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Solar cycle signatures in lightning activity

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Abstract

The cross-correlation between lightning occurrence and cosmic ray intensity, solar activity and solar wind is examined on a global scale using data from the World Wide Lightning Location Network (WWLLN) for the period 2009 to 2022. The cross-correlation coefficients vary depending on the position on the globe. Positive cross-correlation between lightning occurrence and Sun spot number is found in most of Africa, South and Central America, while in parts of Europe and Southeast Asia the cross-correlation is negative. Positive cross-correlation between lightning occurrence and B_y component of heliospheric magnetic field is found for Southern part of South America, part of Europe, and northwestern Asia. Possible mechanisms are discussed. Although local weather and climate play a dominant role in lightning occurrence, observations suggest that changes in solar UV radiation during the solar cycle, together with global circulation and atmospheric waves, may modulate lightning occurrence in tropical and subtropical regions, while the polarity of the heliospheric magnetic field, atmospheric circulation and waves affect lightning occurrence more in mid- and high-latitude regions. The observed changes in cosmic ray intensity play an insignificant role in the global occurrence of lightning.

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1 Introduction

Possible relationship between solar activity and lightning/thunderstorm occurrence frequency has been investigated for many years. Fritz (1878) correlated thunderstorm frequencies with Sun spot number (SSN) for the period 1755-1875 and several European and North-American stations without obtaining a conclusive result. A pioneering and thorough study on a global scale was made by Brooks (1934), who used data from 22 areas in different parts of the world and found that the cross-correlation coefficients between annual thunderstorm frequency and SSN were mostly positive. The best cross-correlation was obtained for Siberia. However, some cross-correlation coefficients also varied considerably over relatively short distances. Other authors studied the cross-correlation between thunderstorms and solar cycle for specific regions. For example, Aniol (1952) investigated the solar influence on thunderstorm frequency in southern Germany over the interval 1881-1950 and found that the cross-correlation coefficients varied significantly for different subintervals. Stringfellow (1974) obtained the cross-correlation coefficient of 0.8 between thunderstorms in Britain and solar cycle over the interval 1930-1973. Pinto Neto et al. (2013) identified the solar cycle in thunderstorm data obtained from selected Brazilian cities for the period 1951-2009.

The above mentioned past studies used daily records of audible thunder and did not deal with thunderstorm intensities or actual number of lightning strokes. This limitation can be overcome by using lightning detection networks. Schlegel et al. (2001) calculated the cross-correlation coefficients between various parameters of solar activity and lightning detected in Germany and Austria using lightning detection systems for the period 1992-2000. In Germany they found a significant cross-correlation between lightning and solar activity, but in Austria the results were inconclusive. In addition, Schlegel et al. (2001) showed that cross-correlation coefficients might differ considerably when using lightning counts from those using only number of thunder days as has been done in the past. Number of studies have also documented that lightning activity can be partially modulated on shorter time scale by the solar rotation, the solar wind and the polarity of the heliospheric magnetic field, HMF (Chronis 2009; Owens et al., 2014; Scott et al., 2014; Owens et al., 2015; Miyahara et al., 2018; Chum et al., 2021). Statistical studies by Voiculescu and Usoskin (2012) and Voiculescu et al. (2013) showed that solar activity might impact cloud cover in specific regions rather than globally.

The exact mechanism of the dependence of lightning activity on solar activity is unknown. Some authors believe that clouds and lightning activity might be modulated by the intensity of the cosmic ray (CR) flux entering the atmosphere, which in turn is controlled by solar activity and HMF; the CR flux is anti-correlated with solar activity (Usoskin et al., 1998). Cosmic rays may influence lightning activity directly by providing the energetic particles (electrons) acting as source of ionization necessary to ignite lightning, a process that is not yet understood in full detail (Dwyer and Uman, 2014; Shao et al., 2020) or indirectly. The indirect influence is based on the potential role of CR in the modulation of cloud condensation nuclei

