Plausible modulation of solar wind energy flux input on global tropical cyclone activity

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ABSTRACT

Studies on Sun-climate connection have been carried out for several decades, and almost all of them focused on the effects of solar total irradiation energy. As the second major terrestrial energy source from outer space, the solar wind energy flux exhibits more significant long-term variations. However, its link to the global climate change is rarely concerned and remains a mystery. As a fundamental and important aspect of the Earth's weather and climate system, tropical cyclone activity has been causing more and more attentions. Here we investigate the possible modulation of the total energy flux input from the solar wind into the Earth's magnetosphere on the global tropical cyclone activity during 1963-2012. From a global perspective, the accumulated cyclone energy variation of solar wind energy flux comparative to solar electromagnetic radiation. However, the variation amplitude of electromagnetic radiation could even exceed 100%, which makes the absolute variation of solar wind energy flux comparable to solar electromagnetic radiation. Massive solar wind energy flux entering into geospace (Esw) via

https://doi.org/10.1016/j.jastp.2018.01.018

Received 3 June 2017; Received in revised form 19 December 2017; Accepted 13 January 2018

Available online xxxx

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magnetic reconnection or viscous interaction can heat the Earth’s atmosphere by three major approaches, auroral particle precipitation and Joule heating at high latitudes, and ring current plasma decay at middle latitudes (Vasyliunas, 2011), and it may drive the Earth’s weather and climate change through some nonlinear interaction mechanisms and enlarge its effects significantly.

The influence of solar activity on the tropical variables has already been revealed by many previous studies. For example, the contribution of 11-year solar cycle to the interdecadal variability of southern oscillation has been widely discussed (Kirov and Georgieva, 2002; Troshichev et al., 2005; Marchitto et al., 2010). Firstly, the magnetospheric energy inputs are not only limited at high latitudes, but also dissipates at mid-latitudes through ring current plasma decay. The energy content of ring current injection is estimated to be about 30% of the total magnetospheric energy inputs (Östgaard and Tanskanen, 2003; Li et al., 2012). Secondly, the magnetospheric energy dissipates at high latitudes can also be linked to tropics through three cells circulation (i.e. Hadley Cell, Ferrel Cell, and Polar Cell; Figure not shown here).

As a fundamental and important aspect of the Earth’s weather and climate system, tropical cyclone (TC) is cyclonic circulations typically polarized by Coriolis force. Figure not shown here). The activity of tropical cyclones is highly variable with large impacts on the in
ducement and regional economies. Nicholls et al. (1995) stated that more than 1.9 million deaths are associated with severe TCs during 1760–1970. Thus, TCs have been causing more and more damages since the 21st century (Webster et al., 2005; Emanuel, 2005). Webster et al. (2005) have shown that the TC number and cyclone days decreased in all cyclone basins except for the North Atlantic during 1995–2005, however, the number and proportion of Category 4–5 hurricanes has a large enhancement.

So far, it is believed that the intensity of a TC or the active level of TCs during a season cannot be attributed to a single factor, such as the global warming or other environment change. Cohen and Sweetser (1975) suggested the correlation between solar cycle and Atlantic TC activities from the similarities in the spectra for the 7-yr running mean TC number in North Atlantic, the 7-yr running mean length of the cyclone season, and the 12-month running mean sunspot numbers. Ivanov (2007) later confirmed the correlation between magnetic storms and TCs in the Atlantic, and found that the linear correlation coefficient changed in different regions from positive to negative values. Elsner and Jagger (2008) found a negative relationship between SSN and U.S. hurricane frequency. Fewer intense tropical cyclones over the Caribbean and Gulf of Mexico are found when sunspot numbers are high. They concluded that the annual U.S hurricane activities are significantly related to solar activity. Elsner et al. (2010) later found that changes in solar ultraviolet radiation (UV) are the major cause. They believed that TCs can reinforce the effect of relatively small changes in solar UV output and thereby, fairly influence the Earth’s climate through the TCs energy dissipation by ocean mixing and atmospheric transport. Recently, Ge et al. (2015) confirmed the high sensitivity of the TC warm core to solar shortwave radiative effect; Haig and Nott (2016) showed that solar forcing (the number of sunspots) contributes to the TC activities over decadal, interdecadal, and centennial scales.

