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Wavelet and cross correlation analysis on some climatology parameters of Nepal

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ABSTRACT

This study has been performed to understand the relationship between sunspot numbers (SSN) with climatology related parameters like temperature and rainfall from 1901 to 2016. The spectral characteristics of sunspot numbers, temperature and rainfall have been observed using continuous wavelet transform. Cross-correlation analyses were also performed to find any relation among temperature, rainfall, and sunspot numbers. The 9–11 year periodicity of sunspot numbers confirmed by wavelet transform in annual scale. The periodicity of high-frequency signals is identified between 4 to 11 years whereas the low frequencies signal is found throughout the periods of observation for temperature. Similarly, it is clear that there is more concentration of power between 8–16 years for rainfall. Cross-correlation analysis shows that the sunspot numbers is highly correlated with rainfall and temperature (correlation coefficient ~ 0.8054). The time lag relationship resulted in the almost simultaneous linear relationship between the temperature, rainfall, and the SSN tendency. Development of convective motions over the subtropics might be affected by the time rate of change of SSN combined with the surface temperature changes of diverse time scales. The convective motions were mostly controlled by the available amount of water vapor and the stability of the atmosphere that had a strong connection with the heat capacity of the concerned region. To produce more authentic findings for policy implications, further comprehensive and appropriate research can be undertaken and implemented in this very important field.

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1. Introduction

The weather can be defined as the daily chaotic, non-linear dynamic system of the atmosphere, while the climate is the average state of the weather. The climate is fairly stable and predictable. The change in the state of climate that can be identified by changes in mean or variability of its properties and that persists for extended periods, typically decades or longer refers climate change [1]. Although there is no particular time frame to define climate, scientists have however been taking variety of weather parameters, such as temperature or rainfall based on data from weather stations in the area of concern or interest. Climate fluctuates annually above or below a long-term mean value. This fluctuation is called climate variability. The climate system shows high natural variability on different time scales. Nepal is located in subtropical latitude constituting for its variations in climates. The climates of different regions vary according to the altitude and seasons throughout the year.It lies in the temperate region of the world when sun's rays are moderate so it have tropical monsoon climate.Summer seasons are becoming hotter; more heavy rainfalls are being reported. Analysis of history of disasters in South Asia reveals that Nepal is the country that experience different types of flood every year with negative impacts on their economies. The plains of the foothills of Nepal mostly traversed by the rivers and tributaries mainly originated from the Himalayas. It falls under the Indian monsoon region with heavy precipitation during the wet monsoon that frequently causes severe floods destroying infrastructures, crops, and vegetations and displacing thousands of people [2].

Climate change is a very important and widely discussed subject in recent years. Climate change manifests in many respects apart from increase in rainfall, resulting into flood and the rising sea level. These include increased frequencies of extreme climatic events like above average daily minimum and maximum temperature. The most common parameters of climate change are increase in average global temperatures and precipitations. Thus, increase in average global temperature and average global precipitation is indicators of climate change. A common method for the assessment of climatic changes is the analysis of historical climatic data, in which trend detection and analysis play important roles [3, 4, 5].

Climatic elements and phenomena such as temperature, precipitation, humidity, and hurricanes are the results of various complex and often periodic processes in the atmosphere [6, 7, 8, 9]. The evaluation of the trend and periodic components of climatic time series separately provides more valuable information than those that can be obtained from direct trend analysis. Signal processing methods have become widely used in atmospheric and hydrological sciences. The wavelet analysis technique analyzes data for local and global climate changes and reveals active frequencies in time series and their changes over time [10-13]. The time series are non stationary in meteorology and climatology so that it is necessary to apply an advanced transformation to decompose a series into the time-frequency domain. At present, the wavelet transform seems to be one of the most appropriate methods for such analyses. Annual and seasonal scales variations of temperature and rainfall with sunspot numbers were considered in the present study. During this eleven-year cycle of sunspots, the sunspot number increases -solar maximum and decreases- solar minimum. In addition, the solar magnetic field, ultraviolet radiation, and other features that may affect climate are found to rise and fall along with the sunspot number.

The main purpose of this research is to investigate how some climatological parameters (temperature and rainfall) vary periodically and temporally over Nepal. The details of the data and data analysis methods adopted herein are briefly explained in next section. Section 3 presents the results and discussion followed by conclusions in section 4. The results indicate the variations of temperature and rainfall with sunspot numbers in a long terms data over Nepal.

