e-ISSN 2409-0360
Zimbabwej.sci.technol

Impact of solar activity on weather patterns in Bulawayo, Zimbabwe.

Oliver Mhlanga[1], Brian C. Jones[2] and Farikayi K. Mutasa[2]

[1]Department of Applied Mathematics,
[2]Department of Statistics and Operations Research,
National University of Science and Technology
P O Box AC 939 Ascot,
Bulawayo, Zimbabwe

Email: olivamhlanga@gmail.com

ABSTRACT

Solar activity is one of the factors influencing climate change. In this study we use time series analysis and spectral analysis techniques to analyse the possible effect of solar activity on local climate in Bulawayo. The results show that, since 1898, periods of high sunspot numbers have been followed by periods of lower rainfall and higher temperatures and vice versa.

Keywords: Solar activity, magnitude spectrum, cross-correlation, sunspot number, weather

Received: 28.07.17 **Accepted:** 17.10.18

1. Introduction

The sun is the primary source of energy on earth. Differences in the composition and intensity of solar radiation reaching the earth affect global and regional climate (NOAA, 2016). The two major sources of solar radiation variation are solar activity and the position of the earth in its elliptical orbit around the sun (Roy, I. et al., 2010; NOAA, 2016). Solar activity can be described as the variable and short-lived disturbances on the sun that affect the energy emitted. Solar activity is manifested in many ways such as the eruption of highly charged particles and rapid release of magnetic energy from the sun, for example, coronal mass ejections, solar flares, solar winds, aurora, sunspots, prominences and filaments. These result in geomagnetic storms that have adverse effects on communication technology (Wernik, A., 2005; Marusek, J. A., 2007; Fletcher, L. et al., 2011; Khalid, M. et al., 2014).

There are mixed outcomes from research about the relationship between solar activity and climate. An assessment of past and present studies has shown that both scientific and predictive models do not simulate well the complex nature of solar activity; this perhaps is due to insufficient of knowledge of the underlying physics (Svalgaard, L., 2013). Bal, S. and Bose, M. (2010) carried out research on climatological relations among solar activity, galactic cosmic ray and precipitation on many regions over the globe and found no hint of any linear relationship. Zhao, J. et al. (2004) in a study in Beijing, found that annual precipitation is closely linked to variation in sunspot numbers. Long-term variations in the earth's temperature show close association with variations in the solar cycle length (Christensen E. F. and Lassen L., 1991; Jange, C. 2008; Lockwood, M. et. al., 2010; Haigh, J., 2011). Since the climatic conditions depend on geographical location it is of value to assess how local weather is influenced by solar activity in Zimbabwe. Zimbabwe seems to have experienced droughts roughly every 10 years. In the recent past, two summer seasons (that is 2014/2015 and 2015/2016) poor harvests were experienced due to long dry spells and very high temperatures. It is of particular importance to try and find possible causes of droughts, or even to be able to predict drought well in advance, in an agro-based economy like Zimbabwe. In general, understanding the impact of solar activity on local regional weather may help societies to know when extreme weather hazards are likely to occur.

There are various indicators of solar activity but sunspot number is the one that has the longest recorded time series. We assume in this paper that sunspot number is an indicator of solar activity and hence the results will hinge on the relationship between sunspot number and solar activity. Currently, there are various predictions of solar activity using different methods such as the precursor method, extrapolation methods and model-based predictions (Kane, R. P., 2007; Zanchettin, D. et al., 2008; Duhau, S. et al., 2012).

2. Data and Methodology

Mean annual sunspot data used is from 1700 to 2015. The source of sunspot data is WDC-SILSO, Royal Observatory of Belgium, Brussels. The monthly rainfall data and dry bulb monthly temperature used was from January 1965 to October 2015 and from January 1975 to September 2015 respectively. Rainfall and temperature data was taken from the Meteorological Services Department of Zimbabwe, Bulawayo weather station. Annual rainfall data used was recorded at Bulawayo Meteorological Station and spans from 1898 to 2014.

Both time domain analysis and frequency domain analysis were used to understand the nature and extent of impact of solar activity on local regional weather. These methods are well documented by Chatfield, C., (2003); Bloomfield, P., (2000); Cooray, T. M. J. A., (2008); Morrison, N. (1994).

2.1 Time Domain Analysis

Auto-covariance function of a stationary time series {Xt} denoted by γ_k:
$\gamma_k = E[(X_t - \mu)(X_{t+k} - \mu)$ where k is the lag and μ is the mean. The Autocorrelation is found by normalising γ_k : $\rho_k = \frac{\gamma_k}{\gamma_0}$ where ρ_k is the autocorrelation function and γ_0 is the variance , k =0, 1, 2, …. is the kth lag. ρ_k is one common tool used to test randomness of a time series. The other test for randomness of a time series it the Ljung-Box test (LBQ-test). The LBQ-test is given by

$$Q = T(T+2)\sum_{k=1}^{m} \frac{\hat{r}_k^2}{T-k} \qquad (1)$$

where $\hat{r}_k^2$ is the estimated autocorrelation function of the series at lag k, T is the sample size and m is the number of lags being tested.