Most previous studies on the relationship between solar activity and TCs focused on the effects from solar electromagnetic radiations. To deepen the understanding of TC activities variation tendency and to improve the prediction accuracy of the climate model, it is worthy to explore other possible driving factors. In this study, we pay our attention on the influence of solar wind energy flux on TCs activities. This paper is organized as follows: the data sets are described in section 2; the results are given in section 3; and the plausible mechanism and summary are presented in section 4 and 5.

2. Data sets

2.1. TC activities

International Best Track Archive for Climate Stewardship (IBTrACS) project aims at merging tropical storm information from all the regional specialized meteorological centers and other international centers and individuals into one product, and providing best track data of TCs in a centralized location (Knapp et al., 2010). The IBTrACS project checks the quality of storm inventories, positions, wind speeds, and pressures. It contains the most complete global set of historical TCs, and is endorsed to be an official archiving and distribution resource for TC best track data by the World Meteorological Organization (Tropical Cyclone Programme). In this study, global TC activity was tabulated by using the IBTrACS Dataset v03r05 from 1963 to 2012 for all tropical cyclone basins. During this half century, a total of 6238 TC events have been recorded in the global context.

ACE for each TC is defined as the sum of the square of 1-minute surface wind speed maximum at 6-hour intervals during the cyclone lifetime (Bell et al., 2000). Annual ACE is the sum of the ACEs for each cyclone in the year. It takes into consideration the number, intensity, and duration period of all the TCs in a year, and can represent the kinetic energy generated by TCs.

2.2. Solar wind energy input

It is still a great observational challenge to accurately monitor the solar wind energy input into the Earth’s magnetosphere on a global scale. Nevertheless, the global three-dimensional magnetohydrodynamic simulation (3D MHD) model makes it possible to do some estimations. Our previous work (Wang et al., 2014) performed 3D global MHD simulations and proposed a empirical formula to estimate the solar wind energy flux input, which is given as follows:

\[ E_{\text{sw}}(W) = 3.78 	imes 10^7 \times n_{\text{sw}}^{2.34} \times V_{\text{sw}}^{1.17} \times B_z^{0.86} \times \left( \sin^2 \theta \right)^{0.25} \]  

Here, \( E_{\text{sw}} \) represents the solar wind energy flux into the magnetosphere in the unit of watts. \( n_{\text{sw}}, V_{\text{sw}}, \) and \( B_z = \sqrt{B_x^2 + B_y^2} \) is the solar wind number density in the unit of \( \text{cm}^{-3} \), the solar wind velocity in the unit of \( \text{km/s} \), and the transverse magnetic field magnitude in the unit of nT, respectively. \( \theta \) is the interplanetary magnetic field clock angle.

The solar wind parameters can be obtained from the OMNI project, which primarily makes a compilation of hourly-averaged solar wind magnetic field and plasma parameters from several spacecrafts since 1963. All the spacecrafts are in geocentric or L1 (Lagrangian point) orbits. The data have been extensively cross compared or cross-normalized, and are well used in space physics studies. Based on the above energy coupling function, the solar wind energy flux entering into the magnetosphere can be obtained when the OMNI 2 data sets are available.

2.3. Geomagnetic activities

In this study, the relative \( q_{\text{pmax}} \) is defined to represent the level of geomagnetic activities during TCs, which is obtained as follows

\[ q_{\text{pmax}} = \frac{q_{\text{pmax}}}{q_{\text{nmax}}} \]  

where \( q_{\text{pmax}} \) is the maximum ap index during a TC event. \( q_{\text{nmax}} \) is calculated based on Monte Carlo method. The time duration of a concerned TC event is recorded as \( \Delta T \). We randomly choose a begin time \( T_0 \) from 1964 to 2012, and then obtain the maximum ap index from \( T_0 \) to \( T_0 + \Delta T \). Then, we repeat the above steps 10^6 times. \( q_{\text{nmax}} \) is the mean value of the 10^6 maximum ap index. When the relative \( q_{\text{pmax}} \) is much greater than 1, it represents that the TC event is during a very disturbed
geomagnetic environment. When the relative apmax is much less than 1, it represents that the TC event is during a very quiet geomagnetic period.

