Solar and Stellar Variability: Impact on Earth and Planets
Proceedings IAU Symposium No. 264, 2009
A. G. Kosovichev, A. H. Andrei & J.-P. Rozelot, eds.

© International Astronomical Union 2010

doi:10.1017/S1743921309992882

Lower and middle atmosphere and ozone layer responses to solar variation

Ana G. Elias[1,2]

[1]CONICET, Consejo Nacional de Investigaciones Cientificas y Tecnicas, Argentina
[2]Lab. Fisica de la Atmosfera, Depto. de Fisica, Facultad de Ciencias Exactas y Tecnologia,
Universidad Nacional de Tucuman, Av. Independencia 1800, 4000 Tucuman, Argentina
email: `aelias@herrera.unt.edu.ar / anagelias@yahoo.com`

Abstract. Global warming in the troposphere and the decrease of stratospheric ozone concentration has become a major concern to the scientific community. The increase in greenhouse gases and aerosols concentration is believed to be the main cause of this global change in the lower atmosphere and in stratospheric ozone, which is corresponded by a cooling in the middle and upper atmosphere. However, there are natural sources, such as the sun and volcanic eruptions, with the same ability to produce global changes in the atmosphere. The present work will focus on solar variation and its signature in lower and middle atmosphere parameters. The Sun can influence the Earth and its climate through electromagnetic radiation variations and also through changes in the solar wind which causes geomagnetic storms. The effects of both mechanisms over the lower and middle atmosphere and ozone layer will be discussed through an overview of selected papers, which by no means cover this subject that is extremely wide and complex. A fundamental understanding of the atmosphere response to solar variations is required for understanding and interpreting the causes of atmospheric variability. This is an essential focus of climate science, which is seeking to determine the extent to which human activities are altering the planetary energy balance through the emission of greenhouse gases and pollutants.

Keywords. Sun: solar-terrestrial relations, Sun: activity, Earth

1. Introduction

A fundamental and challenging component of Earth Science is the proper attribution of observed climate change to variations in solar output. For this purpose, the response of the atmosphere to solar variability must be determined, and the physical mechanism explaining this response should be understood. This is a very complex subject since, among other factors, the effects of the sun occur simultaneously with other natural and anthropogenic influences and present complex spatial patterns.

In general, to analyze a response to any source of variation we can do it in two ways: theory and experiment, and of course a mix of both. In the case of the detection and analysis of atmosphere and ozone layer responses to solar variation these two ways would be: (1) hypothesis based on physical mechanisms and models, like the General Circulation Models (GCMs) in which we can modify the source of variability in order to measure the kind and magnitude of the response, always followed by an experimental proof for validation, and (2) statistical analysis of experimental data using statistical tools such as FFT, wavelet analysis, correlations, filtering techniques, SSA, etc., followed by an "explanation" of the results obtained.

We know that climate is changing in all the atmospheric layers. The external sources responsible for this are anthropogenic sources (i.e. increasing greenhouse gases concentration, deforestation) and natural sources (i.e. solar variation, volcanic activity,

Downloaded from https://www.cambridge.org/core. IP address: 190.3.119.146, on 31 May 2019 at 15:44:32, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S1743921309992882

astronomical factors). Considering solar variation, which is the concern of this paper, it presents trends and cycles which are not constant in time neither in periodicity. The most commonly used index of solar activity is the sunspot number. Its most prominent variability is the 11-year or Schwabe cycle, which has a variable length of 9-14 years for individual cycles. The background for the 11-year cycle is the 22-year or Hale magnetic polarity cycle, which relates to the reversal of the global magnetic field of the sun. The long-term change in the 11-year cycle amplitude is known as the secular Gleissberg cycle, which is rather a modulation of the 11-year cycle envelope with a varying timescale of 60–120 years. Longer cycles cannot be studied using direct solar observations, but several such cycles have been found in cosmogenic isotope data. A cycle with a period of 200–210 years, called the de Vries or Suess cycle in different sources, is a prominent feature, observed in varying cosmogenic data.