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and clouds (Kristjánsson et al., 2008; Kirkby 2008; Svensmark et al.,2009). It is reminded that a number of past studies (e.g., Brooks, 1934; Stringfellow, 1974; Schlegel et al., 2001) found mostly positive correlation between solar activity and lightning, implying a negative correlation with CR, which would reduce the importance of the direct mechanism/ionization. Solar activity and weather/climate can also be linked through ultraviolet (UV) solar radiation, which is absorbed in the middle and upper atmosphere and strongly depends on solar activity. Changes in stratospheric temperatures can then affect global circulation and thus tropospheric weather (Gray et al., 2010). The potential role of planetary waves in this top-down mechanism was discussed, for example, by Arnold and Robinson (1998, 2000) and Balachandran et al. (1999). On the other hand, other studies (Burns et al., 2008; Lam and Tinsley, 2016) have investigated the atmospheric electric field and associated pressure changes in polar regions and discussed the possible relationship between solar wind, namely the polarity of the B_y component of the HMF, and tropospheric weather through changes in the global electric circuit (GEC) that could affect cloud microphysics and thus cloud formation. Voiculescu et al. (2013) showed that HMF partially affects cloud cover, specifically low cloud cover at mid- and high-latitudes, which could be consistent with HMF – driven changes in GEC, while it is possible that UV changes (a top-down mechanism) may play a more important role at low latitudes. Considerable attention is paid to the chemical dynamical coupling caused by energetic particle precipitation (EPP) that includes both energetic electron precipitation from radiation belt and solar proton events during enhanced geomagnetic and solar activity as a potential link between solar activity and climate. EPPs cause changes in the chemical composition of the mesosphere and stratosphere, leading to changes in radiative balance and atmospheric temperature (Seppälä et al., 2009; Anderson et al., 2014; Mironova et al., 2015; Sinhuber et al., 2018). The role of planetary waves, polar vortex and phase of quasi-biennial oscillation on the effects of EPP on the atmosphere is often discussed, with inconsistent results so far (Seppälä et al., 2013; Maliniemi et al., 2013, 2016; Salminen et al., 2019). Another hypothesis involving atmospheric waves was put forward by Prikryl et al. (2018), who based on previous statistical studies, suggested that high-speed solar wind streams are together with associated magneto-hydrodynamic waves responsible for enhanced Joule heating in high-latitude thermosphere and ionosphere that in turn generate atmospheric gravity waves that propagate equatorward. Some of the energy transported by these waves may reach the troposphere, initiate convection and cloud formation.

The above review of possible coupling mechanisms indicates that further experimental and theoretical studies are needed to evaluate the relative role of different mechanisms that may link solar activity to climate and lightning frequency. The present study investigates the relation between the solar activity (SSN), the B_y, B_z components of the HMF, CR and lightning activity in various regions around the globe using World Wide Lightning Location Network.

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2 Measurement setup and methods

The near Earth solar wind data and data of solar activity were retrieved from NASA/GSFC's Space Physics Data Facility OMNIWeb service (https://omniweb.gsfc.nasa.gov/form/). The solar data are also compared with the CR flux measured by neutron monitor (NM) with the cut-off rigidity of 3.84 GV located on the summit of Lomnický štít (49.195°N, 20.213°E) at an altitude of 2634 m. The NM is filled with BF_3 and is of NM-64 type. More information about the NM can be found in Kudela and Langer (2009) and Chum et al. (2020).

Global lightning data is obtained using the World Wide Lightning Location Network (WWLLN), which consists of approximately 70 sensors operating in the frequency range 3-30 kHz that receive electromagnetic signals generated by lightning strokes and propagating in the waveguide between the Earth's surface and the lower ionosphere (Rodger at al., 2004). The lightning counts in 3° latitude x 6° longitude bins are used. The data available to the authors start in 2009. It should also be noted that the number of WWLLN sensors was substantially lower before 2009, and therefore the detection efficiency was also significantly lower than today. It is estimated that the current detection efficiency for strokes with peak current at least 30 kA is approximately 30% globally (wwlln.net).

To investigate the possible dependence of lightning activity on the solar cycle, we applied a cross-correlation analysis using one-year lightning counts and one-year averages of Sun spot number, NM counts, B_y, B_z components of HMF. The one-year values were used to remove the seasonal dependence of lightning occurrence. The lightning and, to some extent, the NM data show trends over the 2009-2022 interval. The trend in lightning data is likely caused by increasing network efficiency due to the increasing number of WWLLN sensors. The slight trend in NM data may be caused by changes in the geomagnetic field. Therefore, the trends are first removed from the time series before cross-correlation analysis. The trends were estimated using quadratic polynomial fits, resulting in larger cross-correlation coefficients than if only linear trends were removed.

To compare time series with different units and scales, the data are first normalized using equation (1).

$$a_{norm} = \frac{a - mean(a)}{\sigma_a}, \qquad (1)$$

where a is the analyzed quantity (for example lightning counts, SSN, components of HMF, NM counts etc.) and σ_a is the standard deviation of its distribution. The cross-correlation coefficients are calculated for the normalized variables. To reduce potential influence of quasi-biennial and El Niño–Southern Oscillation on thunderstorm occurrence, the cross-correlation coefficient are also computed for smoothed normalized lightning counts $a_{s,i}$

$$a_{s,i} = \frac{1}{2}\left(\frac{1}{2}a_{Lnorm,i-1} + a_{Lnorm,i} + \frac{1}{2}a_{Lnorm,i+1}\right), \qquad (2)$$

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where $a_{Lnorm,i-1}$, $a_{Lnorm,i}$ and $a_{Lnorm,i+1}$ are the normalized lightning counts in the given region for the successive years i-1, i, and i+1. Equation (2) represents a weighted 3-year running mean with effective width of 2-years.

It should be noted that the solar wind electric field components $E_{zSW} \sim -v_x B_y$ and $E_{ySW} \sim v_x B_z$ are believed to penetrate and add to the internal Earth's electric field between the ionosphere and ground (Rycroft et al., 2000; Lam and Tinsley, 2016), but since the relative changes in B_y, B_z are much larger than the relative changes in the Earthward solar wind speed v_x, the dependencies on B_y or B_z have been studied primarily for simplicity. We verified that differences between the results obtained for $|v_x|B_y$, ($|v_x|B_z$) and B_y, (B_z) are negligible.