3. Results

We present the relationships of the annual parameters, e.g., sunspot number (SSN, Fig. 1A), total solar irradiation (TSI, Fig. 1B), solar F10.7 irradiation (F107, Fig. 1C), tropical sea surface temperature (SST, Fig. 1D), south oscillation index (SOI, Fig. 1E), the total energy flux input parameter (Ein, Fig. 1F) with the global tropical cyclone activity intensity indicated by the annual ACE over all TC basins from 1963 to 2012. Note that, the detrending and normalizing processes are made for these parameters. SSN, TSI and F107 all show obvious 11-year periodic variations because of the variability of solar activity. However, their long-term variations are not significant. SST represents a lasting gradual enhancement until 2005, thereafter, SST remains at that level. SOI has a 4-year or 5-year periodic variation. During 1975–2007, the SOI is almost negative, indicating an El Nino episodes in the Pacific Ocean. Ein represents a clear 11-year variation as well, with the peak value in 1991 and the minimum value in 2009. For the long-term variation, Ein represent a significant enhancement before 1987, and then a gradual decreases till now. ACE has a peak around 1992. During the latter 20 years, only the decreasing of long-term variation of Ein matches accordingly the lasting decrease of ACE. The correlation coefficient between Ein and ACE is 0.365, which is much stronger than the others, e.g., 0.075 for SSN, 0.006 for TSI, 0.076 for F107, 0.023 for SST, −0.251 for SOI. The threshold value is 0.235, 0.279, and 0.361 for correlation at the 90%, 95%, and 99% confidence level, respectively. It thus concludes that the TC activity (represented by annual ACE) is only correlated with Ein, but not with the SSN, TSI, F107, SST and SOI.

For comparison, the correlation analysis are performed for all the indices with a time lag from 1-yr to 10-yr. The results are listed in Table 1. To alleviate the effect of sample size, the parameter P-value, p, is calculated to quantifying the strength of the correlation relationship which is independent of the sample number. Generally speaking, $p > 0.1$ indicates no linear; $p = 0.05 \sim 0.1$ indicates a weak linear relationship; $p = 0.01 \sim 0.05$ indicates a moderate linear relationship; $p = 0.001 \sim 0.01$ indicates a strong linear relationship; and $p < 0.001$ indicates a very strong linear relationship.

Considering the situations with 1-yr time lag, the correlation co-

![Fig. 1. Overview of the relationships of the annual parameters, e.g., SSN (A), TSI (B), F107 (C), SST (D), SOI (E), and Ein (F) on the global tropical cyclone activity intensity, the annual ACE over all TC basins from 1963 to 2012. Note that the detrending and normalizing processes are all made for these parameters. For a dataset with 50 samples, the threshold value of the correlation coefficient at 90%, 95%, and 99% confidence level is calculated to be 0.235, 0.279, and 0.361, respectively.](image)
en of a few hundred keV (Daglis et al., 1999). There are dominant loss
riers of the storm ring current are protons with energy from several keV
ACE is not close to 1. More work should be done in the future.

Table 1
Correlation Coefficients (upper values in each row) and P-values (bottom values in each
row) of SSN, TSI, F107, SST, SOI, and E\textsubscript{0} with ACE over all TC basins from 1963 to 2012.
Column 2 gives the values without time lag considered. Column 3 gives the values with 1-yr
lag considered. Column 4 gives the values with a time lag from 1-yr to 10-yr. Column 5
gives the time lag for the best values.

