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

Hui Li [a,*], Chi Wang [a,f], Shengping He [b], Huijun Wang [b,c,e], Cui Tu [d], Jiyao Xu [a], Fei Li [e], Xiaocheng Guo [a]

[a] State Key Laboratory of Space Weather, National Space Science Center, CAS, Beijing, 100190, China
[b] Climate Change Research Center, CAS, Beijing, 100029, China
[c] Nanjing University for Information Science and Technology, Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters/Key Laboratory of Meteorological Disaster, Ministry of Education, Nanjing, 210044, China
[d] Laboratory of Near Space Environment, National Space Science Center, CAS, Beijing, 100190, China
[e] Nansen-Zhu International Research Center, Institute of Atmospheric Physics, CAS, Beijing, 100029, China
[f] University of Chinese Academy of Sciences, Beijing, 100049, China

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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 increases gradually since 1963 and starts to decrease after 1994. Compare to the previously frequently used parameters, e.g., the sunspot number, the total solar irradiation, the solar F10.7 irradiation, the tropical sea surface temperature, and the south oscillation index, the total solar wind energy flux input exhibits a better correlation with the global tropical cyclone activity. Furthermore, the tropical cyclones seem to be stronger with more intense geomagnetic activities. A plausible modulation mechanism is thus proposed to link the terrestrial weather phenomenon to the seemingly-unrelated solar wind energy input.

1. Introduction

Since 1970, the affecting factors of global climate change have gradually becoming the central topics in the science community, the general public, and the policy-makers as well. Besides human activities, solar variability is another significant natural contributor. Herschel (1801) first proposed that solar activity may affect the Earth's climate system. Thereafter, various studies confirmed that the Earth's weather and climate changes are significantly affected by solar activity variations (e.g., Gray et al., 2010). The time scale ranges from several hours or several days (Tinsley and Deen, 1991; Tinsley and Heelis, 1993; Veretenenko and Thejll, 2004; Kniveton and Tinsley, 2004) to a decade or a century, or even longer time scale (Friis-Christensen and Lassen, 1991; Bond et al., 2001; Neff et al., 2001; Wang et al., 2005; Camp and Tung, 2007; van Loon et al., 2007).

There are two major forms of the solar irradiance, electromagnetic radiation and corpuscular radiation. The electromagnetic radiation is so-called solar photons, and the corpuscular radiation is referred to the solar wind energy flux here, which contains the solar wind, the interplanetary magnetic field, and solar energetic particles. In general, the energy content of electromagnetic radiation enters into the terrestrial system is of 4-5 orders higher than the solar wind energy flux, therefore it is no surprise that most of the researches about the solar influences on the Earth's climate change focused on the effects of solar electromagnetic radiation. However, the variation amplitude of electromagnetic radiation during a solar cycle (about 11 years) is quite small, of only about 1 Wm^{-2} or $\sim 0.1\%$ (Fröhlich, 2013). In contrast, the decadal variation of the solar wind energy flux could even exceed 100%, which makes the absolute variation of solar wind energy flux comparative to solar electromagnetic radiation. Massive solar wind energy flux entering into geospace (E_{in}) via

* Corresponding author.
E-mail address: hli@nssc.ac.cn (H. Li).

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magnetic reconnection or viscous interaction can heat the Earth's atmosphere by three major aprroaches, 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 (Østgaard 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 forming over the tropical and subtropical oceans. On the average, there are about 80 TCs throughout the world every year. It is estimated that the power of a mature TC is as high as 6×10^{14} W. In general, TCs can transport the thermal energy from the equator to high-latitudes and contribute to maintain the global heat balance. In the meantime, TC is one of the disaster weather phenomena, which could cause very enormous loss of life and property. Nicholls et al. (1995) stated that more than 1.9 million deaths are associated with severe TCs during 1780–1970. Thus, TCs have been causing more and more attentions 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:

$$E_{in}(\mathbf{W}) = 3.78 \times 10^{7} \times n_{SW}^{0.24} \times V_{SW}^{1.47} \times B_{T}^{0.86} \times \left[\sin^{2.70}\left(\frac{\theta}{2}\right) + 0.25\right] \tag{1}$$