The cross-correlation is also calculated separately for large positive (negative) values of B_y and B_z, where large positive (negative) values are considered to be B_y > 3 nT (B_y < -3 nT) and B_z > 1 nT (B_z < -1 nT), respectively. The threshold B_y = ±3 nT has been used in previous studies (Burns et al., 2008, Lam and Tinsley, 2016) and the absolute threshold values $|B_y|$ = 3 nT and $|B_z|$ = 1 nT are approximately √2 times larger than the averages of $|B_y|$ and $|B_z|$, respectively.

In addition, the cross-correlation is also computed between normalized lightning counts and magnetopause reconnection electric field (Kan and Lee, 1979). This electric field, namely its perpendicular component, can serve as a proxy for ionospheric electric currents at high latitudes (namely Region 1) during geomagnetic storms, potential across a polar cap (Kan and Lee, 1979; Mannucci et al., 2014) or large scale traveling ionospheric disturbances (LSTID) - waves in the upper atmosphere and ionosphere (Borries et al., 2023). The perpendicular component (related to the magnetic field lines at the magnetopause) of the Kan-Lee electric field (Kan and Lee, 1979) is

$$E_{perp} = v_x B_T sin^2(\varphi/2), \qquad (3)$$

where B_T is $\sqrt{(B_y^2 + B_z^2)}$ and φ is a clock angle between B_y and B_z, φ=atan(B_y/B_z).

Kan and Lee (1979) also pointed out that the parallel component of the electric field should not be neglected.

$$E_{par} = v_x B_T sin(\varphi/2)\cos(\varphi/2). \qquad (4)$$

3 Results

Figure 1 shows on a world map the global distribution of the total number of lightning strikes recorded by the WWLLN during the analyzed period 2009-2022. The color scale indicates the common logarithm of lightning strikes in each 3° x 6° (latitude x longitude) bin for the latitude range from -66° to 66°. Thunderstorm centers can be identified in tropical and subtropical regions over the continents, namely Central Africa, South and Central America, East Asia and Indonesia. Significant numbers of lightning have also been recorded in the Mediterranean.

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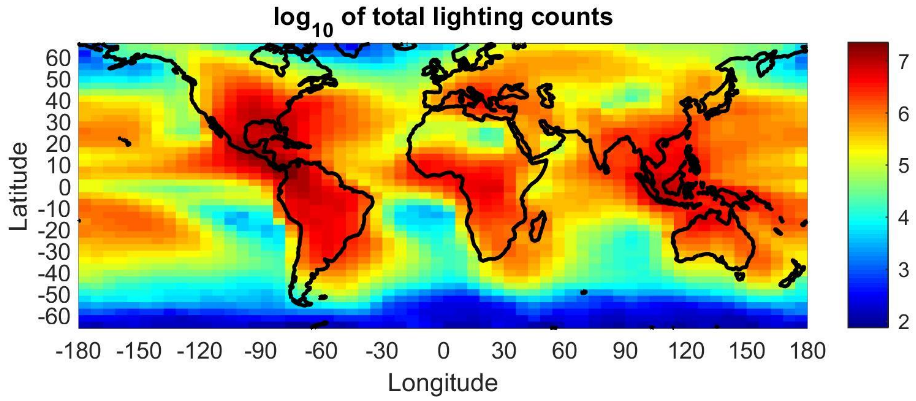

Fig. 1 Common logarithm of total numbers of lightning during the analyzed period, 2009-2021.

The cross-correlation coefficients between normalized yearly SSN and the smoothed normalized yearly lightning counts are shown in Figure 2a. The cross-correlation coefficients are displayed only for those bins, in which the total number of lightning strikes was larger than $2{\cdot}10^4$ for the entire period, which corresponds to an average yearly number of lightning larger than ~1400. The same threshold for the required number of detected lightning strikes per bin is used in the following analogous figures. Red color indicates cross-correlation coefficients close to 1, whereas dark blue stands for large negative values of cross-correlation coefficients. It is obvious that lightning activity is in phase – correlates well with solar activity represented by the SSN in most of Africa, South and Central America. On the other hand, some parts of South-East Asia or South-East Europe exhibit anti-correlation.

Figure 2b displays the cross-correlation coefficients between normalized yearly NM counts and the smoothed normalized yearly lightning counts. A comparison of Figure 2a and Figure 2b shows that the cross-correlation coefficients between lightning and NM counts have opposite sign to the cross-correlation coefficients between lightning and SSN. This is expected since it is known that the CR flux characterized by NM data is anti-correlated with solar activity (e.g., Usoskin, 1998). This is also demonstrated for the analyzed time period in Figure 3 which displays the time series of normalized annual SSN (Figure 3a) and normalized annual NM counts measured at Lomnický Štít (Figure 3b). An example of the time series of the normalized annual number of lightning strikes for the selected bin (latitude from -12° to -9° and longitude from 30° to 36°), in which one of the highest cross-correlation coefficients was obtained in Figure 2a, is shown by the dashed line with square symbols in Figure 3c, whereas the smoothed data using Equation (2) are drawn by solid line with asterisks. The similarity of the annual normalized lightning counts with the annual normalized SSN is clear; the cross-correlation coefficient for the smoothed data obtained by Equation (2) is 0.98 and 0.94 for the annual normalized counts.