<table>
<thead>
<tr>
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<th>no time lag</th>
<th>1-yr lag</th>
<th>Maximum</th>
<th>Time lag</th>
</tr>
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<tbody>
<tr>
<td>SSN</td>
<td>0.075</td>
<td>0.200</td>
<td>0.366</td>
<td>3-yr</td>
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<tr>
<td>TSI</td>
<td>0.607</td>
<td>0.164</td>
<td>0.0991</td>
<td></td>
</tr>
<tr>
<td>F107</td>
<td>0.965</td>
<td>0.375</td>
<td>0.039</td>
<td></td>
</tr>
<tr>
<td>SST</td>
<td>0.023</td>
<td>0.147</td>
<td>0.147</td>
<td>1-yr</td>
</tr>
<tr>
<td>SOI</td>
<td>-0.251</td>
<td>-0.206</td>
<td>-0.322</td>
<td>2-yr</td>
</tr>
<tr>
<td>E\textsubscript{0}</td>
<td>0.131</td>
<td>0.093</td>
<td>0.162</td>
<td>2-yr</td>
</tr>
<tr>
<td></td>
<td>0.365</td>
<td>0.466</td>
<td>0.466</td>
<td>1-yr</td>
</tr>
<tr>
<td></td>
<td>0.0091</td>
<td>0.00064</td>
<td>0.00064</td>
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efficients, except for SOI, are larger than the results without a time lag considered.
However, only the correlation coefficient between E\textsubscript{0} and ACE, 0.466, passes the confidence test with a 99% level. The corre-
ponding p is 0.00064, less than 0.001, indicating a very strong linear
relationship in a statistical sense. Among the maximums of correlation coefficients with a time lag from 1-yr to 10-yr considered, the parameter E\textsubscript{0} performs best.

Note that, there may be several impact factors jointly contributing to
the TC activities, which is why the correlation coefficient between E\textsubscript{0} and ACE is not close to 1. More work should be done in the future.

The ring current energy content is one of the two major energy sinks
of solar wind energy flux input into the magnetosphere. The main car-
riers of the storm ring current are protons with energy from several keV
to a few hundred keV (Daglis et al., 1999). There are dominant loss
d processes of the ring current energetic ions. One is the Coulomb collision
with cold dense plasmas in the plasmasphere (Wentworth et al., 1959).
The other one is the charge exchange with neutral atoms (Dessler and
Parkar, 1959). Recently, Ebihara et al. (2014) evaluated the Coulomb
lifetime and Change exchange lifetime of ring current ions. Based on their
results, the Coulomb lifetime and Change exchange lifetime are esti-
mated to be ∼ 330 days and ∼ 220 days for the ring current protons with
the energy of 200 keV at L = 4.5. Thus, 1-yr time delay of the modulation
of E\textsubscript{0} on TC activities is expected. The correlation coefficient between E\textsubscript{0} and ACE is indeed even better of 0.466 if 1-yr time delay is considered.

Traditionally, areas of tropical cyclone formation could be divided
into six basins, including the western Pacific Ocean (WP), the eastern
Pacific Ocean (EP), the southern Pacific Ocean (SP), the northern Atlantic
Ocean (NA), the northern Indian Ocean (NI), and the southern Indian
Ocean (SI). We further study the relationship between the solar wind
energy flux input and regional tropical cyclone activities, as shown in

Table 2. Tropical cyclone activities reveal a positive correlation relation-
ship with E\textsubscript{0} at the 95% confidence level at the basin of WP, EP, and
SP (0.420, 0.407, 0.315). A negative correlation of −0.285 is found at
the basin of NA, which is in agreement with the findings by Elnser and Jagger
(2008). No significant relationship is found at the basin of NI and SI.

If the solar wind energy flux can indeed modulate the global TC ac-
tivity as shown before, a natural thought is that a TC activity should be
more intense during the period when more solar wind energy flux enters
into the magnetosphere. In the early age of space era, there are many data
gaps of E\textsubscript{0} for many TCs. Magnetospheric studies reveals that the more
solar wind energy flux input would cause more intense geomagnetic
disturbances (Li et al., 2012). The well-used geomagnetic index, 3-hourly
ap index, has no data gap for any TC and thus is used as a proxy of E\textsubscript{0}
here. As shown in Fig. 2A, there is a linear relationship between the solar
wind energy input and the ap index, with the correlation coefficient of
0.92. The mentioned natural thought is confirmed by Fig. 2B, which
clearly shows that the maximum wind speed of TC events during severe
geomagnetic activities tends to be greater than that during quiet
geomagnetic activities.