All solar activity parameters (F10.7, group sunspot number, sunspot area, etc.), which include also geomagnetic indices (Kp, Ap, aa, Dst, etc.), present the mentioned cycles. There are also short and mid-term periodicities in the solar output such as the 27-day rotational period and the semiannual variation which is prominent only in geomagnetic data.

In the present work I will emphasize the statistical approach in order to detect the lower and middle atmosphere and ozone layer responses to solar variation through an overview of selected papers that cover only a small part of this extremely wide and complex subject in the field of Sun-Earth interactions.

2. Lower atmosphere

The first papers dealing with climate-sun associations date back to late eighteenth century. For a very good review see Le Treut (2007). Although there were many papers showing statistically significant correlations between troposphere temperature and solar variations, there was not a physical explanation for these statistical results due to the complexity of the climate system. The total solar irradiance, TSI, which corresponds to the wavelength-integrated irradiance reaching the Earth, is the channel through which solar output can impact on troposphere climate. In fact, the incoming solar radiation provides the energy budget and the external forcing for the Earth-atmosphere system. However, the TSI variation in an 11-year solar cycle is 0.1%, which is not enough, according to models, to produce any noticeable effect on climate.

Figure 1 shows global and hemispheric temperature anomaly from Jones *et al.* (2009) for the period 1850-2008, together with Rz and TSI. A 10-year running mean was applied to the time series. The long term variation noticed in Rz, and also in TSI, corresponds to the Gleissberg cycle with a minimum around 1900 and a maximum around 1950. The correlation coefficients between temperature and Rz are 0.77, 0.71 and 0.75 for the Northern Hemisphere, Southern Hemisphere and global respectively. In the case of TSI, these values increase to 0.87, 0.83 and 0.87. That is, Rz can explain between 50% and 60% of temperature variance and TSI between 69% and 76%. But, if the radiative forcing associated to solar variation is not enough according to models to produce the observed temperature changes, how can we obtain such high correlation coefficients?

Another problem is that associations change according to the periods considered, appearing also negative correlations. This can be seen in Figure 2, which shows as an example the running correlation with a 40-year window between global temperature and Rz, and between global temperature and TSI. Also shown, in dashed line, are the correlations considering the whole period. We can think that the response may change in

Downloaded from https://www.cambridge.org/core. IP address: 190.3.119.146, on 31 May 2019 at 15:44:32, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S1743921309992882

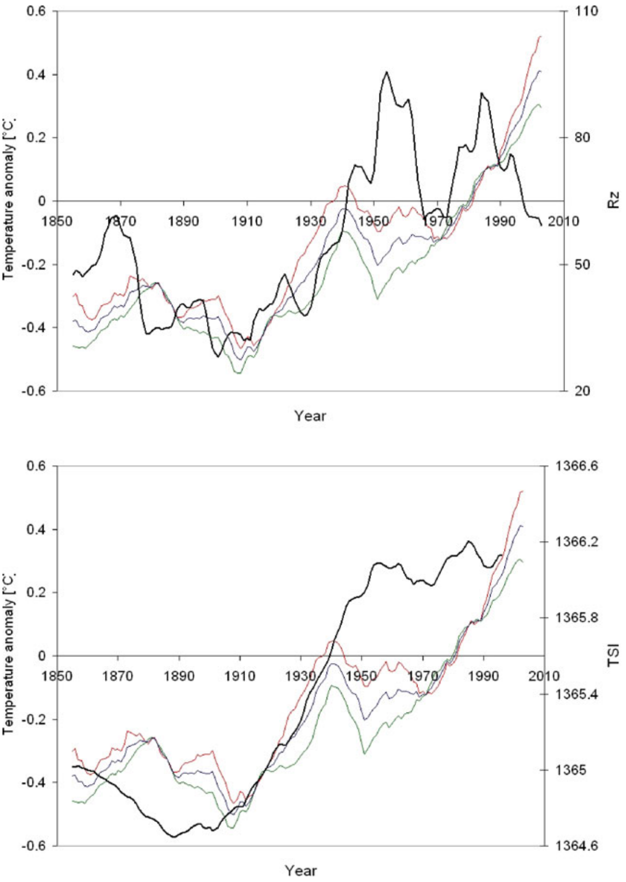

Figure 1. Northern hemisphere (red), Southern hemisphere (green) and global (blue) surface temperature anomalies relative to the 1961-1990 Mean, from Jones *et al.* (2009) and: (a) sunspot number, Rz (black), (b) total solar irradiance, TSI (black). A 10-year running mean was applied to the monthly time series.

time due to interaction with other sources of variation or to environmental changes that would affect sun-Earth association.