Dataset

The climate of Nepal is diverse as the country's topography, which encompasses eight of the ten highest mountains in the world and extends to the rim of the Gangetic plains that have elevations below 300 meters above mean sea level basically subtropical; exhibiting two climatic sessions (dry and wet) annually. Monthly average temperature as well as monthly total rainfall data of Nepal, spanning 116 years; from 1901 to 2016 were collected from World Bank Data Group (https://climateknowledgeportal.worldbank.org/). The annual temperature in Nepal is defined as the mean of the temperature over all the months (January to December) of the year while the annual average rainfall accounted for the sum of all the total monthly rainfall divided by total number. Sunspot data where obtain from the Sunspot Index and Long-term Solar Observations (http://www.sidc.be/silso/datafiles). Sunspot number is the longest solar activity index available and it is a representative of the general state of solar activity [14].

2. Methodology

To achieve the objective of detecting the responses and significant periodicities of the temperature and the rainfall to SSN, the continuous wavelet transforms and cross-correlation analysis were employed.

Wavelet Transform

The wavelet transform (WT) is a strong mathematical tool that provides a time-frequency representation of an analyzed signal in the time domain [15]. Wavelet transform has advantages over classical spectral analysis, because it allows the analysis of different scales of temporal variability and it does not need a stationary series [16]. Thus, it is appropriate to analyze irregular distributed events and time series that contain non-stationary power at many different frequencies. Wavelet analysis maintains time and frequency localization in a signal analysis by decomposing or transforming a one-dimensional (1-D) time series into a diffuse 2-D time-frequency image simultaneously. Then, it is possible to get information on both the amplitude of any periodic signals within the series, and how this amplitude varies with time. For instance, in comparison with the Fourier transformation, it is possible to differentiate not only values of particular frequencies in non-stationary series, but also their location in time can be determined [17]. On the other hand, the possibility of time-frequency representation relates to a problem of resolution. Another advantage of wavelet analysis is that this method, contrary to the other types of transformation providing time-frequency presentation, like the windowed Fourier transformation, solves the dilemma of resolution to a certain extent [18].

Continuous Wavelet Transform

The continuous wavelet transform (CWT) is the mathematical tool able to analyze any non stationary time-series, showing the temporal variability of the power spectral density. The "wavelet" word indicates a set of functions with the form of small waves created by dilations, $\psi(t) \to \psi(2t)$, and translations, $\psi(t) \to \psi(t+1)$ applied on a simple generator function, $\psi(t)$, which is called mother wavelet.Mathematically, the wavelet function is given by

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right) \tag{1}$$

where s represents the scale associated to the dilation and contraction of the wavelet, and τ is the temporal location, which relates to the translation in time. For each value of the s and τ coefficients, we obtain a set of wavelet functions, called daughter wavelets [19].The wavelet transforms, W is then defined as a convolution integral of the time series with the wavelet function:

$$W^x(s,\tau) = \frac{1}{\sqrt{s}} \int x(t)\psi^*\left(\frac{t-\tau}{s}\right)dt = \int x(t)\psi^*_{(s,\tau)}\,dt \quad (2)$$

where $x(t)$ is the time series, $\psi_{s,\tau}(t)$ is the wavelet function and * represents the complex conjugate. Here, s and τ are real and $s > 0$. We used the Morlet wavelet, a continuous and complex wavelet adapted to wavelike signals that allows identifying the main periodicities [10], [20]. It is a plane wave modulated by a Gaussian envelope and can be described by Equation 3:

$$\psi(t) = \pi^{-1/4} e^{i\omega_0 t} e^{-t^2/2} \quad (3)$$

where ω_0 represents the dimensionless frequency. In this work this value of parameter was set up as 6.0, since its shape gives good localization in time [10], which is a monochromatic wave modulated by a Gaussian of unit width.