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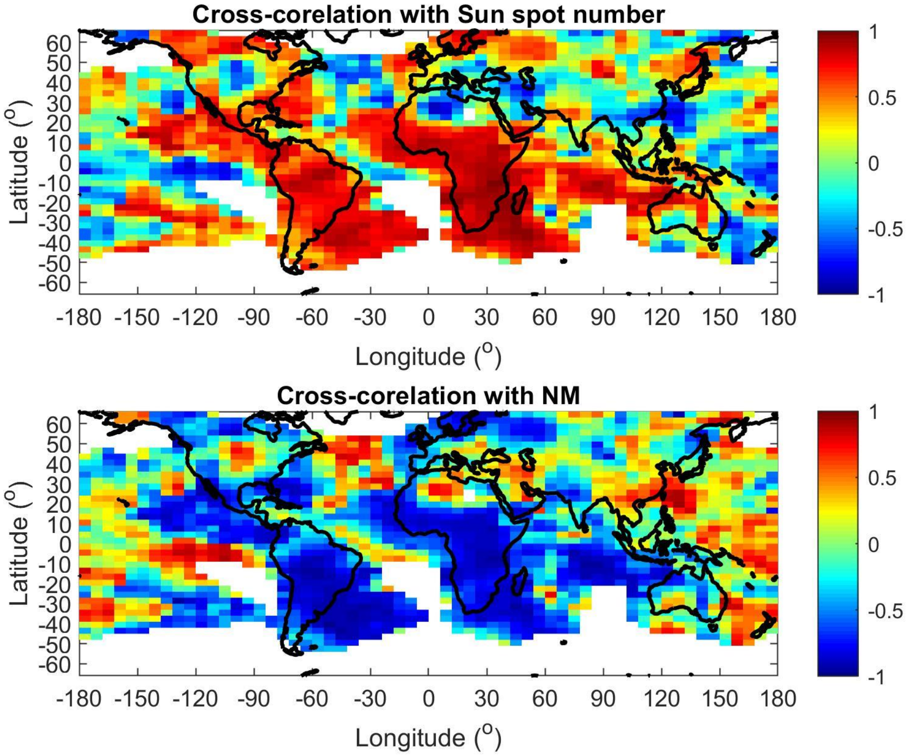

Fig. 2 a) Cross-correlation coefficient between normalized yearly Sun spot number and lightning for regions in which total number of lightning exceeded $2 \cdot 10^4$. b) Cross-correlation coefficient between normalized yearly neutron monitor count on LS and lightning for regions in which total number of lightning exceeded $2 \cdot 10^4$.

As discussed in the Introduction, some of the previous studies (Burns et al., 2008; Voiculescu et al., 2013; Owens et al. 2014 among others) showed a relation between the HMF polarity and atmospheric electricity or cloud cover. Therefore, in addition to the cross-correlation of lightning with SSN and NM, the cross-correlation with HMF components is also investigated. Figure 4 shows the cross-correlation coefficients between yearly normalized values of B_y, B_z components of HMF and lightning counts. It is obvious that lightning activity correlates with B_y over much of South America (except tropical regions), Europe and northwestern Asia (Fig. 4a), while only smaller parts of the Earth show higher values of the cross-correlation between lightning and B_z (Fig. 4b). A comparison of Figure 2a and Figure 4a reveals that the regions that exhibit high values of cross-correlation between the lightning strikes and both the SSN and the B_y component overlap only to a small extent.