A controversial paper by Friis-Christensen and Lassen (1991) intensified the ever existing debate on the role of the sun in climate change. Their achievement was to use the solar cycle length (SCL) instead of Rz, or any other solar proxy. SCL lags ahead Rz around 20 years, and this was enough to match almost exactly the time series of the Northern Hemisphere temperature. Butler (1994) showed later that a single location, Armagh (54.3°N, 6.6W), also presents a high correlation with SCL. The mechanism proposed to explain this association was cloud cover variations caused by cosmic ray flux which is modulated by solar activity (Svensmark and Friis-Christensen 1997; Svensmark 2000; Marsh and Svensmark 2003; Kirby 2007; Carslaw 2009). In this way, a plausible physical mechanism, although still very controversial, was able to explain the statistical results.

Another association between climate and solar activity is linked to climate dynamics and geomagnetic activity, caused by solar variability, mostly by variations of solar-wind properties and the interplanetary magnetic field. In fact, the solar influence on Earth's surface can also consist of a dynamical response to the solar forcing transmitted from the

Downloaded from https://www.cambridge.org/core. IP address: 190.3.119.146, on 31 May 2019 at 15:44:32, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S1743921309992882

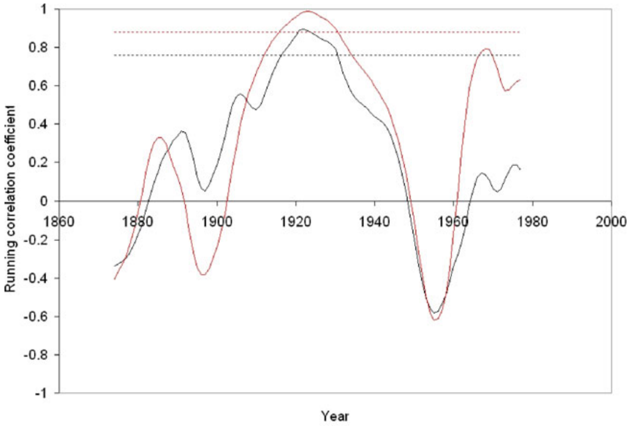

Figure 2. Running correlation with a 40-year window between global temperature and Rz (black solid line) and between global temperature and TSI (red solid line). Dashed lines correspond to the correlation coefficient considering the whole period: 0.75 for temperature vs Rz (black dashed line) and 0.87 for temperature vs TSI (red dashed line). Global temperature from Jones *et al.* (2009).

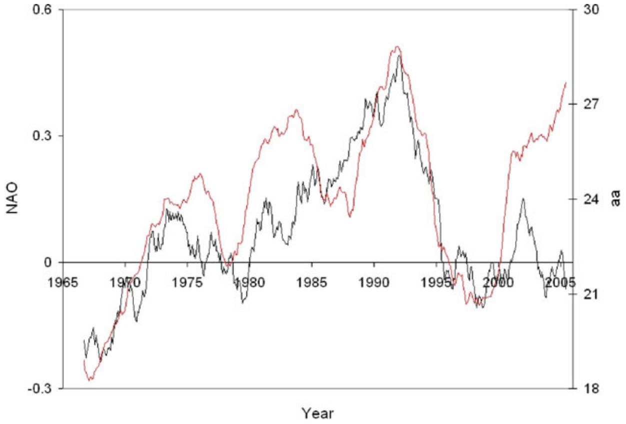

Figure 3. The North Atlantic Oscillation, NAO, index (obtained from ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices) (black) and geomagnetic aa index (red). Both monthly series were smoothed with a 6-year running mean.

stratosphere, rather than a direct radiative effect. As an example Boberg and Lundstedt (2002), Bucha (2002), Thejll *et al.* (2003), Palamara and Bryant (2004), to mention a few, analyzed the North Atlantic Oscillation, NAO, defined as the normalized pressure difference between the Azores and Iceland, which refers to a redistribution of atmospheric mass between the Arctic and subtropical Atlantic producing large changes in the heat and moisture transport between the Atlantic and the neighboring continents. The general conclusion is that enhanced geomagnetic forcing acting on the stratosphere propagates its influence downward and leads to the intensification of the westerly flow affecting the NAO.