Wavelet power spectrum

The wavelet power spectrum (WPS) is defined as $\left|W^x(s,\tau)\right|^2$ and represents the squared absolute value of the wavelet transform coefficients. The WPS (which is sometimes also referred as Local Wavelet Power Spectrum (LWPS)) is plotted as a function of time and period in a 2-dimensional graph. Concerning the fact that the wavelet power spectrum gives more information in one picture, it is often practical to show the information as the averaged value of the result in the range of scale or time.The parameters used for the wavelet analysis of the yearly temperature and rainfall data in this study were: δt = 1year and $S_0 = 2\,\delta$t, δj = 0.25 to do 4 sub-octaves per octave, $j_1 = 7/\delta$j to do 7 powers-of-two with δj sub-octaves each. Information on the relative power of a particular scale and a particular time is provided by power of the yearly temperature and rainfall data. It reveals the magnitudes of the scaled and shifted version of the mother wavelet in addition to their actual oscillations.

Global wavelet power spectrum

The average wavelet power (also known as Global Wavelet Power Spectrum (GWS)) showed the average variations of the whole time series on every scale which is defined as [10]

$$GWS = \int \left|W^x(s,\tau)\right|^2 d\tau \quad (4)$$

The scales are a series of fractional powers of 2 and are defined as: sj=s02kδjk=0, 1,…,J, where s_0 is the least resolvable scale and *J* determines the highest scale. Moreover, the scale δ_j= 0.25 is used, which will do 4 sub octaves per octave. The smaller values of δ_j give a finer resolution [10].

Cone of influence

The cone of influence (COI) is the errors occur at the beginning and at the end of wave power spectrum when considering a time series of finite length. The edge effects are reduced when number of the elements of the time series is equal to a power of 2. Thus, there is need to pad the time series with zeros to bring the length of the time series to the next higher power of 2 before calculating wavelet transform [10]. The padding reduced the amplitude at the edges, as more zeros were involved in the analysis. The region of the wavelet spectrum in which edge effects become important is referred to as the cone of influence (COI). And it is defined as the e-folding time for the autocorrelation of wavelet power at each scale [10].

Cross-Correlation Analysis

The cross-correlation analysis (CCA) is a well-known method used to find where two signals match. Several authors have used this method [21-25]. The classical correlation is calculated by the displacement of one series relative to the other by units of time (t), which provides the lag of the correlation [25]. We calculated the cross-correlation coefficients for the leading and lagging shifts between SSN with temperature and rainfall. The correlation coefficient also defines how well correlated the two series are, varying from -1 to 1.

3. Results and Discussion

We plotted time series of yearly average sunspot number (SSN), yearly average temperature of Nepal and yearly average rainfall of Nepal during

1901-2016. This time series for yearly average sunspot numbers, temperature and rainfall of Nepal (1901- 2016) as shown in Figure 1. It is evident from Figure 1 that both temperature and rainfall data appear irregular and random, while sunspot numbers have a clear cyclic character. This variability might be suggestive of coupled global ocean–atmospheric dynamics or some other factors, such as deforestation, anthropogenic, high latitudinal influence etc. [27].

Figures 2(b), 3(b) and 4(b) show the power (absolute value squared) of the wavelet transform for the yearly sunspot numbers, temperature and rainfall for 116 years in Nepal presented in Figures 1(a)-(c). The (absolute value) ^{2} gives information on the relative power at a certain scale and a certain time. These figures show the actual oscillations of the individual wavelets, rather than just their magnitude. Observing these figures, the concentration of power can be easily identified in the frequency or time domain.Wavelet power decreases according to the following order: red, orange, yellow and blue.The cross-hatched regions in these figures are the cone of influence, where zero padding has reduced the variance. Because we are dealing with finite-length time series, errors will occur at the beginning and end of the wavelet power spectrum [27]. The black contours in the same figures are the 5% significance level, using a red-noise background spectrum.

As declared before, the absolute value squared offers info on the relative power at an explicit scale and an explicit time that shows the particular oscillations of the individual wavelets, instead of simply their magnitude. Observing the global wavelet spectrum in Figures 2(b)-4(b), it is clear that there is more concentration of power between the 8 – 16 years band. Wavelet power spectrum at 95% significant level presents an important peak for sunspot numbers, temperature and rainfall episodes with characteristic scale of 9 - 11-years. The wavelet spectrum of sunspot numbers shows strong periods between 9 to 11 years [28-30] for the entire time span. Contour lines delimit the periods significant at 95% confidence level. The parabolic curve delimits the cone of influence region. From this Figure 2a the signal near 11-year is the strongest feature and is persistent during the entire series indicating the non-stationary behavior of the sunspot time series. The wavelet spectrum of temperature (Figure 3a) shows strong amplitudes in the interval of 2–8 years. The signal is non-stationary with the periodicities alternating i.e., present at sometimes and absent in others. The wavelet power spectrum of rainfall variability (Figure 4a) reveals significant power concentration at time scales of 8–16 years and at 11 years solar time scales [31]. A dominant amplitude mode is also seen in the low frequency range at around 1920-1940 years (at periods 30–35).