The Cross-Correlation Function (CCF) of two jointly stationary processes {Xt}and {Yt} is a measure of self-similarity between the two processes and is obtained by normalising the cross-covariance as follows:

$$\rho_{xy}(\omega) = \frac{\gamma_{xy}(\omega)}{\sqrt{\gamma_x(0)\gamma_y(0)}} \qquad (2)$$

where $\gamma_{xy}(\omega)$ is the cross-covariance of {Xt} and {Yt} at lag ω, $\gamma_x(0)$ and $\gamma_y(0)$ are the variances of {Xt} and {Yt} respectively.

2.3 Spectral Analysis

Traditional spectral analysis is a modified form of Fourier analysis so as to make it suitable for fitting stochastic rather than deterministic functions of time.

$$X_t = \alpha_0 + \sum_{k=1}^{\frac{N-1}{2}, N/2} [\alpha_k \cos(2\pi f_k t) + \beta_k \sin(2\pi f_k t)] + \epsilon_t, t = 1,2,\dots, N \qquad (3)$$

Where $f_k = \frac{k}{N}$ is the k^{th} harmonic of the fundamental frequency $\frac{1}{N}$, ϵ_t is white noise.

Harmonics are integer multiples of the fundamental frequency. N is the number of observations and periodicity (p): $p = \frac{1}{f_k}$. $R_k = \sqrt{{\alpha_k}^2 + {\beta_k}^2}$ is the amplitude of the k^{th} harmonic and $\varphi_k = \tan^{-1}\left(\frac{-\beta_k}{\alpha_k}\right)$ is the phase angle of the k^{th} harmonic.

$\alpha_0 = \overline{x_{t,}}$ $\alpha_k = \frac{2}{N}\sum_{t=1}^{N} x_t \cos(2\pi f_k t), \quad k = 1, \dots \dots .., \frac{N}{2}$,

$\beta_k = \frac{2}{N}\sum_{t=1}^{N} x_t \sin(2\pi f_k t), \quad k = 1, \dots \dots .., \frac{N}{2}$

A magnitude spectrum is a plot of magnitude or amplitude against frequency. Magnitude (Ik):

$I_k = \frac{NR_k}{2}, \ k = 1,2, \dots .. \frac{N}{2}$ and the angular frequency $\omega_k \coloneqq 2\pi f_k, k = 1,2, \dots . \frac{N}{2}$.

However, several expressions for the magnitude spectrum exist in the literature, in which case various lag windows are employed to smoothen the spectrum (Bloomfield P., 2000).

3. Results

Magnitude spectral analysis and cross-correlation methods are applied to Mean Monthly Sunspot Number, Annual Rainfall, de-seasonalised Monthly Rainfall and de-seasonalised Monthly Dry Bulb Temperature.

3.1 Analysis of Annual Sunspot numbers

Figure 1 shows existence of cycles which are not exactly periodic. The extrema of the cycles are also different. A Fast Fourier Transform is employed to find the approximate periodicity of the time series in Figure 1.

