Spatio-temporal influence of solar activity on global air temperature

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Abstract. Previous studies on the impact and influence of solar activity on terrestrial weather has yielded contradictory results in literatures. Present study presents, on a global scale, the correlation between surface air temperature and two solar activity indices (Sunspot number, 'Rz', and solar radio flux at 10.7, 'F10.7') at different time scales during solar cycle 23. Global air temperature has higher correlation values of ±0.8 with F10.7 compared to Rz (±0.3). Our results showed hemispheric delineation of the correlation between air temperature and solar activity with negative correlation in the southern hemisphere and positive correlation in the northern hemisphere. At the onset of the solar cycle, this hemispheric delineation pattern was prevalent, however, an inverse hemispheric delineation was observed at the recession of the solar cycle.

Keywords: solar cycle, sunspot number, F10.7 index, space - earth coupling.

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1. INTRODUCTION

The Sun influences weather on Earth through changes in solar irradiance, variability in solar ultraviolet, and effect of galactic cosmic rays (Mufti and Shah, 2011). The impact of solar activity on the Earth's climate can either be direct or indirect. It is pertinent to estimate the contribution of solar activity to global warming and climate change. Over the years, scientists have developed indices to measure and quantify solar activity. One of the most common indices for solar activity is the sunspot number, Rz. Sunspots are regions of reduced temperature on the Sun photosphere. Sunspot number Rz, was one of the earliest proxies for solar activity with data as far back as the 16th century. The solar 10.7 cm radio flux (F10.7) is defined as the measurement within one hour, of all emissions on the solar disc at a wavelength of 10.7 cm (Tapping, 2013). The F10.7, has been found to be a better representation of solar activity than Rz because it produces less noisy results (Ulrich et al., 2007; Mielich and Bremer, 2013; Okoh and Okoro, 2020). Clette (2021) had observed the preference of F10.7 to the sunspot number for short-term forecasts of solar irradiance in the UV to X-ray domain and of its influence on the Earth environment (ionosphere, stratospheric temperatures, chemistry of the upper atmosphere), and for the resulting applications (radio propagation, atmospheric drag on low-Earth orbiting satellites). This he attributed to the fact that the daily F10.7 flux offers a better proxy for ultraviolet (UV) and X-ray fluxes produced in the chromosphere, the transition region and the solar corona. A similar, E10.7 index based on the extreme ultraviolet radiation 10.7 cm radio flux has also been proposed (Tobiska et al., 2000). The flare index is a short-lived solar activity to quantify the daily flare activity over a 24-hour period (Kleczek, 1952). The total sunspot area, obtained by measuring the area of each sunspot group, has been proposed as a measure of solar activity (Sarychev and Roshchina, 2006). These indices provide a means to quantify the effect of solar activity on atmospheric parameters.

The impact of solar activity on atmospheric variables has been investigated.

Values of coefficient of determination r2 between Rz and rainfall were found to be 0.89 in Rome using long term data (Thomas, 1993). Correlation coefficient between Rz and rainfall in India has

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been reported to be in the range -0.86 to +0.55 (Ananthakrishnan and Parthasarathy, 1984; Hiremath and Mandi, 2004; Chattopadhyay and Chattopadhyay, 2011; Hiremath, 2006; Selvaraj et al., 2009; Chakraborty and Bondyopadhyay, 1986; Jain and Tripathy, 1997). The differences in correlation coefficient values in India could be attributed to different time periods, different number of locations, and method of computation considered. In other regions of the world, correlation values between Rz and annual rainfall has been reported as -0.1 for Southern Brazil (Echer et al., 2008), 0.48 – 0.99 for several African countries, (Fleer, 1982), 0.40 in Portugal (Lucio, 2005), -0.10 in Santa Maria (Rampelotto et al., 2012), and 0.24 in Italy (Mazzarella and Palumbo, 1992). Sunspot activities have also been reported to have correlation with lake volumes/water levels, river flows (Mauas et al., 2011). Furthermore, the impact of Rz has been reported on large scale teleconnection patterns such as El Nino-southern oscillation (ENSO) (Zaffar et al., 2019), North Atlantic Oscillations (Hern´andez et al., 2020; Kuroda et al., 2022), and Pacific Decadal Oscillation (PDO) (Ormaza-Gonz´alez and Espinoza-Celi, 2018).