The power in 8 - 16-year band in rainfall shows the dry and wet years which means when the power decreases substantially it means a dry year similarly for the maximum of power it is a wet year. In the years 1920 and between the years 1985 to 2010 an extreme increase in power can be found which corresponds Nepal has a wet year. Since 1960 to 1980 a dry period that contains certain reductions can be identified.

Also, there are intense periods around 16–32 years both in temperature and rainfall. Higher order periods are also observed around 43 years, but they are insignificant as it lies under the hatched region. Periods around 16 years also shows weak signal. Like the sunspot numbers, the wavelet results of annual rainfall show periods around 11 years from 1910– 1920. Shorter periods like 3–5 years are also visible in the beginning of the time series. There are periods greater than 32 years and lies above COI from 1910–1950. This annual rainfall of Nepal shows shorter periods between 2 and 6 years. The power is intense at the beginning. More intense power is visible but lies near COI, so neglected. The brief discussion of the results of wavelet transform implies that oscillations of annual temperature and rainfall are likely driven, at least partly, by solar variability. The general correspondence of prominent rainfall changes with variations in solar activity implies a solar influence on area-scale rainfall oscillations during the past

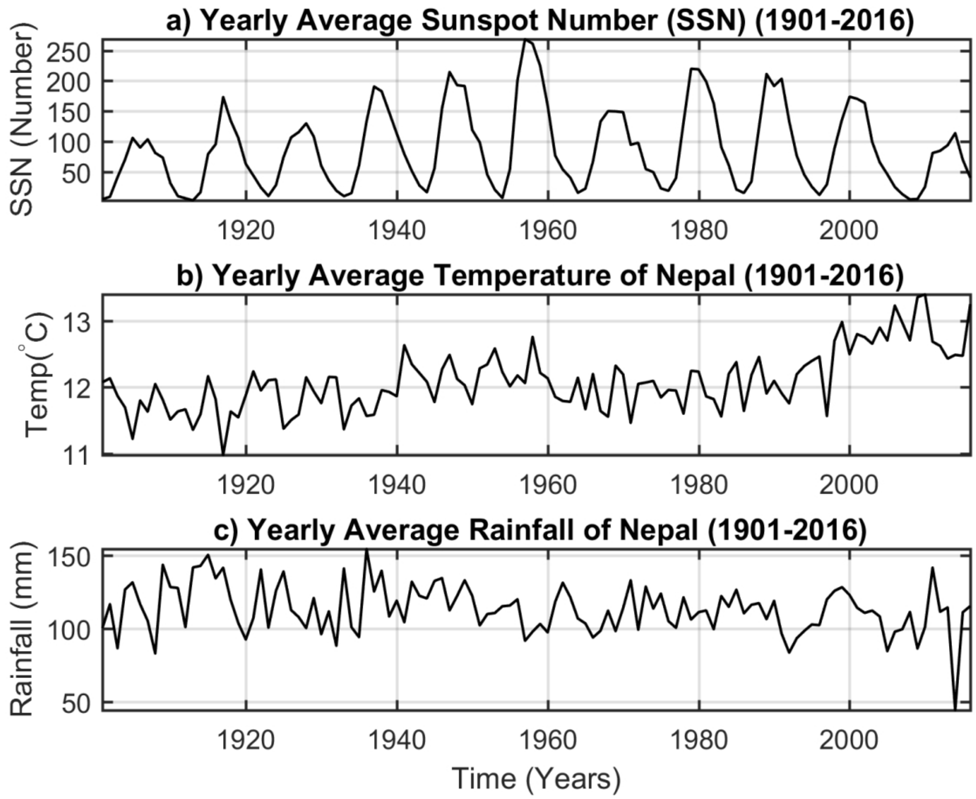

Fig. 1 :. Figure from top to bottom a) yearly average sunspot number (1901-2016), b) yearly average temperature of Nepal (1901-2016), and c) yearly average rainfall of Nepal (1901-2016).