Here, E_{in} represents the solar wind energy flux into the magnetosphere in the unit of watts. n_{SW}, V_{SW}, and B_T ($= \sqrt{B_Y^2 + B_Z^2}$) is the solar wind number density in the unit of cm^{-3}, the solar wind velocity in the unit of km/s, and the transverse magnetic field magnitude in the unit of nT, respectively. θ 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 (Lagrange 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 ap_{max} is defined to represents the level of geomangeitc activities during TCs, which is obtained as follows

$$\textbf{relative}\ ap_{max} = ap_{max} \Big/ \overline{ap_{max}} \tag{2}$$

where ap_{max} is the maximum ap index during a TC event. $\overline{ap_{max}}$ is calculated based on Monte Carlo method. The time duration of a concerned TC event is recorded as ΔT. 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+ΔT. Then, we repeat the above steps 10^6 times. $\overline{ap_{max}}$ is the mean value of the 10^6 maximum ap index. When the relative ap_{max} is much greater than 1, it represents that the TC event is during a very disturbed geomagnetic environment. When the relative ap_{max} 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 (E_{in}, 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. E_{in} 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, E_{in} 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 E_{in} matches accordingly the lasting decrease of ACE. The correlation coefficient between E_{in} 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 E_{in}, 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-

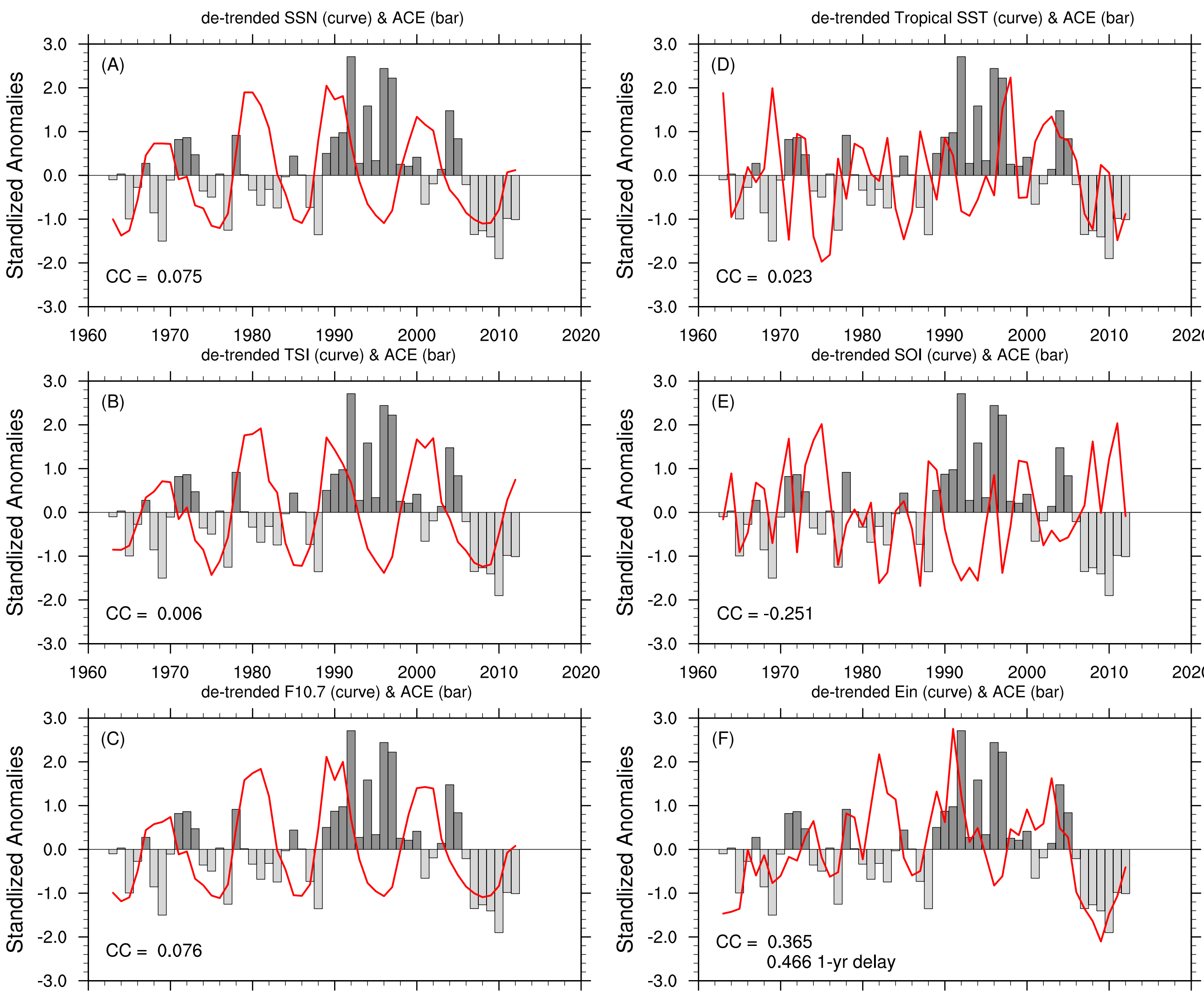

Fig. 1. Overview of the relationships of the annual parameters, e.g., SSN (A), TSI (B), F107 (C), SST (D), SOI (E), and E_{in} (F) on the global tropical cyclone activity intensity, the annual ACE over all TC basins from 1963 to 2012. Note that the detrending and normalizing processes are all made for 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.

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_{in} 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 best values with a time lag from 1-yr to 10-yr. Column 5 gives the time lag for the best values.

	no time lag	1-yr lag	Maximum	Time lag
SSN	0.075	0.200	0.366	3-yr
	0.607	0.164	0.0091	
TSI	0.006	0.128	0.293	3-yr
	0.965	0.376	0.039	
F107	0.076	0.206	0.372	3-yr
	0.601	0.150	0.0074	
SST	0.023	0.147	0.147	1-yr
	0.875	0.309	0.307	
SOI	−0.251	−0.206	−0.322	2-yr
	0.079	0.151	0.019	
E_{in}	0.365	0.466	0.466	1-yr
	0.0091	0.00064	0.00064	