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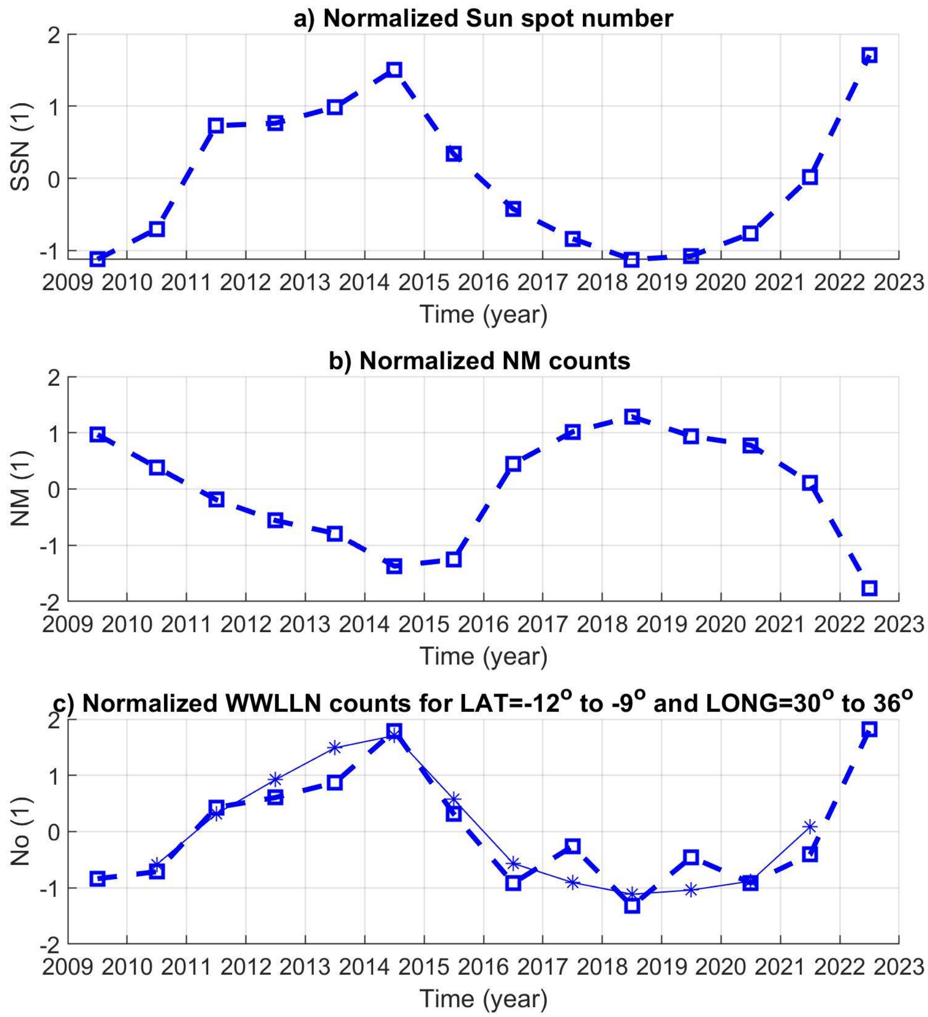

Fig. 3 a) Detrended normalized yearly Sun spot number. b) Detrended normalized yearly Neutron monitor count measured at Lomnický Štít. c) Detrended normalized number of lightning in the selected bin, latitude from -12° to -9° and longitude from 30° to 36°. Dashed line with square symbols represents annual data and solid line with asterisks show the smoothed data using equation (2).

Burns et al (2008) and Lam and Tinsley (2016) observed distinct changes of atmospheric electricity at high latitudes for $|B_y| > 3$ nT. Figure 5a and 5b shows the cross-correlation coefficients between yearly

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normalized values of B_y > 3 nT and B_y < -3 nT, respectively, and normalized lightning counts. While no significant cross-correlation with lightning activity is observed when only values B_y > 3 nT are used (Figure 5a), regions which show large negative cross-correlation coefficients can be identified when only values B_y < -3 nT are used (Figure 5b). These regions are nearly identical to the regions that were characterized by large positive cross-correlation coefficients between normalized lightning counts and B_y (compare Figure 4a and 5b).