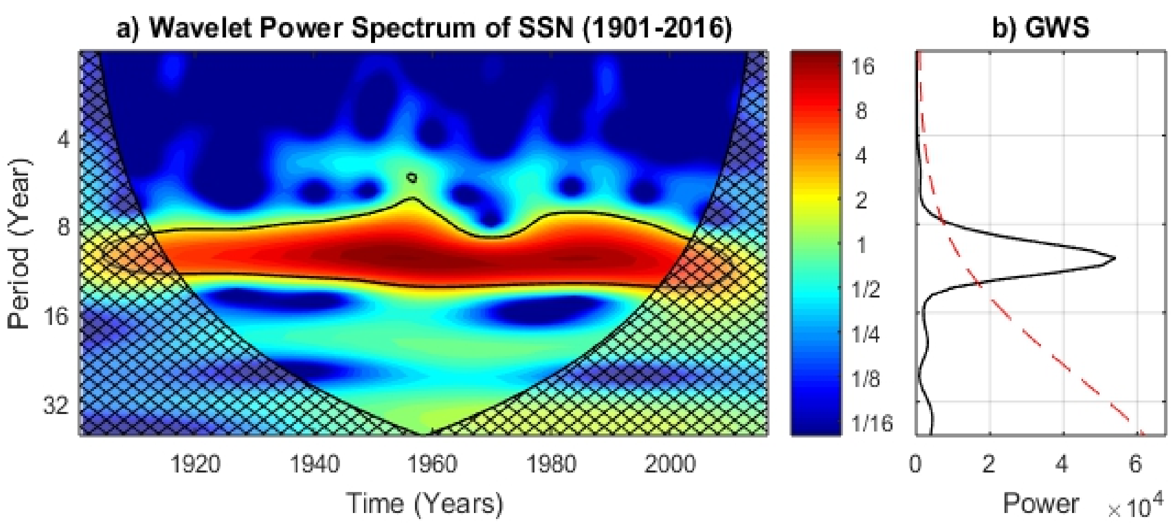

Fig. 2 : a) Wavelet power spectrum of sunspot numbers (SSN) (1901-2016); cross-hatched regions on either end indicate the 'cone of influence' where edge effects become important. b) The global wavelet power spectrum. The dashed line indicates 5% significance level for the global wavelet spectrum.

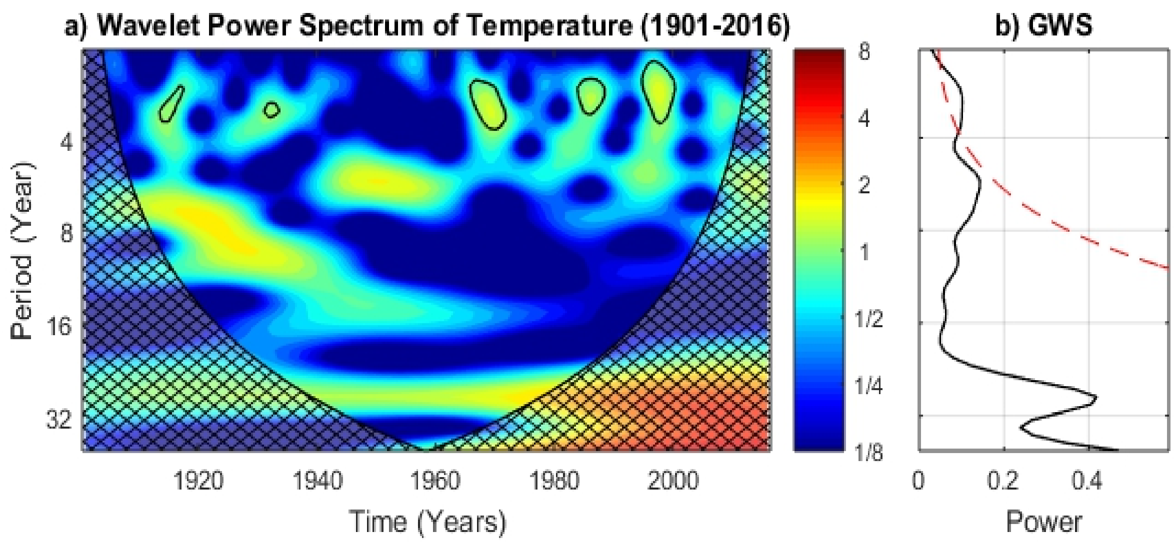

Fig. 3: a) Wavelet power spectrum of temperature (1901-2016); cross-hatched regions on either end indicate the 'cone of influence' where edge effects become important. b) The global wavelet power spectrum. The dashed line indicates 5% significance level for the global wavelet spectrum.