4. Plausible mechanism and discussion

The modulation mechanism of solar wind energy flux on TC activity
remains mysterious. However, previous studies might give some clues.
The solar wind energy flux is the primary energy source for the magne-
tosphere. Vasyliunas (2011) summarized the energy conversion and
dissipation/loss processes in the magnetosphere. In short, the solar wind
energy flux can heat the atmosphere unevenly by ring current precipi-
tation, auroral electron precipitation, and Joule heating, especially dur-
ing geomagnetic active time period. Such atmosphere heating is usually
occurred at the altitude of 80–200 km, which is called thermosphere. The
detailed coupling between thermosphere and troposphere is not clear so
far. However, the modulation of thermospheric temperature by solar
wind energy flux could cause indirectly dynamic variation in the lower
atmosphere (Kodera and Kuroda, 2002).

We proposed a plausible mechanism to interpret the possible modu-
lation process, as shown in Fig. 3. As solar activities enhance, the solar
wind energy flux increases, resulting in 1) geomagnetic activities en-
hancements (Li et al., 2012), 2) reduction of cosmic rays reaching the
atmosphere due to an enhanced IMF shielding (Singh and Singh, 2008),
and 3) enhancement of atmosphere heating (Vasyliunas, 2011). Under an
enhanced geomagnetic field environment, the transport coefficient of

cosmic rays along the mean magnetic field decreases (Giacalone and
Jokipii, 1999), causing less cosmic rays could reach the atmosphere as
well. As a verification, the correlation coefficient between the annual
solar wind energy flux and the cosmic ray intensity at Oulu station is
−0.79 in our study. The global cloud coverage was found to be positively
correlated with cosmic ray flux (Svensmark and Friis-Christensen, 1997).
Thus, the global cloud coverage (tcdc) decreases for enhanced solar ac-
tivities, and the sea water would absorb more solar irradiance energy and
result in an increase of the sea surface temperature (SST) and latent heat.
As a major energy source, latent heat release could issue in rapid inten-
sification and development of tropical cyclones (Pauley and Smith, 1988;
Kuo and Low-Nam, 1990). Meanwhile, the gradient of sea level pressure
(SLP) from the continent to the sea enhances the tcdc decrease. The
enhancements of the SLP gradient and the atmosphere heating contribute
to the reduction of the vertical wind shear over the tropical oceans, which
leads to an enhancement of TC activity (Gray, 1968; Gray et al., 1993).
Composite maps in Fig. 4 provide indirect evidences to support our
interpretation. When the solar wind energy flux increases, 1) the tcdc
over tropical Pacific and Indian Oceans decreases, while the situation
over tropical NA reverses, as shown in Fig. 4A; 2) the SLP over tropical
Pacific Ocean decreases, while it increases over tropical Atlantic and
Indian Oceans, as shown in Fig. 4B. It means that the SLP is significantly
higher over the western hemisphere and North Atlantic Ocean than that

Table 2
Correlation Coefficients (upper values in each row) and P-values (bottom values in each
row) of SSN and E\textsubscript{0} for different TC basins from 1963 to 2012. Column 2 gives the
values without time lag considered. Column 3 gives the values with 1-yr lag considered.
Column 4 gives the best values with a time lag from 1-yr to 10-yr. Column 5 gives the time
lag for the best values.