One of the greatest interests in Sun-Earth relationship, is the influence of solar activity on tropospheric temperature. The solar contribution to tropospheric temperature has been estimated to be 7% - 60% (Solomon et al., 2007; Solanki and Krivova, 2003; De Jager et al., 2010; Scafetta, 2010). The correlation between mean global air temperature and sunspot number has been estimated at 0.27 (Valev, 2006). Correlation values reported between Rz and air temperature at various location and time periods are in the range -0.42 – 0.66 (Schonwiese, 1978; Blanco and Catalano, 1975; Rabiu et al. 2005; Rabiu et al. 2005; Echer et al., 2009). Another approach to estimate the influence of solar activity on air temperature is using the length of the solar cycle. Solheim et al. (2012) observed significant negative trend between Norwegian air temperature and length of previous solar cycle. A high correlation was observed between solar cycle length and air temperature in the northern hemisphere (Friis-Christensen and Lassen, 1991). This correlation between solar cycle length and air temperature have also been confirmed at Northern Ireland (Butler and Johnston, 1996), Svalbard at 12-year lag (Solheim et al., 2011), and Qinghai-Xizang railway at 5-year lag (Li et al., 2004). Correlation between Rz and winter temperature has been estimated as −0.3 in Canada (Laing and Binyamin, 2013), +0.42 in Holland (De Jager, 1981), and −0.91 to −0.63 in Bulgaria (Georgieva et al., 2005).

Weather across the world is connected. Previous studies on the relationship between Rz and air temperature have largely focused on aggregated data and specific locations. However, it is imperative to study the interaction of solar on global weather to determine large scale patterns and trends. This makes it difficult to make inference on the global impact of solar activity. The aim of this study is to characterize the relationship between solar and geomagnetic activities and global air temperature at long term, seasonal and annual time scales across the world. This will give insight into the contribution of solar and geomagnetic contributions to climate activities across different regions of the world.

2. METHODOLOGY

For this study, Rz and F10.7 were used as proxies for solar activity during solar cycle 23 (1997 - 2008). The daily NCEP-NCAR Reanalysis (http://www. psl.noaa.gov/data/gridded/data.ncep.reanalysis.html) air temperature data at 2 m was used. Daily Rz and F10.7 values were obtained from the OMNI database (https://omniweb.gsfc.nasa.gov/form/dx1.html). The seasonal consideration was based on the Lloyd's season where J-season includes May, June, July, and August; D-season months are November, December, January, and February; while the E-Season months are March, April, September, and October.

The Spearman correlation (ρ) was used in this study. It is defined as

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \quad (1)$$

The values of ρ are in the range ±1. Negative values denote negative correlations between the two variables which implies that an increase in one variable corresponds to a decrease in the other variable. The significance of the correlation was computed using the two tailed p-value. In this study, all results were considered at 95% confidence interval.

southern hemispheres, except in tropical land masses. However, in tropical land and oceans, it showed similar significant negative correlation as in the case of Rz index. The only significant positive correlation between air temperature and F10.7 index were also around Celebes Sea (Pacific Ocean) and Queen Elizabeth Islands in North America.

The correlation between global air temperature and Rz were also considered at the three seasons (Figure 2). In the J-season, significant negative correlations were predominant in many regions. Significantly high negative correlations were found across the equator except the Indian Ocean. Regions north and southeast of Australia showed significantly high positive correlations between air

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temper- ature and Rz index. During this season, significant correlations were not found over the continental land masses except in Greenland and small regions in Africa and Europe. During the D-season, there were no significant negative correlations in the Pacific

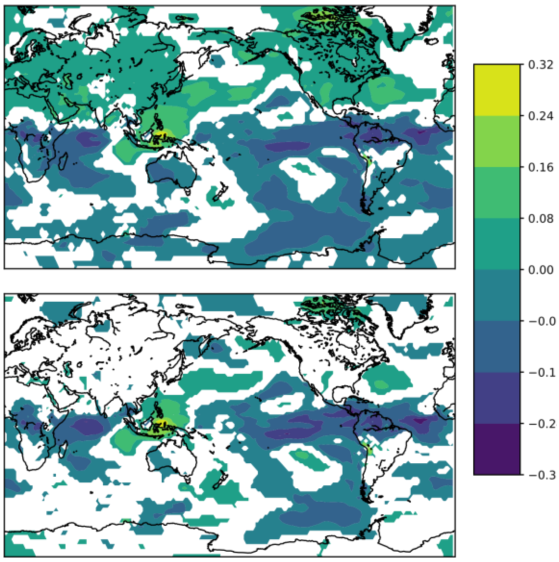

Figure 1: Spatial variation in significant correlation at 95% confidence interval between air temperature and (top) Rz and (bottom) F10.7. White patches represent statistically insignificant correlation values.