Figure 3 shows the NAO index (obtained from ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices) and the geomagnetic aa index, both smoothed with 6-year running mean. The similar behavior of both curves can be clearly noticed. The correlation coefficient between them is 0.68.

Downloaded from https://www.cambridge.org/core. IP address: 190.3.119.146, on 31 May 2019 at 15:44:32, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S1743921309992882

3. Middle atmosphere

The middle atmosphere, that is stratosphere and mesosphere, is affected by the UV spectral band of TSI. Temperature and dynamical responses are expected, but as in the lower atmosphere, results are still controversial. In addition, as we go higher in the atmosphere, the period for which measurements exist becomes shorter, making it more difficult to obtain reliable results.

The temperature response to solar UV changes is expected through ozone and oxygen absorption processes in the middle atmosphere. Keckhut *et al.* (2005) obtained a positive correlation between stratosphere temperature and solar activity with an effect of 1-2 K in the upper stratosphere between minimum and maximum solar activity levels. A similar positive response is obtained by Fadnavis and Beig (2006) for the lower and upper stratosphere, but a negative response for the middle stratosphere. For the mesosphere, model studies suggest an in-phase response to the UV flux, peaking in the upper mesosphere, with a 2 K amplitude, and at the stratopause, with a 1-2 K amplitude (Brasseur 1993; Matthes *et al.* 2004). However, experimental results do not completely agree, revealing much smaller solar signatures and, in some cases, no significant solar signal at all. Beig *et al.* (2008) present an excellent overview and up-to-date status of the mesosphere response to solar variation based on recently available observational data, concluding that mesosphere temperature responds to solar variation depending on season, height and location, with an average of in 1-3 K per 100 sfu.

Regarding dynamics, solar UV variation, which is around 6-10% from solar minimum to solar maximum, produce ozone heating variations that affect temprature and zonal winds. Zonal wind anomalies alter planetary waves propagation, which in turn alters tropospheric circulation (Balachandran and Rind 1995; Kodera 2006). Dynamical processes may also mask solar effects, ending in responses that can be detected only after special filtering procedures, as is the case of some stratosphere parameters. The group of Physics of the Middle Atmosphere of the Freie Universitat Berlin in several publications (Labitzke, 1987, 2004, 2005; Labitzke and van Loon, 1988; Labitzke and Kunze, 2009) showed that there exists a strong signal of the 11-year sunspot cycle, but this signal can only be identified, if the data are stratified according to the phase of the quasi-biennial oscillation, QBO.

4. Ozone layer

The solar UV radiation is an essential factor in ozone production, so it directly affects its concentration. Hood (1997), applying multiple regression methods, estimates the solar cycle variation of total ozone using TOMS data. He obtains maximum variations from solar minimum to maximum of approximately 11 Dobson units around 30°N latitude. Labitzke and van Loon (1997), analyzing also TOMS ozone data, obtained the highest correlation coefficients between F10.7 and the total ozone between 5° and 30° latitude in either hemisphere, thus in regions where ozone is transported poleward. Statistically insignificant correlations are obtained for the equatorial regions where ozone is produced, and for the subpolar regions where it is most plentiful. They conclude then, that it is unlikely that the high correlations are a result of direct radiative interaction between the Sun and ozone but may rather be due to a solar influence on the poleward transport of ozone.

Soukharev and Hood (2006) obtained a vertical structure of the tropical ozone response to the 11-year solar cycle characterized by statistically significant positive responses in the upper stratosphere (40-50 km altitude) and lower stratosphere (below 25 km altitude) and by statistically insignificant responses in the middle stratosphere (28-38 km altitude).