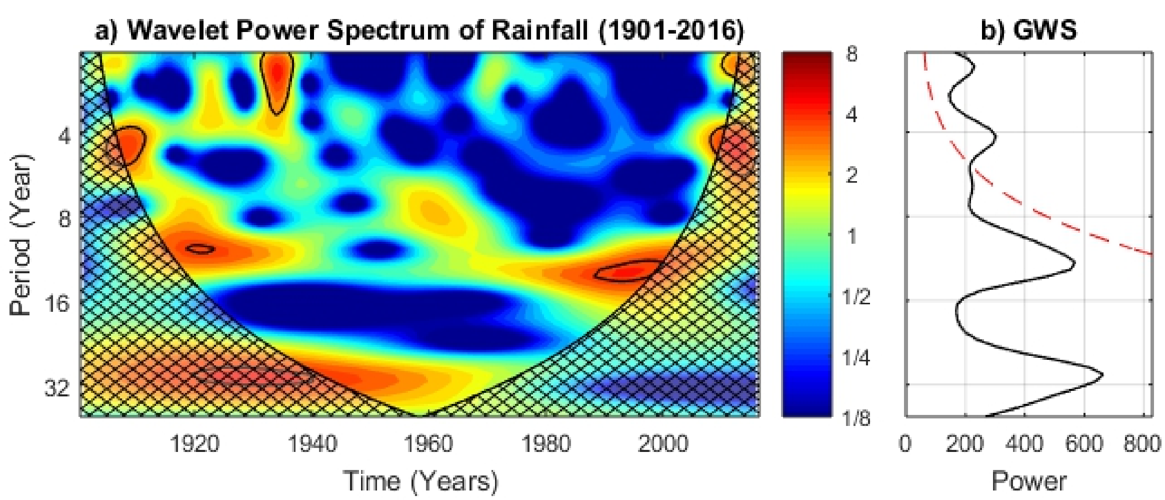

Fig. 4: a) Wavelet power spectrum of rainfall (1901-2016); cross-hatched regions on either end indicate the 'cone of influence' where edge effects become important. b) The global wavelet power spectrum. The dashed line indicates 5% significance level for the global wavelet spectrum.

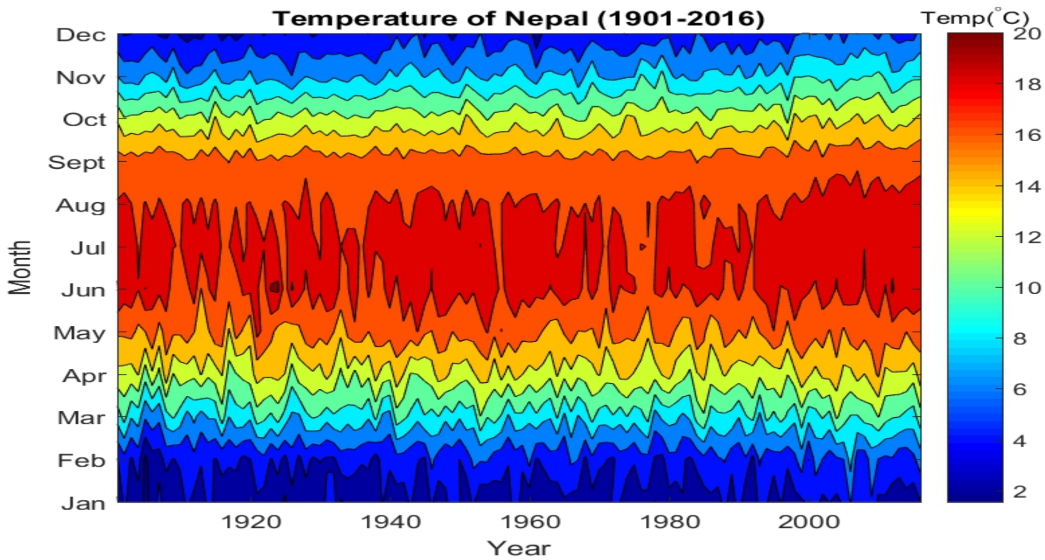

Fig. 5: Temperature contour of Nepal 1901–2016.