efficients, except for SOI, are larger than the results without a time lag considered. However, only the correlation coefficient between E_{in} and ACE, 0.466, passes the confidence test with a 99% level. The corresponding 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_{in} performs best.

Note that, there may be several impact factors jointly contributing to the TC activities, which is why the correlation coefficient between E_{in} 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 carriers 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 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 Parker, 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 estimated to be $\sim$ 330 days and $\sim$ 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_{in} on TC activities is expected. The correlation coefficient between E_{in} 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 relationship with E_{in} 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 Elsner and Jagger (2008). No significant relationship is found at the basin of NI and SI.

Table 2
Correlation Coefficients (upper values in each row) and P-values (bottom values in each row) between E_{in} and ACE 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.

	no time lag	1-yr lag	Maximum	Time lag
WP	0.420	0.398	0.420	0-yr
	0.0024	0.0042	0.0024	
EP	0.407	0.538	0.538	1-yr
	0.0033	0.000057	0.000057	
SP	0.315	0.301	0.315	0-yr
	0.026	0.034	0.026	
NA	−0.285	−0.291	−0.285	1-yr
	0.045	0.040	0.045	
NI	−0.267	−0.139	−0.267	0-yr
	0.061	0.336	0.061	
SI	0.131	0.093	0.162	2-yr
	0.363	0.520	0.260	

If the solar wind energy flux can indeed modulate the global TC activity 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_{in} 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_{in} used 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 magnetosphere. 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 precipitation, auroral electron precipitation, and Joule heating, especially during 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 modulation process, as shown in Fig. 3. As solar activities enhance, the solar wind energy flux increases, resulting in 1) geomagnetic activities enhancements (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 activities, 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 intensification 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 as 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

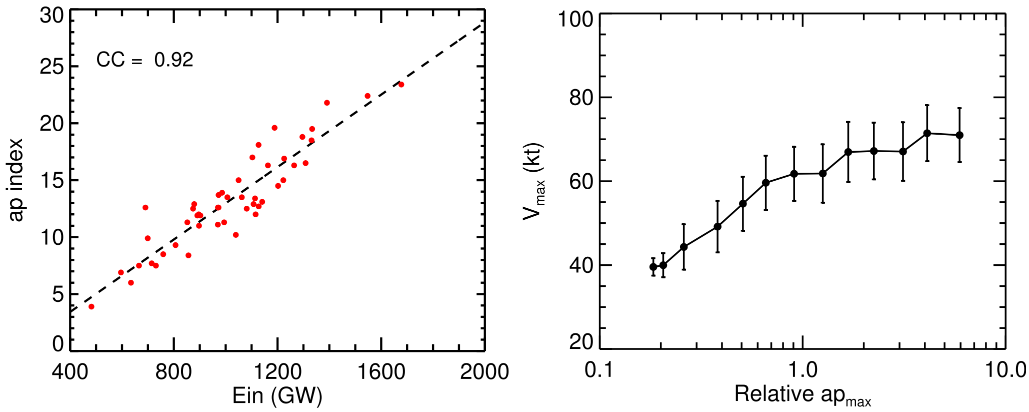

Fig. 2. Relationship between the solar wind energy flux input and TC intensity and geomagnetic activity intensity. (A) linear relationship between the solar wind energy input and the ap index, with the correlation coefficient of 0.92; (B) the maximum wind speed of TC events during different relative relative ap_{max}.