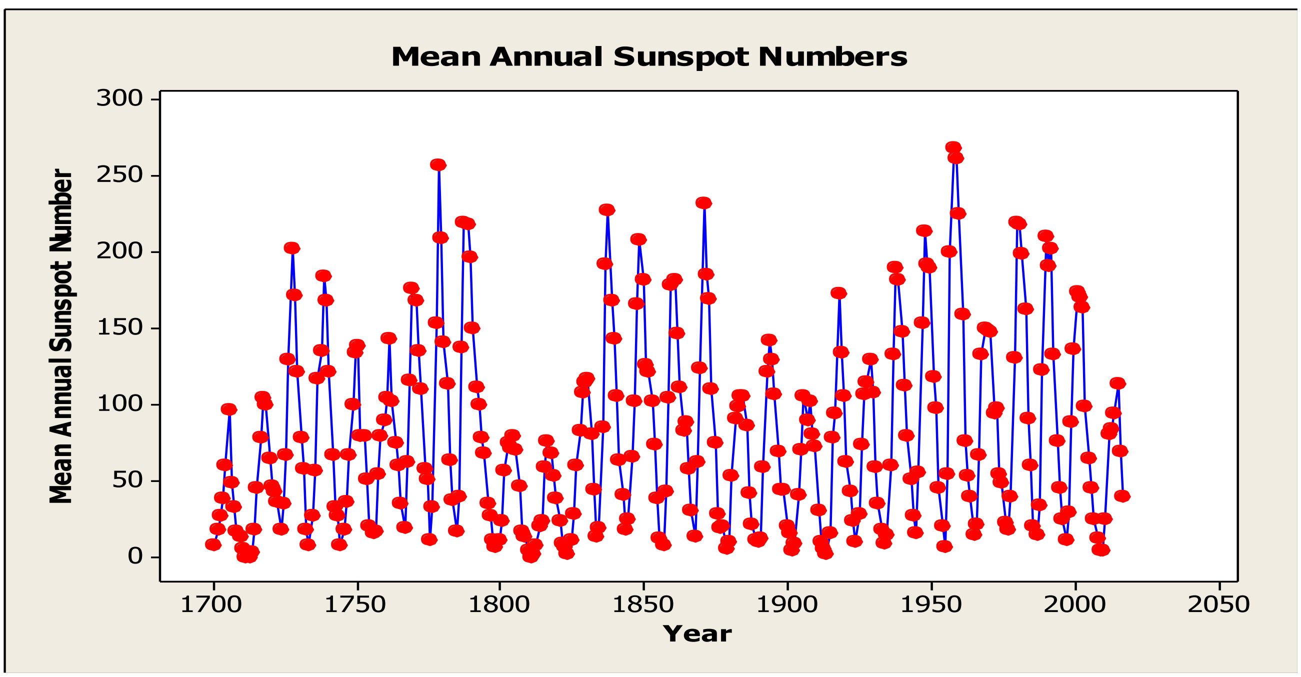

Figure 1. Time series plot of Annual Sunspot Numbers

Figure 2 shows that the Mean Annual Sunspot Number has a peak at a frequency of 0.591rads/sample implying a significant periodicity of 10.6 years.

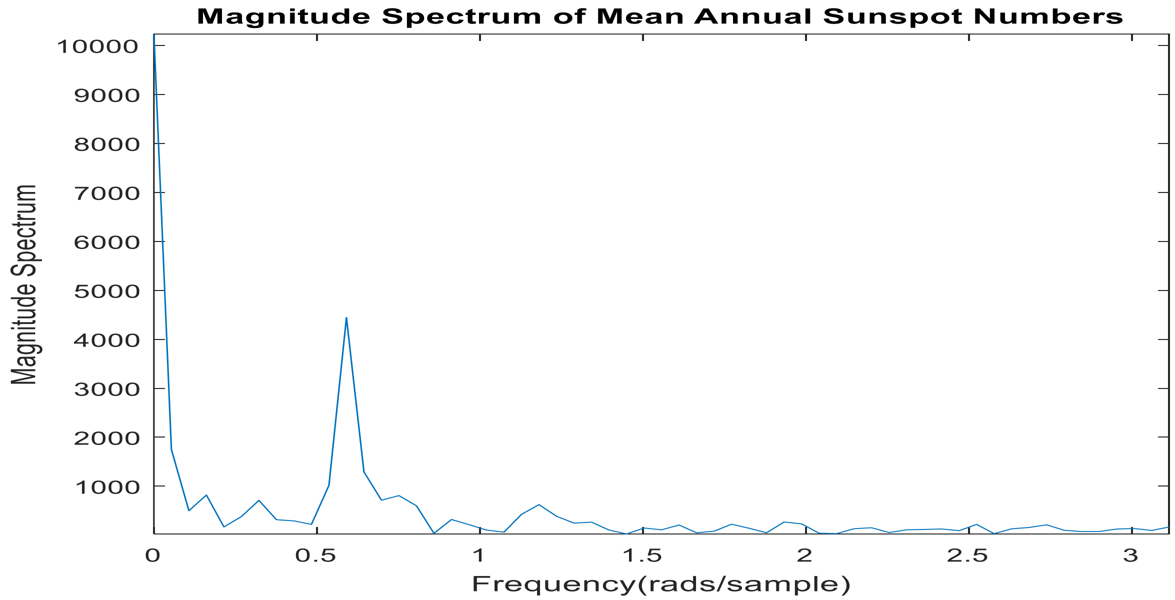

Figure 2. Mean Annual Sunspot Magnitude Spectrum.

Analysis of Precipitation in Bulawayo

The time series in Figure 3 shows no clear periodicity, the annual rainfall is lying between 200mm and 1260mm.

Figure 4 shows no prominent peaks. This means there are no significant periodicities as in the case of sunspot numbers.