Islands, as in the J-season. However, significant high positive correlations were found in the Queen Elizabeth Islands, west of Greenland. Unlike the J-season, significant negative correlations were found in south Atlantic Ocean and Indian Ocean. Also, larger portion of North America showed significant correlations. The correlations around the Equator were found to be weaker and not predominant as in the J-season. Correlations between air temperature and Rz during the E-Season were generally subdued with less spatial coverage compared to the J-season and D-season. The negative Equatorial correlations and positive Pacific Island correlations were observed to be weakest during this season. The correlation between air temperature and F10.7 index (Figure 3) at the three seasons showed identical patterns with the Rz correlations.

In Figure 4, the annual correlation between global air temperature and Rz were considered from 1997 to 2008. The correlation values were found to be in

the range ±0.32. Hemispheric delineations were pronounced at the onset of the solar cycle from 1997 to 1999. Specifically in the northern hemisphere, predominantly significant positive correlations were observed while the southern hemisphere was found to have prevalent significant negative correlations. In 2000, although the hemispheric delineation was present, they were observed only on continental land mass and the Arctic Ocean. However, in 2001 the correlations were only observed on large water bodies. From 2002 to 2005, there were sparse

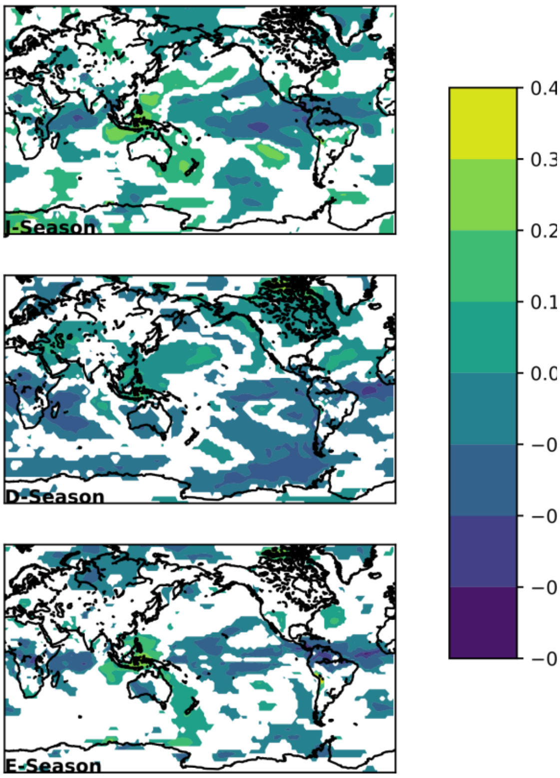

Figure 2: Seasonal spatial variation in significant correlation at 95% confidence interval between air temperature and Rz. White patches represent statistically insignificant correlation values.

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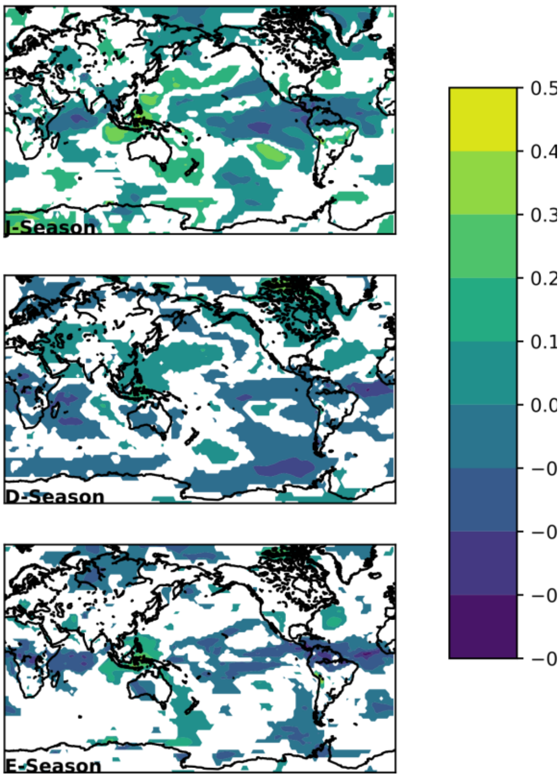

Figure 3: Seasonal spatial variation in significant correlation at 95% confidence interval between air temperature and F10.7. White patches represent statistically insignificant correlation values.