116 years. So, in this paper an attempt was made to study the relationship between temperature, rainfall, and solar activity [32-35].

Figure 4(b) showed the significant peaks around the years of 1928, 1940, 1970 and 1990. The average yearly total rainfall of Nepal from the year 1901 to 2016 is shown in 4(a). Figure 4(b) revealed multi-level power peaks on the global wavelet spectrum, with the maximum of 600 occurring around the 32-year- period but which lies above COI. However, the power peak of about 2 occurring around the 11-year- period is the most significant at the 5% significance level.

Figure 5 depicts the detail information of temperature throughout the months of the given years. The range of temperature varies from 2 °C to 10°C. The result reveal that the temperature increases gradually from 18 °C to 20 °C in the month of May and then around 19 °C to 20 °C (brown color) in the month of Jun (the hottest month). Thereafter the temperature begins to decrease until a minimum around 2 °C to 4 °C in the month of December whereas another maximum turning point was observed in the month of October (light-olive green color). Finally, the temperature decreases to around 3 °C in the month of December. It has been noticed that the intense temperature of 20 °C (dark brown color) was recorded in the months of April to August of the years.

Figure 6 illustrates the annually season variation of rainfall from 1901 to 2016 in Nepal. It has been noticed that the rainfall picks up its momentum gradually, becoming more intense from July and reaching its maximum around August; and thereafter begins to decrease.

We have also analyzed the correlative analysis of 116 years data of the sunspot, temperature, and rainfall. It has been found that the effect of the 22-year solar cycle with a 0-year lag on global temperature is more significant rather than that of 11-year cycle. Thus, the 22-year magnetic field solar cycle plays a greater role than that of 11-year sunspot cycle in global climate change. Additionally, we notice that solar activity cannot explain the upward trend of global temperatures after 1970. This shows that positive correlation coefficient exists between rainfall and solar activity during the investigation. The positive value may be due to low temperature regions or months. The correlation of sunspot numbers with rainfall should have high correlation coefficient value [36] and the present study shows similar result. The calculation of correlation between the datasets of sunspot numbers, temperature, and rainfall, found maximum positive correlation coefficient approximately 0.8054. The time lag relationship resulted in the almost simultaneous linear relationship between the temperature, rainfall, and the SSN tendency. Development of convective motions over the subtropics might be affected by the time rate of change of SSN combined with the surface temperature changes of diverse time scales. The changes came from an annual cycle, the diurnal variation, and other various mechanisms. The convective motions were mostly controlled by the available amount of water vapor and the stability of the atmosphere that had a strong connection with the heat capacity of the concerned region.