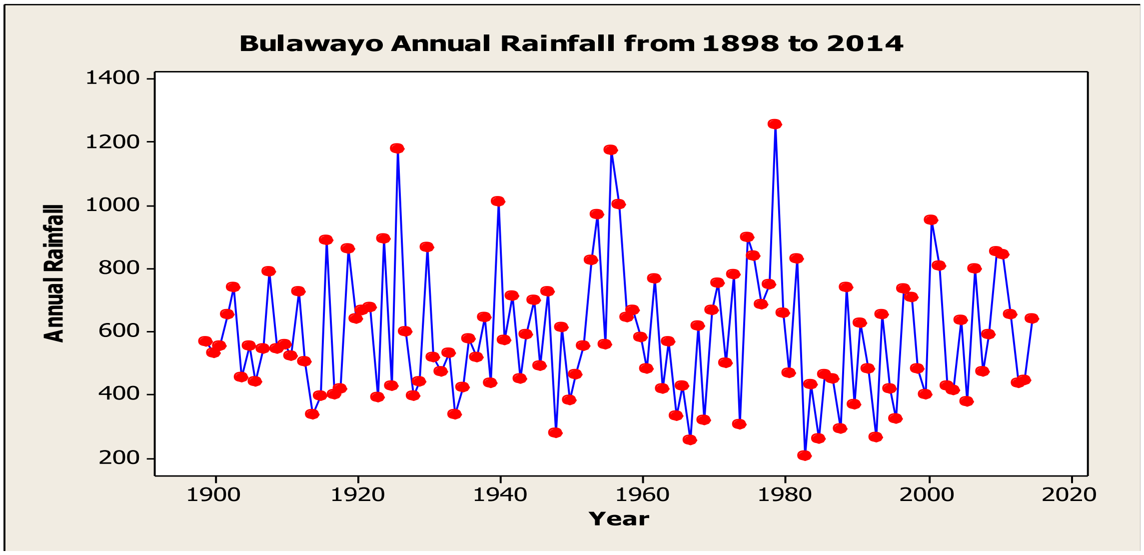

Figure 3. Time series for Bulawayo Annual Rainfall (mm)

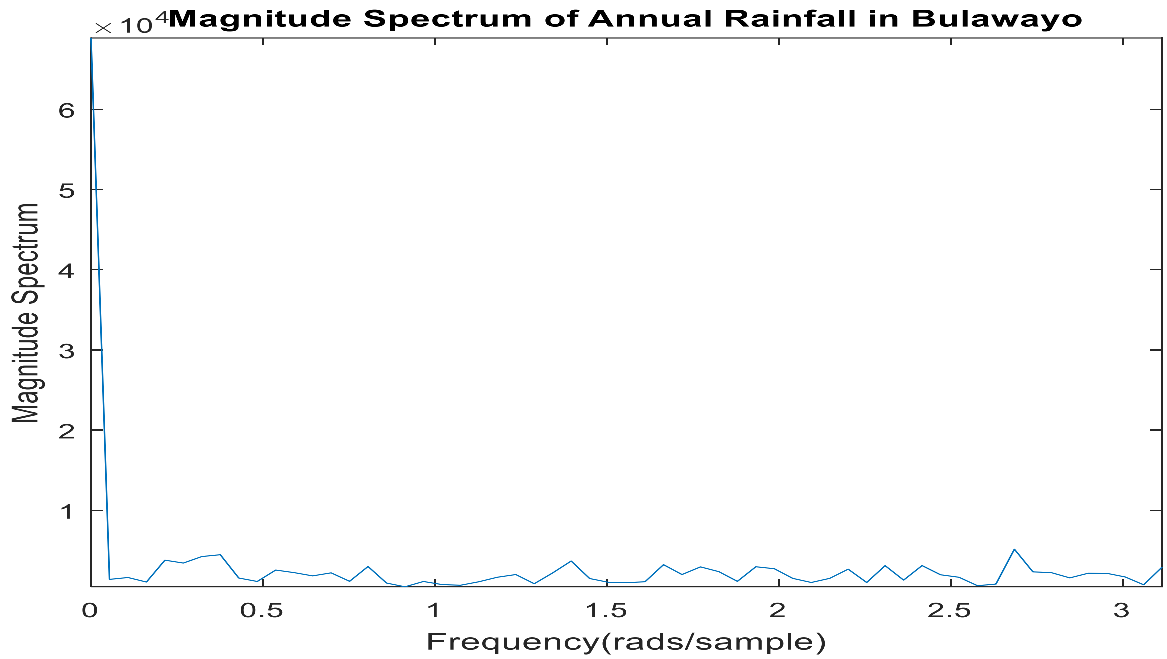

Figure 4. Periodogram of Annual Rainfall.

Figure 5 confirms the result that there are no significant periodicities for annual rainfall in Bulawayo, but it does suggest that it may depend slightly on rainfall 8 to 12 years previously. A Ljung-Box test for the autocorrelation up to lag 13 is shown:

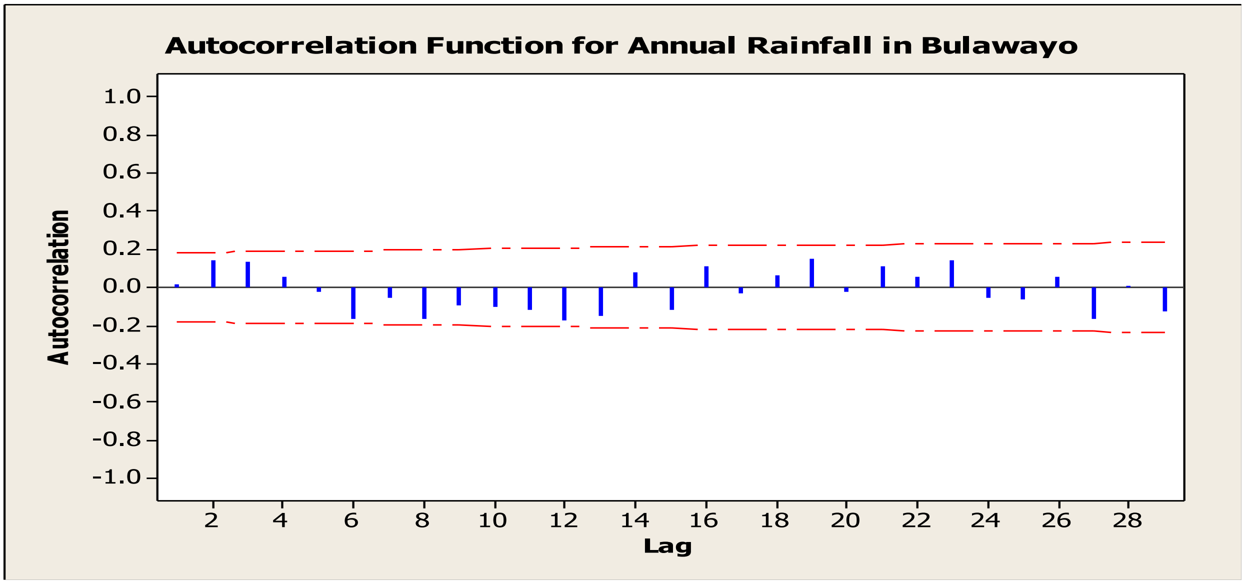

Figure 5. Autocorrelation function for Annual rainfall in Bulawayo (lag in years).

Cumulative Distribution Function

Chi-Square with 13 DF x P(X <= x) 23.9 0.967938

This supports that the time series of annual rainfall in Bulawayo does exhibit significant serial correlation up to lag 13.

3.2 Relationship of annual sunspot and annual rainfall in Bulawayo

Figure 6 shows that there is no clear contemporaneous relationship between annual rainfall and annual sunspot numbers.

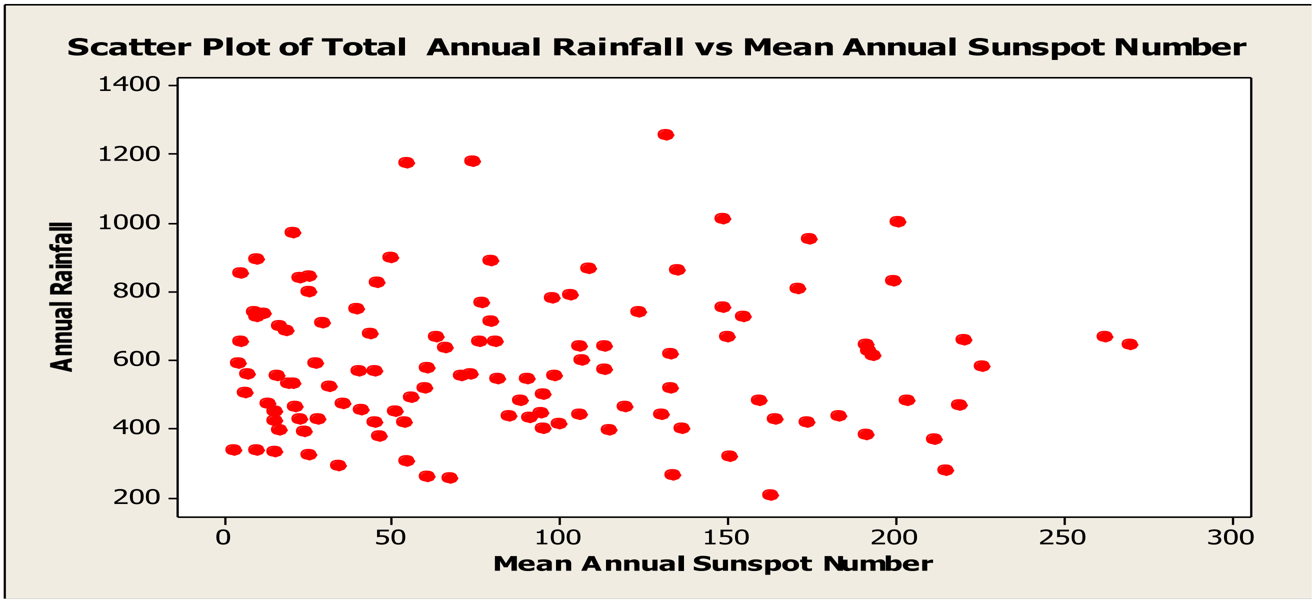

Figure 6. Scatter plot annual rainfall vs annual sunspots.

Figure 7 indicates that there are times when the impact of solar activity on rainfall is negative and also times when the impact is positive as shown by the oscillating cross-correlation function. There is a relatively high correlation of 0.191 at a lag of -3. There tends to be higher rainfall for the few years after low sunspot times, peaking after about three years. The cross-correlation function also shows a periodic behaviour of around ten years.