Downloaded from https://www.cambridge.org/core. IP address: 190.3.119.146, on 31 May 2019 at 15:44:32, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S1743921309992882

Geomagnetic activity also takes its part in the ozone layer response to solar variations. Geomagnetic storms and sub-storms inject energetic particles that penetrate down into the Earth's mesosphere and upper stratosphere ionizing molecules and producing large enhancements of odd nitrogen species at high latitudes that intervene in catalytic ozone destruction. According to Lastovicka and Mitch (1999) and Lastovicka and Krizan (2005) the ozone response can also be a redistribution. They observe significant effects of strong geomagnetic storms on total ozone but only during winter and under specific conditions: high solar activity levels and easterly QBO phase.

5. Conclusions

The response of the atmosphere to solar variations is manifest in several parameters (temperature, precipitation, winds, constituent concentrations, etc.) but in such a complex way, that in most cases cannot be detected in a simple way and with usual statistical tools. Here, I tried to give a general and very compact outline of the subject covering only a small portion of this extremely wide and complex theme.

Why is important to understand and measure the lower and middle atmosphere and ozone layer response to solar variation? We live in the Earth and we want to understand and predict the atmosphere behavior which is essential for human life. And, in the present context, a fundamental understanding of the atmosphere response to solar variations is an essential focus of climate science, which is seeking to determine the extent to which human activities are altering the planetary energy balance through the emission of greenhouse gases and pollutants.

Acknowledgements

I gratefully acknowledge the travel support by the Observatorio Nacional of Rio de Janeiro to attend the IAU Symposium 2009, and also thank to Alexander G. Kosovichev and Jucira L. Penna.

The work was supported by the Projects "Geomagnetic activity and Earth's magnetic field as possible causes of long-term trends in the ionosphere" (CONICET/PIP 114-200801-00470) and "Atmosphere and climate variability and long-term trends" (CIUNT/26-E345)

References

Balachandran, N. K. & Rind, D. 1995, Modeling the effects of UV variability and the QBO on the troposphere-stratosphere system. Part I:The middle atmosphere, *Journal of Climate*, 8, 2058–2079.

Beig, G., Scheer, J., Mlynczak, M. G., & Keckhut, P. 2008, Overview of the temperature response in the mesosphere and lower thermosphere to solar activity, *Reviews of Geophysics*, 46, RG3002, doi:10.1029/2007RG000236.

Boberg, F. & Lundstedt, H., 2002, Solar Wind Variations Related to Fluctuations of the North Atlantic Oscillation, *Geophys. Res. Let.*, 29, doi10.1029/2002GL014903.

Brasseur, G. 1993, The response of the middle atmosphere to long-term and short-term solar variability: A two dimensional model, *J. Geophys. Res.*, 98, 23, 079–23, 090, doi:10.1029/93JD02406.

Bucha, V. 2002, Long-term trends in geomagnetic and climatic variability, *Physics and Chemistry of the Earth*, 27, 427–431.

Butler, C. J. 1994, Maximum and minimum temperatures at Armagh obsservatory, 1844-1992, and the length of the sunspot cycle, *Solar Physics*, 152, 35–42.

Carslaw, K. 2009, Cosmic rays, clouds and climate, *Nature*, 460, 332-333.

Fadnavis, S. & Beig, G. 2006, Decadal solar effects on temperature and ozone in the tropical stratosphere, *Ann. Geophys.*, 24, 2091–2103.

Downloaded from https://www.cambridge.org/core. IP address: 190.3.119.146, on 31 May 2019 at 15:44:32, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S1743921309992882

Friis-Christensen, E. & Lassen, K. 1991, Length of the Solar Cycle: An indicator of Solar Activity Closely Associated with Climate, *Science*, 254, 698–700.

Hood, L. L. 1997, The solar cycle variation of total ozone: Dynamical forcing in the lower stratosphere, *J. Geophys. Res.*, 102, 1355–1370.

Jones, P. D., Parker, D. E., Osborn, T. J., & Briffa, K. R. 2009, Global and hemispheric temperature anomalies-land and marine instrumental records. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi: 10.3334/CDIAC/cli.002.

