreversible damage to spacecraft [*Lakhina et al.*, 2006]. Studying and predicting the characteristics of such extreme events will help us take remedial measures for their worst effects. Through this paper, we studied one such Carrington-like extreme geomagnetic storm that occurred in the 21st century, especially focused on the production and enhancement of Joule heating and its dependence on the

AE/SME index. Empirical models of Joule heating are compared with the findings of SWMF simulation for this study. The simulations predict an almost similar or lesser value of Joule heating relative to empirical assessments utilising the AE/SME index, and the correlation is only 0.53. Also, we examined the relationship between correlation coefficients and solar wind characteristics, including velocity, proton density, temperature and interplanetary magnetic field (IMF-Bz), during extreme storms. Our findings indicated that there is no substantial evidence to suggest that these parameters influence the connection between SWMF and empirical models. This agrees with studies of *Bagheri and Lopez* [2023]. Therefore, in extreme storm events, the AE index alone cannot be used as an indicator of Joule heating enhancement. Also, SWMF simulation can be used for real-time predictions with moderate accuracy since it agrees with the available AE-based empirical models.

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