Let B_1 and θ_1 represent the group and Annual Rainfall 3 years after times when sunspot number >150 and let B_2 and θ_2 represent the group and Annual Rainfall 3 years after times when sunspot number <50.

$$H_0: \theta_1 - \theta_2 = 0$$
$$H_1: \theta_1 - \theta_2 < 0$$

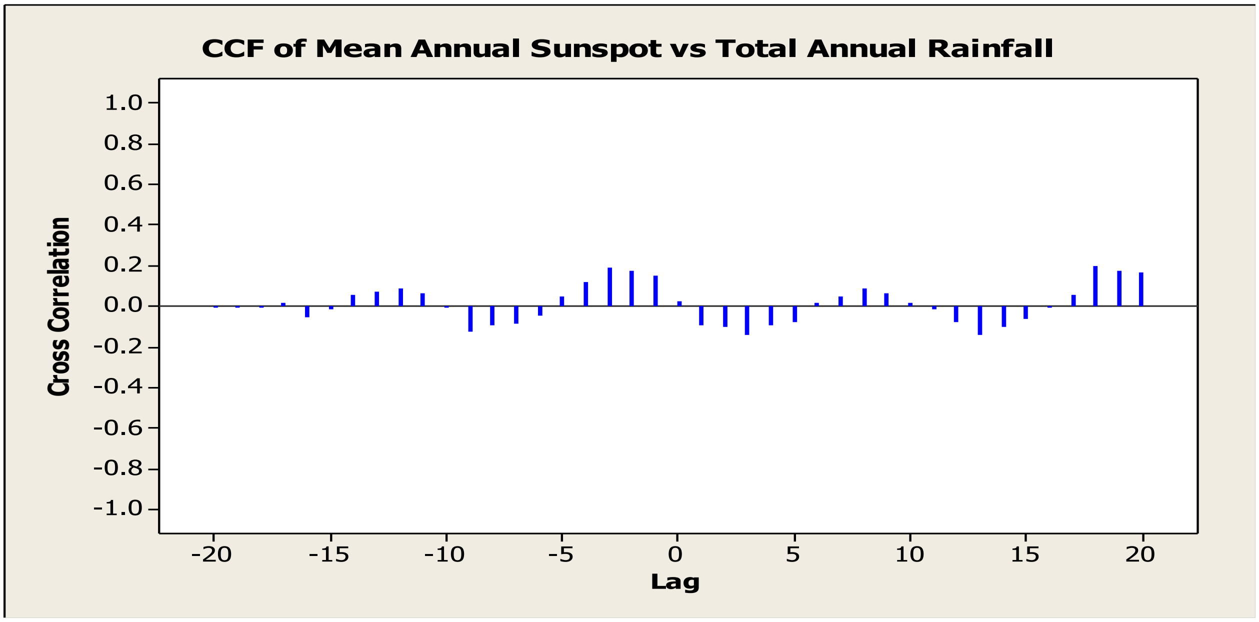

Figure 7. CCF of Mean Annual Sunspot Number and Total Annual Rainfall (lag in years).

From Table 1 we obtain that $t_{cal} = -1.91035$ ($p - value \approx 0.0281$), we reject the null hypothesis that there is no difference in Annual Rainfall patterns and accept the alternative hypothesis that Annual Rainfall following periods of high sunspots is less than that following periods of low sunspots at 5% level of significance. This implies that the relationship between solar activity and Annual Rainfall patterns in Bulawayo province is significant over a few years.

Table 1. Summary statistics to test difference of two means for Annual Rainfall.

Group	n	Mean	Variance
B_1	23	505.3826	25850.39
B_2	45	611.4356	57437.53

There is limited data available for monthly rainfall but, as illustrated in Figure 8, the cross-correlation function again suggests that rainfall increases after times of low sunspot numbers.

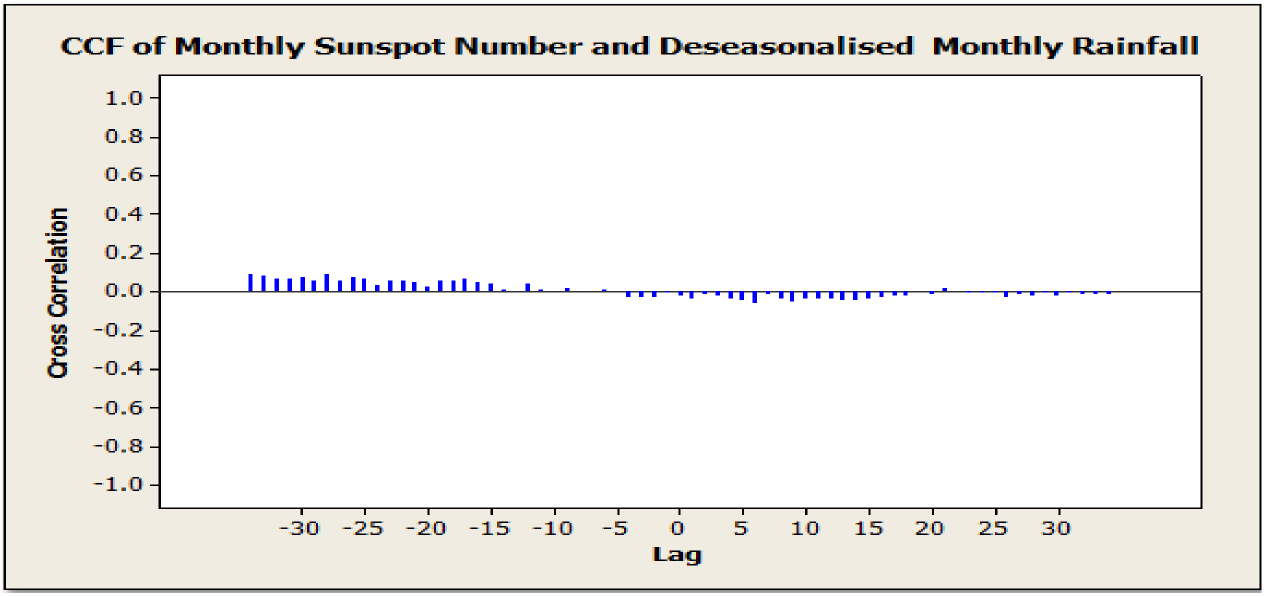

Figure 8. CCF of Mean Monthly Sunspot Number and Monthly Rainfall (lag in months).