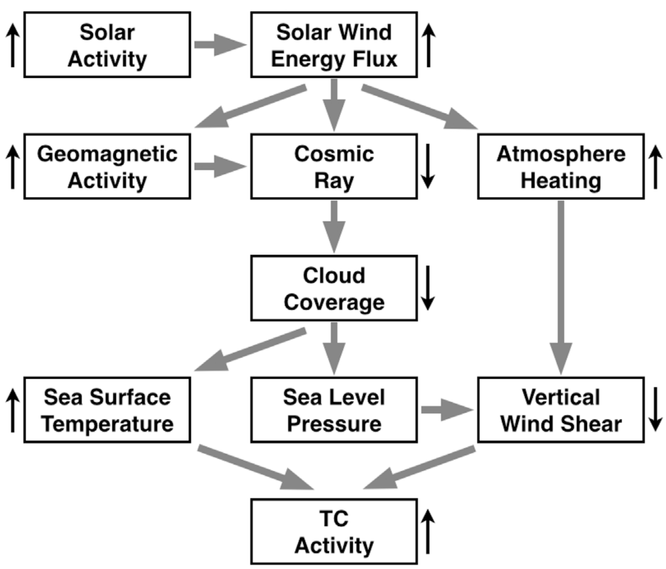

Fig. 3. Sketch of modulation mechanism.

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

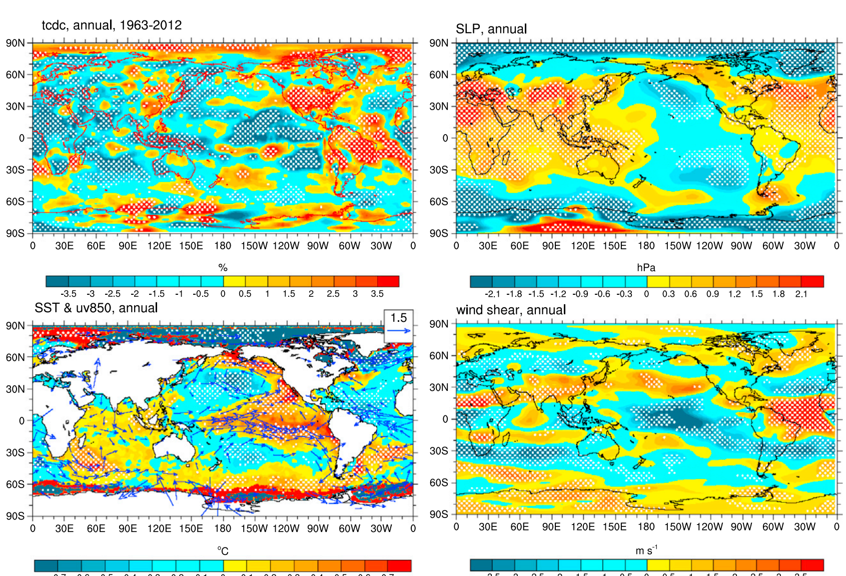

Fig. 4. Composite maps of some parameters in 1963–2012 between large and small E_{in} years. (A) annual mean total cloud cover (tcdc)). (B) the sea level pressure (SLP). (C) annual mean sea surface temperature (SST)) and 850-hPa wind anomalies (ms^{-1}) in blue arrows. (D) the vertical wind shear (ms^{-1}). Stippled regions indicate significant correlations at the 90% confidence level. Large E_{in} years are defined as the standardized $E_{in} \geq 1.0$ standard deviation, resulting 1982, 1983, 1984, 1989, 1991, 1992, 2003. Small E_{in} years are defined as the standardized $E_{in} \leq 1.0$ standard deviation, resulting 1963, 1964, 1965, 2007, 2008, 2009, 2010, 2011. The map is generated by the the software of NCAR Command Language (Version 6.3.0, 2016, Boulder, Colorado: UCAR/NCAR/CISL/TDD. https://doi.org/10.5065/D6WD3XH5). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

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 complicate. 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 complicate 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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