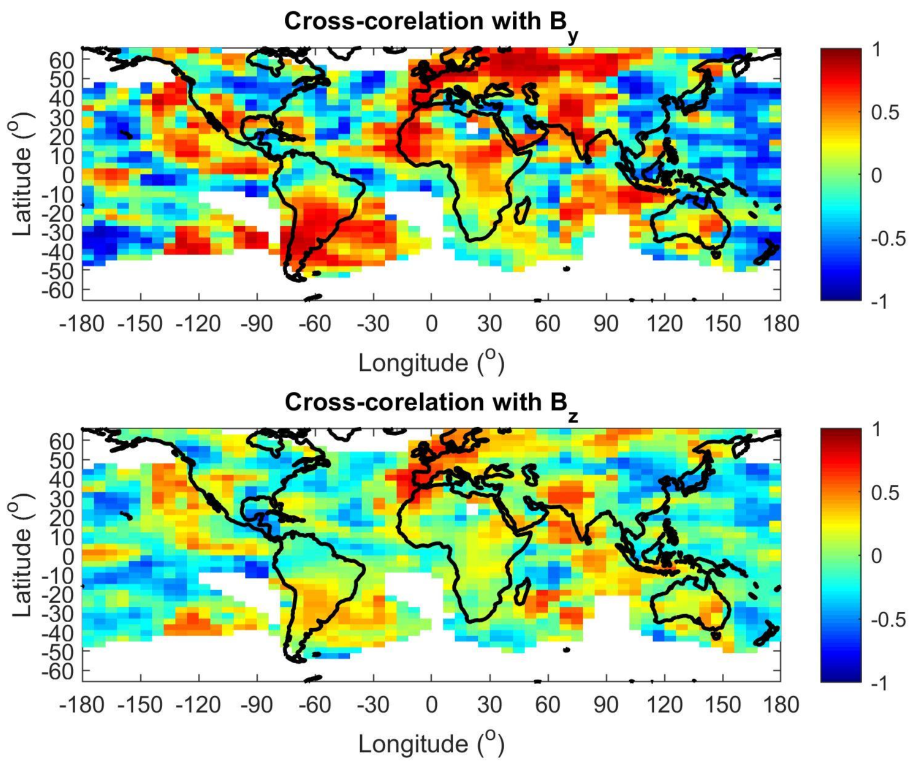

Fig. 4 a) Cross-correlation coefficient between normalized yearly B_y component of HMF and lightning for regions in which total number of lightning exceeded $2{\cdot}10^4$. b) Cross-correlation coefficient between normalized yearly B_z component of HMF and lightning for regions in which total number of lightning exceeded $2{\cdot}10^4$.

As mentioned in Section 2, the threshold $|B_y|$ = 3 nT represents about √2 times the average of $|B_y|$. An analogous threshold for $|B_z|$ is approximately 1 nT. Figure 6a and 6b shows the cross-correlation coefficients between yearly normalized values of B_z > 1 nT and B_z < -1 nT, respectively, and normalized lightning counts. The cross-correlation analysis for B_z > 1 nT (Figure 6a) gives similar results (although not identical,

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the cross-correlation coefficients are bit smaller in this case) to the cross-correlation analysis for SSN (compare Figures 2a and 6a). The cross-correlation analysis for B_z < -1 nT (Figure 6b) does not yield large values for the cross-correlation coefficients.

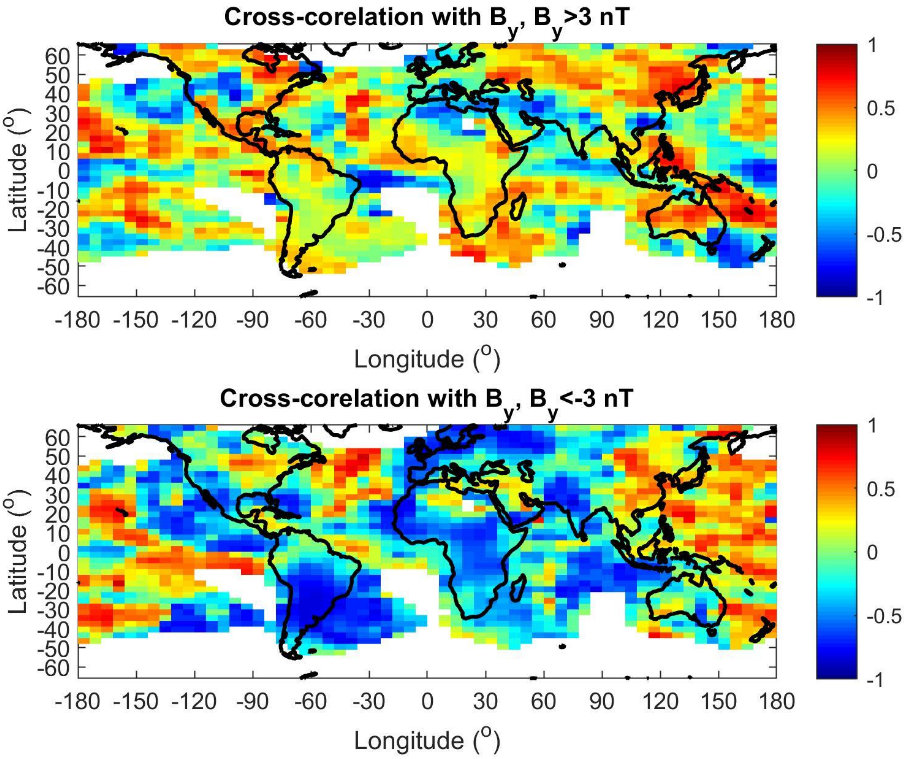

Fig. 5 a) Cross-correlation coefficient between normalized yearly B_y > 3 nT component of HMF and lightning for regions in which total number of lightning exceeded $2{\cdot}10^4$. b) Cross-correlation coefficient between normalized yearly B_y < -3 nT component of HMF and lightning for regions in which total number of lightning exceeded $2{\cdot}10^4$.

The cross-correlation coefficients between the smoothed normalized lightning counts and components of the magnetopause reconnection electric field (Kan-Lee) are shown in Figure 7. Large values are obtained in South America, northwestern Asia, and northeastern Europe) both for the perpendicular component (Figure 7a) and parallel component (Figure 7b). However, both the cross-correlation coefficients and the size of these regions are larger in the case of the parallel component of the electric field. The cross-correlation for the parallel component of the Kan-Lee electric field is very similar to the cross-correlation for B_y (compare Figures 4a and 7b). It is actually not surprising because $|B_y|$ is usually larger than $|B_z|$.

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Therefore $B_T \approx |B_y|$ in the first approximation, and since, in addition, the absolute value of the term $sin(\varphi/2)\cos(\varphi/2)$ peaks for B_z=0 (|φ|/2=45°), the fluctuations of the parallel component of the Kan-Lee electric field defined by equation (4) roughly follow the fluctuations of B_y, including the sign.