We now check the CCF of Mean Monthly Sunspot Number versus Monthly Dry Bulb Temperature.

Relationship of monthly sunspots and monthly dry bulb temperature in Bulawayo

Figure 9 shows the cross-correlation function of Mean Monthly Sunspot Number and Deseasonalised Monthly Dry Bulb Temperature of -0.171 at lag -32. Even though the cross-correlation function value is small, the result implies that Monthly Dry Bulb Temperature in Bulawayo gets slightly higher following periods of high sunspot numbers and slightly lower following periods of low sunspot numbers at time lags of around 30 months. However, there is limited Monthly Dry Bulb Temperature data to ascertain the results.

We now test the difference of two means at $\alpha = 5\%$. Let G_1 and μ_1 represent the group and mean for Monthly Dry Bulb Temperature 30 months after times when sunspot number >150 and let G_2 and μ_2 represent the group and mean for Monthly Dry Bulb Temperature 30 months after times when sunspot number <50.

$$H_0: \mu_1 - \mu_2 = 0$$
$$H_1: \mu_1 - \mu_2 > 0$$

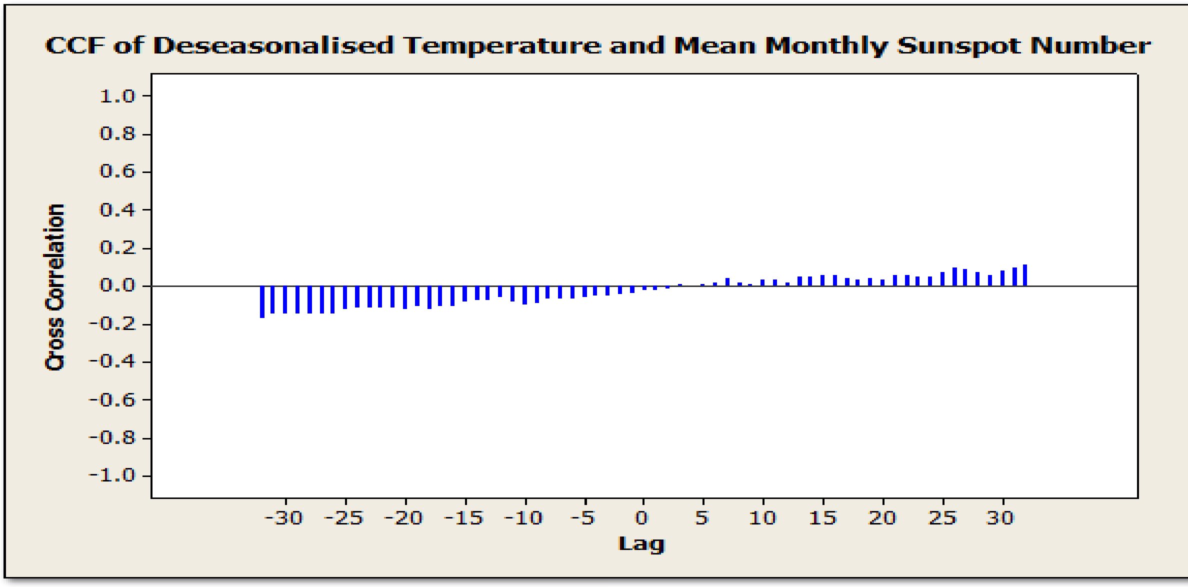

Figure 9. CCF of Mean Monthly Dry Bulb Temperature and Mean Monthly Sunspot Number (lag in months)

From Table 2 we obtain that $Z_{cal} = 1.796$ $(p - value \approx 0.038)$, we reject the null hypothesis that there is no difference in mean temperatures and accept the alternative hypothesis that mean temperature following periods of high sunspots is greater than that following periods of low sunspots at 5% level of significance. This reinforces the findings that periods of high solar activity have been followed by periods of high temperatures and periods of low solar activity have been followed by periods of low temperatures.

Table 2. Summary statistics to test difference of two means for temperature.

Group	n	Mean	Variance
G_1	111	19.50084854	1.164946
G_2	190	19.28120496	0.935652

We can conclude that there exists a significant relationship between solar activity and temperature patterns in Bulawayo at a time lag of 30 months, in addition the results shows that there is a significant relationship between solar activity and rainfall patterns in Bulawayo at time lag of 3 years.

4. Discussion

We confirmed using the Fourier Analysis that solar activity has an approximately 10.6-year period whereas annual rainfall had no significant periodicity.