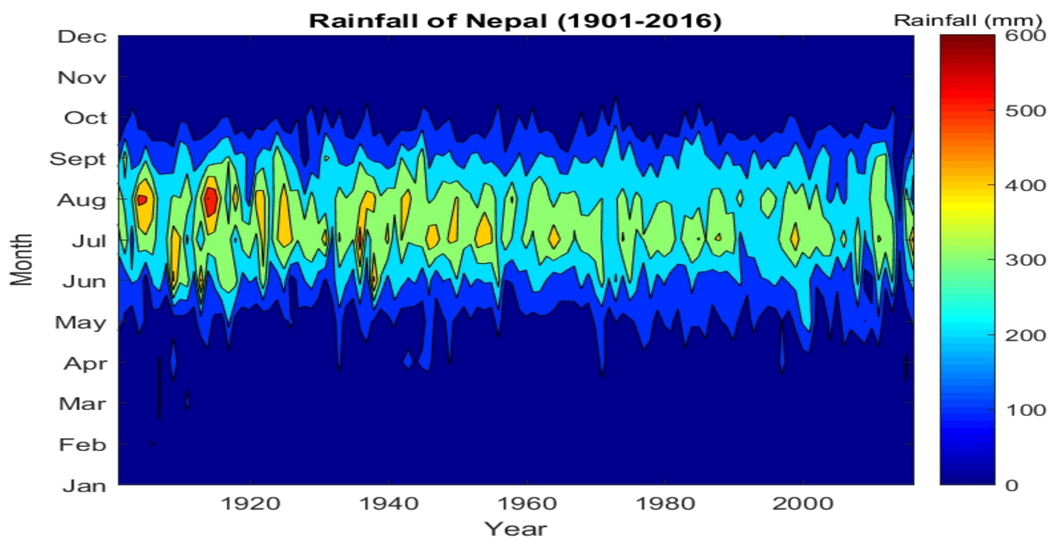

Fig. 6: Rainfall contour of Nepal 1901–2016.

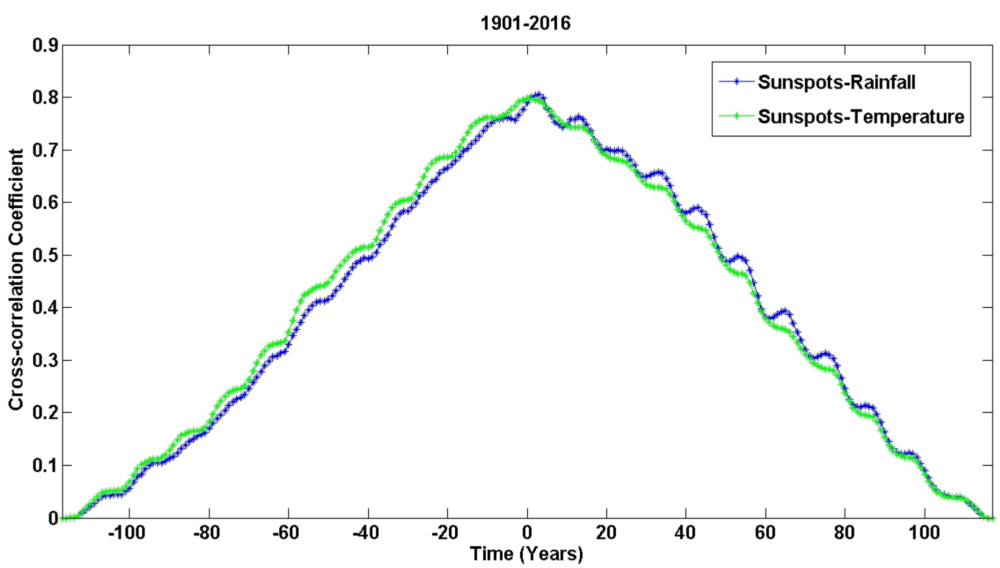

Fig. 7: Cross-correlation between sunspot numbers (SSN) with temperature and rainfall.

4. Conclusions

The present paper is an attempt to quantify the relation between Sunspot numbers and climatic related parameters. We applied waveletand cross-correlation analysis to analyze the 116-year time series of temperature and rainfall of Nepal with sunspot numbers. With spectral wavelet analysis, the time-frequency characteristics of the analyzed data were estimated. This analysis provides an insight into the dynamic behavior of the observed average temperature and rainfall over time. For both the yearly average temperature and rainfall of the analyzed time series, several local maximums were identified in the GWS graphs, where the largest is that in a 9–11-yearperiod, showing that these time series have strong relations with sunspot numbers. Change in climate is attributed to natural variability and anthropological activities. Variation of solar activity reaching the Earth is thought to influence rainfall, but we are still searching for better physics to understand how the periodic variation of the solar activity influences the variation of the rainfall of land. The wavelet analysis shows almost all kinds of periodicities on one time or other ranging from 2 to 11 years and more. Therefore, it should be further studied to investigate any quantitative effect of solar activity on other parameters. The calculated correlation coefficient values arehigh. Climate change in Nepal got tremendous momentum since the advent of 90's in terms of rainfall. The adverse impact of this climate change in Nepal has become the most vulnerable and this process continues at an increasing rate. The findings of this study show that Nepal is a vulnerable country to climate change in terms of rainfall. To produce more authentic findings for policy implications, further comprehensive and appropriate research can be undertaken and implemented in this very important field.

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