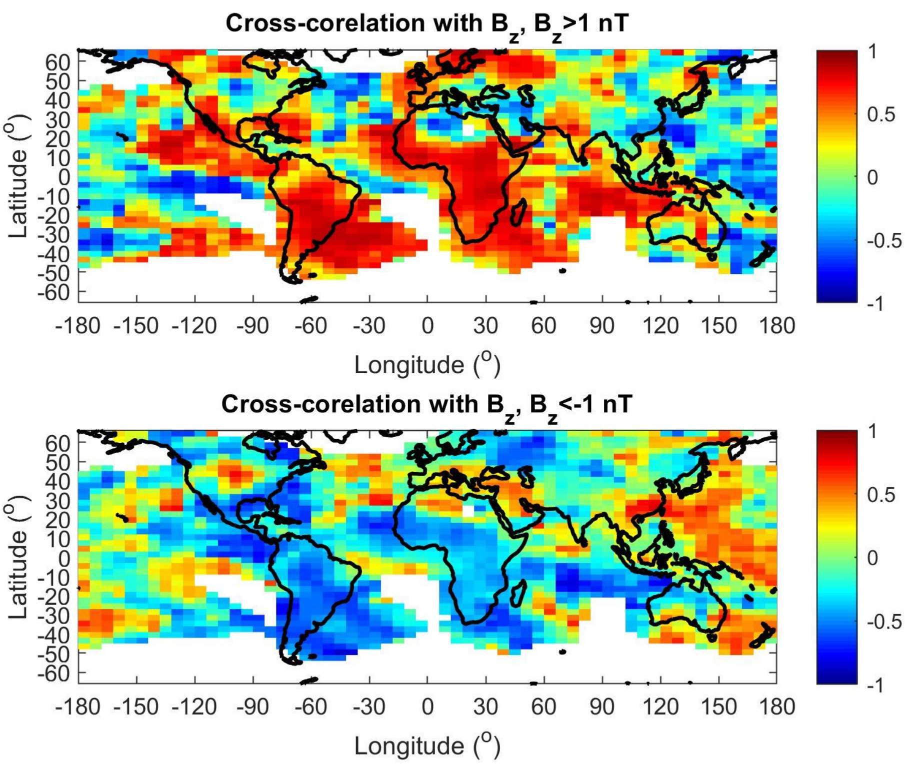

Fig. 6 a) Cross-correlation coefficient between normalized yearly B_z > 1 nT component of HMF and lightning for regions in which total number of lightning exceeded $2{\cdot}10^4$. b) Cross-correlation coefficient between normalized yearly B_z < -1 nT component of HMF and lightning for regions in which total number of lightning exceeded $2{\cdot}10^4$.

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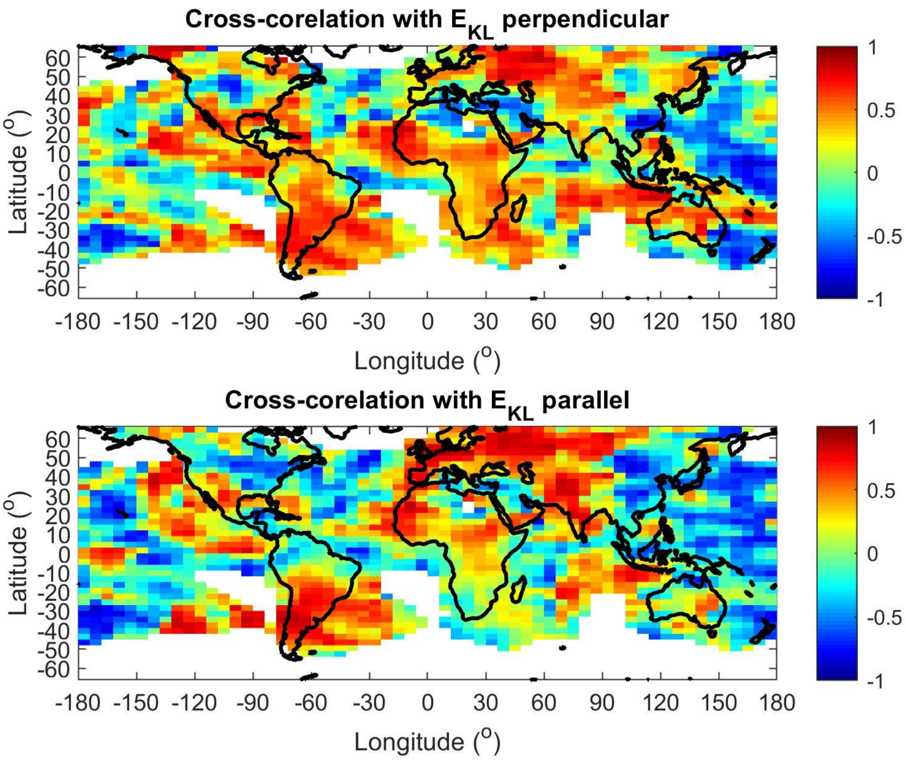

Fig. 7a) Cross-correlation coefficient between normalized reconnection Kan-Lee electric field (perpendicular component) and lightning for regions in which total number of lightning exceeded $2{\cdot}10^4$. b) Cross-correlation coefficient between normalized reconnection Kan-Lee electric field (parallel component) and lightning for regions in which total number of lightning exceeded $2{\cdot}10^4$.