After carrying out several different tests, we found a very weak relationship between solar activity and Bulawayo weather patterns for short time scales and a significant impact for long time scales. Periods of high solar activity have been followed by periods of slightly lower rainfall and higher temperature, that of low solar activity have been followed by periods of relatively higher rainfall and lower temperature for time lags of up to $2 - 3$ years.

5. Conclusion

Solar activity has been found to be related to local weather and climate in Bulawayo. The difference in annual rainfall after times of higher sunspot number (>150) and lower sunspot number (<50) have been of the order of 100mm and that for monthly dry bulb temperature is of order 0.22 ^{0}C.

El Nino-Southern Oscillation (ENSO), which is a result of variation in wind and Sea Surface Temperatures (SST) in the eastern Pacific Ocean, is said to have adverse effects on weather in Sub Saharan Africa. Severe effects of El Nino in Sub Saharan Africa are low rainfall and very high temperatures, but we have found that high temperature and low rainfall conditions may also be associated with the sun and space weather impacts. Therefore, further studies which include multi-collinearity among the natural drivers of climate change need to be studied to understand their combined impacts at local level.

6. References

Bloomfield, P. Fourier Analysis of Time Series. An Introduction. Second Edition. John Wiley and Sons (2000). Inc.

Chatfield, C. Time Series Forecasting. Chapman and Hall/CRC (2000)

Christensen, E. F. and Lassen, L. Length of Solar cycle: an indicator of solar activity closely associated with climate. JSTOR science, New series, vol. 254, No. 5032 (1991).

Cooray, T. M. J. A. Applied Time Series Analysis and Forecasting. Alpha Science International Ltd. Oxford, U.K., 2008.

De Jange, C. Solar activity and its influence on climate. Netherlands Journal of Geosciences-Geologie Mijnbouw |87-3|207-213|2008

Duhau Silvia and Martinez Enersta A. . Solar dynamo transitions as drivers of sudden climate changes (2012). http: //dx.doi.org/10.5772/51814

Fletcher, L. & Denis, B. R. & Hudson, H. S. & Krucker, S. & Phillips, K. & Veronig, A. & Battaglia, M. & Bone, L. & Casp, A. & Chen, Q. & Gallagher, P. & Grigis, P. T. & Liu, H.J.W Milligan, R.O. & Temmer, M. An observatory overview of solar flares. Space Science Rev (2011) 159:19-106

Haigh, J. Solar influences on climate. Briefing paper No. 5.F ebruary2011. www.imperial.ac.uk/climatechanges/publications

Kane, R. P. A preliminary estimate of the size of the incoming solar cycle 24, based on Ohl's precursor method. Solar Physics (2007)243DOI 10.1007/s11207 − 007 − 0475 − 4.

Khalid, M. & Sultana, M. and Zaidi, F. Prediction of solar cycle 24 using Fourier Series Analysis. The Nucleus 51, NO.2 (2014) 159-161, A Quarterly Scientific Journal of Pakistan Atomic Energy Commission, NCLEAM, ISSN 0029-5698.

Lockwood, M. & Harrison, R. G. & Woollings, T. and Solanki, S. K. Are cold winters in Europe as- associated with low solar activity? IOP PUBLISHING, Environ. Res. Lett. 5 (2010) 024001 (7pp), doi:10.1088/1748-9326/5/2/024001

Marusek, J. A. Solar Storm Threat Analysis. Impact 2007, Bloomfield, Indiana 47424

Morrison, N. Introduction to Fourier Analysis. A Wiley-Interscience Publication, John Wiley and Sons, INC. 1994

Sello, S. Solar cycle forecasting: A nonlinear dynamics approach. AA 377, 312 320 (2001) DOI:10.1051/0004-6361:20011068 ESO 2001

Sourabh Bal and Bose, M. A. climatological study of the relations among solar activity, galactic cosmic ray and precipitation on various regions over the globe. J. Earth Syst. Sci. 119, No. 2, April 2010, pp. 201-209, Indian Academy of Sciences

Source: WDC-SILSO, Royal Observatory of Belgium, Brussels. http://www.sidc.be/silso/datafiles

Space Weather, Storms from the sun. http://www.srh.noaa.gov/srh/jetstream/downloads/space-weather-booklet.pdf, March 9, 2016.

Svalgaard, L. Solar activity - past, present, future. J. Space Weather Space Clim. 3 (2013) A24 DOI:10.1051/swsc/2013046

Wernik, A. What is Weather? Space Research Centre- Polish Academy of Sciences, Warzawa Poland. CAS 2004/2005

Zanchettin, D. & Rubino, A. & Traverso, P. & Tomasino, M. Impact of variation in solar activity on hydrological decadal patterns in northern Italy. Journal of geophysical research, Vol113, D12102.doi10.1029/2007J D009157, 2008.

Zhao, J. & Han Yan-Ben and Li Zhi-An. The Effect of Solar Activity on the Annual Precipitation in the Beijing Area. Chinese Journal of Astronomy and Astrophysics.Vol. 4 (2004), No. 2, 189-197

www.nasa.gov/2017