Kodera, K. 2006, The role of dynamics in solar forcing, *Space Science Reviews*, 125, 319–330.

Keckhut P., Cagnazzo, C., Chanin, M. L., Claud, C., & Hauchecorne, A., 2005, The 11-year solar-cycle in the temperature in the upper-stratosphere and mesosphere: Part I: Assessment of observations, *J. Atm. Terr. Sol. Phys.*, 67, 940–947.

Kirby, J. 2007, Cosmic Rays and Climate, *Surv. Geophys.*, 28, 333–375.

Labitzke, K. 1987, Sunspots, the QBO, and the stratospheric temperature in the north polar region, *Geophys. Res. Lett.*, 14, 535–537.

Labitzke, K. & van Loon, K. 1997, Total ozone and the 11-yr sunspot cycle, *Journal of Ammpherrc and Solar-Terreslrial Physics*, 59, 9–19.

Labitzke, K. 2004, On the Signal of the 11-Year Sunspot Cycle in the Stratosphere and its Modulation by the Quasi-Biennial Oscillation (QBO), *J. Atmos. Solar-Terr. Phys.*, 66, 1151–1157.

Labitzke, K. & van Loon, H. 1988, Association between the 11-year solar cycle, the QBO and the atmosphere. Part I: The troposphere and stratosphere in the northern hemisphere in winter, *J. Atmos. Terr. Phys.*, 50, 197–206.

Labitzke, K. 2005, On the Solar Cycle-QBO-Relationship: A Summary, *J. Atmos. Solar-Terr. Phys.*, 67, 45–54.

Labitzke, K. & Kunze, M. 2009, Variability in the stratosphere: The sun and the QBO, In: *Climate and Weather of the Sun-Earth System (CAWSES): Selected Papers from the 2007 Kyoto Symposium*, Edited by T. Tsuda, R. Fujii, K. Shibata, and M. A. Geller, pp. 257-278, Terrapub, Tokyo.

Lastovicka, J. & Mlch P. 1999, Is ozone affected by geomagnetic storms?, *Advances in Space Research*, 24, 631–640.

Lastovicka, J. & Krizan, P. 2005, Geomagnetic storms, Forbush decreases of cosmic rays and total ozone at northern higher middle latitudes, *Journal of Atmospheric and Solar-Terrestrial Physics*, 67, 119–124

Le Treut, H., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson T., & Prather, M. 2007, Historical Overview of Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Marsh, N. & Svensmark, H., 2003, Solar influence on Earth's climate, *Space Science Reviews* 107, 317–325.

Matthes, K., Langematz, U., Gray, L. L., Kodera, K., & Labitzke, K. 2004, Improved 11-year solar signal in the Freie Universitat Berlin Climate Middle Atmosphere Model (FUBCMAM), *J. Geophys. Res.*, 109, D06101, doi:10.1029/2003JD004012.

Palamara, D. R. & Bryant, E. A. 2004, Geomagnetic activity forcing of the Northern Annular Mode via the stratosphere, *Annales Geophysicae*, 22, 725–731.

Soukharev, B. E. & Hood, L. L. 2006, Solar cycle variation of stratospheric ozone: Multiple regression analysis of long-term satellite data sets and comparisons with models, *J. Geophys. Res.*, 111, D20314, doi:10.1029/2006JD007107.

Svensmark, H. 2000. Cosmic rays and Earth's climate, *Space Science Reviews* 93, 175–185.

Svensmark, H. & Friis-Christensen, E., 1997, Variation of cosmic ray flux and global cloud coverage-a missing link in solar-climate relationships, *Journal of Atmospheric and Solar-Terrestrial Physics* 59, 1225–1232.

Thejll, P., Christiansen, B., & Gleisner, H. 2003, On correlations between the North Atlantic Oscillation, geopotential heights, and geomagnetic activity, *Geophys. Res. Lett.*, 30, 1347, doi:10.1029/2002GL016598.

Downloaded from https://www.cambridge.org/core. IP address: 190.3.119.146, on 31 May 2019 at 15:44:32, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/S1743921309992882