4. Discussion and Conclusions

The presented results show that high cross-correlation coefficients between solar activity (SSN) and lightning are observed in tropical regions of Africa and America for the period 2009-2022, which may indicate the importance of the top-down mechanism associated with greater UV flux and stratospheric heating during increased solar activity (Arnold and Robinson, 1998, 2000; Balachandran et al., 1999). Longitudinal differences and some asymmetry between the northern and southern hemispheres, particularly in the African and American sectors, may be due to the climatic differences in various regions such as typical atmospheric circulation and planetary waves characteristics. Lower cross-correlation coefficients

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(or even their opposite sign) in tropical regions in Asia corresponds to the areas characterized by monsoons (Zafirah et al. 2017), with different thunderstorm mechanisms but this needs further investigation.

Outside tropical regions, in mid-latitudes, the SSN seems to modify large-scale modes of variability and atmospheric blocking (Barriopedro et al. 2008), i.e. factors modulating surface weather and climate patterns (Masato et al. 2012). However, the relationships between SSN and atmospheric circulation in the troposphere were significant only in boreal winter, when the lightning activity is relatively low compared to summer. An unusually large number of winter lightning in northwestern Europe during the peak of solar cycle 24 (2014/2015) was studied by Kolmašová et al. (2022), who hypothesized that the increase of lightning activity was due to the positive phase of North Atlantic Oscillation and cold-to-warm transition of El Niño. The effect of El Niño on lightning activity was also pointed out by Williams et al. (2021), On the other hand, Holzworth et al. (2019) found a similarity between SSN and number of superbolts, particularly in northwestern Europe and Mediterranean in winter.

The B_y component of the heliospheric magnetic field and the reconnection Kan-Lee electric field is well correlated with lightning occurrence over significant portions of the globe from mid to high altitudes, including the northwestern Europe. This may suggest that solar wind, reconnection and particle precipitation can be responsible for changes in the upper and middle atmosphere in the polar and auroral regions. These changes may then modulate the usual tropospheric weather indirectly, through changes in the general circulation, radiation and atmospheric waves, leading to the observed influence of the solar wind on the occurrence of lightning at middle and high latitudes and to the observed longitudinal differences.

Cosmic rays do not contribute to the global occurrence of lightning because they are not positively correlated in most regions. More important are suitable weather conditions. This does not rule out the possibility that cosmic rays play a role in igniting individual lightning strikes in developed thunderclouds (Shao et al., 2020).

The analyzed period 2009-2022 covers solar cycle 24 and the beginning of cycle 25. It is not clear whether the obtained pattern of cross-correlation coefficients between lightning and solar activity or solar wind also applies to other time periods and solar cycles. Some local previous studies based on thunder days, such as that of Aniol (1952) in Germany, suggest that this may not be the case. Similarly, Chum et al. (2021) identified a solar rotation in lightning occurrence for Central Europe and the period 2016-2019. However, extending their study to a longer time interval revealed that the periods observed for lightning occurrence and solar wind are generally asynchronous, although they may be close together. It should also be noted that Europe is a region in which the cross-correlation coefficients obtained in this study vary significantly over relatively small distances, probably due to the heterogeneous climate (coastal, orographic effects) and diverse mechanisms governing the occurrence of thunderstorms (Kottek et al. 2006). It is therefore

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reasonable to expect that even if the global pattern remained roughly the same over multiple solar cycles, regional changes would be observed in Europe even due to relatively small fluctuations. This underlines the importance of the global studies over as long a time interval as possible.

Abbreviations

CG: Cloud to ground discharge; CR: Cosmic rays; CSD: Cross-spectral density; EUCLID: European Cooperation for Lightning Detection; HMF: Heliospheric magnetic field; IC Intra-cloud or inter-cloud discharge; LS: Lomnický štít; NM: Neutron monitor; PSD: Power spectral density; SW: Solar wind; WWLLN: World-wide lightning location network;

Data Availability

WWLLN archival data are copyrighted by the University of Washington and are available to the public at nominal cost. The Solar activity and HMF data can be found at NASA/GSFC's Space Physics Data Facility's OMNIWeb (https://omniweb.gsfc.nasa.gov/).
The NM data can be downloaded from http://data.space.saske.sk/status/ (access is provided by R. Langer, langer@saske.sk, on request).

Author Contributions

JC designed and wrote the paper and performed most of the analysis. RL and IS are responsible for and provided the SCR data. IK provided the lightning data and contributed to the discussion. OL and JR contributed to the discussion. All authors read and approved the submitted version.

Competing Interest

The authors declare that they have no conflict of interest.

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