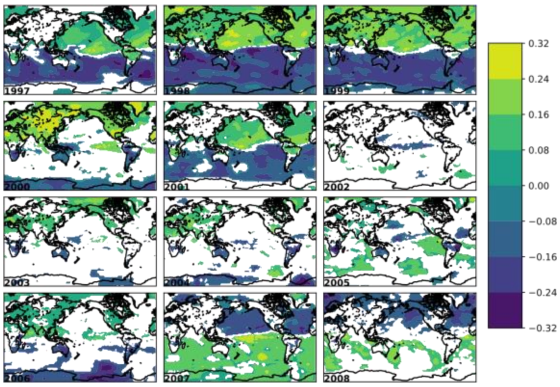

Figure 4: Spatial variation of significant correlation between Rz and air temperature at 95% confidence interval for each year in solar cycle 23. White patches represent statistically insignificant correlation values.

spatial distribution of significant correlations between air temperature and Rz index. The year 2002 witnessed the sparsest spatial distribution of correlation values as only Equatorial Atlantic Ocean and a few other locations were found to be correlated. In 2003, the continental land mass of Africa, Europe, Australia, Asia, as well as North America and the Arctic Sea showed significant correlation values. However, significant correlation values were not observed in the Arctic Ocean but over South America in 2004. In 2007 and 2008, there was an inversion of the hemispheric delineation. During 2007 and 2008, significant negative correlations were observed in the Northern Hemisphere while significant positive correlations were found in the Southern Hemisphere. However, the spatial distribution of the inverse hemispheric delineation was smaller in 2008 compared to 2007.

Figure 5 showed the spatial correlation between global air temperature and F10.7 index for each year in solar cycle 23. The years 1997 to 1999 showed similar patterns as observed in the correlation with Rz but with higher values. In 2001, the continental land mass in the northern hemisphere which did not show significant correlations under Rz were found to exhibit negative correlations with F10.7 while the continental land mass in the southern hemisphere showed positive correlations. During the year 2002, an inverse hemispheric delineation was observed with negative correlations in the northern hemisphere and positive correlations in the southern hemisphere. This implies that F10.7 contribute more to global air temperature compared to Rz index. Sparse spatial distribution of correlation values was also observed in the years 2003 to 2006, with 2005 showing the highest distribution. The correlation values in 2007 and 2008 also showed inverse hemispheric delineation but with larger spatial distribution compared with Rz.

The seasonal correlation between solar activity (F10.7 and Rz) for selected years (1997,1998,1999,2001,2002,2006,2007,2008) were considered (Figs. 6 and 7). There are two important observations in the seasonal correlation for these years. First, the weakest global correlations were observed in the J-season which improved in the D-season. The highest correlation values across the world were reported in the E-season. Second, there were no hemispheric delineations in the J-season, however both D-season and E-season showed hemispheric delineation. Positive correlations were observed in the northern hemisphere while negative correlations were observed in the southern hemisphere. Stronger correlations were observed for F10.7 compared to Rz. During the E-Season, the correlations over the ocean were found to be greater than the correlation over land in both F10.7 and Rz. In the J-Season, positive correlations were observed in the northern hemisphere ocean while most land surfaces, especially Asia, showed negative correlations.

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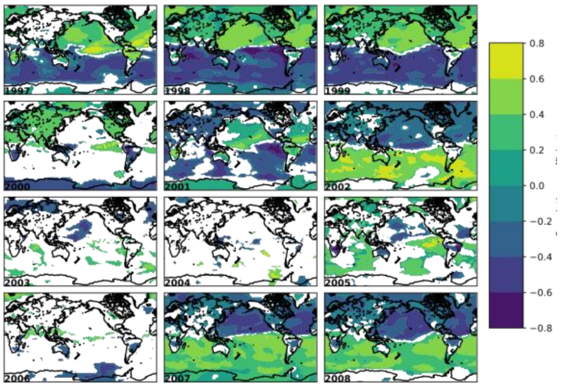

Figure 5: Spatial variation of significant correlation between F10.7 and air temperature at 95% confidence interval for each year in solar cycle 23. White patches represent statistically insignificant correlation values.

4. CONCLUSION

There has been no scientific consensus on the impact of solar activity on atmospheric weather. In this study, we have investigated the correlation between surface air temperature and two solar activity indices (Rz and F10.7) on the global scale during solar cycle 23. This approach will help identify large scale patterns which can give more insight into the relationship between atmospheric weather and solar activity. Our study was conducted at seasonal, annual, and long-term time scales for a clearer understanding. Our results showed hemispheric delineation at seasonal, annual, and long-term considerations. Furthermore, while the years preceding the solar minimum showed preference for positive correlations in the north and negative correlations in the south, the receding years favours the opposite.

Disclosures

The authors declare no financial interests or conflict of interests in this manuscript.

Data, Materials, and Code Availability

Data used in this study is publicly available and links have been provided in the manuscript.

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