<table>
<thead>
<tr>
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<td>0.420</td>
<td>0.398</td>
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<td></td>
<td>0.0024</td>
<td>0.0042</td>
<td>0.0024</td>
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<tr>
<td>EP</td>
<td>0.407</td>
<td>0.538</td>
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<td>1-yr</td>
</tr>
<tr>
<td></td>
<td>0.0033</td>
<td>0.000057</td>
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<td></td>
</tr>
<tr>
<td>SP</td>
<td>0.315</td>
<td>0.301</td>
<td>0.315</td>
<td>0-yr</td>
</tr>
<tr>
<td></td>
<td>0.026</td>
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</tr>
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<td>NA</td>
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<td>-0.291</td>
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</tr>
<tr>
<td></td>
<td>0.045</td>
<td>0.040</td>
<td>0.045</td>
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</tr>
<tr>
<td>NI</td>
<td>-0.267</td>
<td>-0.139</td>
<td>-0.267</td>
<td>0-yr</td>
</tr>
<tr>
<td></td>
<td>0.061</td>
<td>0.336</td>
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<td></td>
<td>0.363</td>
<td>0.520</td>
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over the eastern Pacific, which would lead to eastward/westward pressure gradient over the tropical Pacific/Atlantic and further influence the zonal wind and SST in situ. As shown in Fig. 4C, the SST over tropical Pacific and Indian Oceans increases, while the situation reverses for tropical Atlantic Ocean. The positive/negative SST anomaly at lower latitudes (30S-30N) is well confined where negative/positive tcdc anomaly is located (Fig. 3A). This is reasonable due to the existence of cloud-radiation feedback. Meanwhile, the 850-hPa wind anomalies represent west wind enhancement over tropical Pacific and India Oceans, while east wind enhancement over tropical Atlantic Ocean. These features are consistent with the results shown in Fig. 4A and B. At last, the vertical wind shear over tropical Pacific Ocean reduces, while the situations reverse for tropical Atlantic and Indian Oceans, as shown in Fig. 4D. The reduction of vertical wind shear and enhancement of SST over tropical Pacific Ocean jointly contribute to the intensification of tropical cyclone activities in WP, EP, and SP. This is consistent with the positive correlation of tropical cyclone activities at WP, EP, and SP basin on $E_{in}$. The enhancement of vertical wind shear and reduction of SST over tropical Atlantic Ocean contribute to the decrease of tropical cyclone activities in NA, which is consistent with the negative correlation of tropical cyclone activities at NA basin on $E_{in}$. The competitive contributions from enhancements of SST and vertical wind shear over tropical Indian Ocean complicate the variation of tropical cyclone activities at NI and SI basins, and there exists no significant correlations with $E_{in}$ as shown before.

Note that, the increasing of regional SST together with a decreasing vertical wind shear can result in an increasing tropical cyclone activity. As shown in Fig. 4, the significant SST anomalies are mainly located in

Fig. 2. Relationship between the solar wind energy flux input and TC intensity and geomagnetic activity intensity. (A) linear relationship between the solar wind energy input and the ap index, with the correlation coefficient of 0.92; (B) the maximum wind speed of TC events during different relative relative $\phi_{ap}$.
central eastern tropical Pacific and tropical North Atlantic. Note that, the SST used in Fig. 1D was the average value for the global tropical seas. It implies that the global tropical SST does not exert uniform impact on the TC activities.

The physical mechanism is very complex. The proposed mechanism is just a plausible one based on our knowledge and some observation clues. More works are quite needed in the future.

5. Summary

Many studies presented that solar variability do play an significant role in affecting the Earth’s climate change. Almost all of previous studies focused on the effects of solar total irradiation energy. As the second major source, the solar wind energy flux exhibits more significant long-term variations, but its effect has been rarely concerned. Although the energy content of solar wind energy flux is of 4-5 orders lower than that of irradiation energy, its long-term variation is much more significant.

For the first time, we find some observational clues indicating the potential modulation of the solar wind energy flux on the global tropical cyclone activity, and propose a plausible mechanism. We believe this will open a new window to discuss the natural driver of the climate change. In this study, the global tropical cyclone activity is found to be modulated by solar wind energy flux, but not the solar irradiation and the Earth’s weather and climate parameters. A possible mechanism is proposed and some evidences are also presented. The physical mechanism is very complex and far from well understood. More further works are quite needed. Nevertheless, the findings are helpful to our understanding of solar impact on the Earth’s climate change. More attentions on solar wind energy flux is suggested to be paid in the future studies.

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