



Wavelet Approach to Identify Wind Speed Characteristics of Northern Province of Sri Lanka

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Abstract: Northern Province of Sri Lanka was identified as a region with high wind resources adequate for wind power plant development. Hence, this study was conducted to identify the wind speed characteristics of Northern Province of Sri Lanka. Wind speed data of the region was analyzed and compared with the data obtained from three weather stations in southern coast, west coast and the central part of Sri Lanka which were introduced by many literatures as the regions with high wind resources. Prior to the analysis, missing values were imputed using multiple imputation by chained equations method. Wavelet analysis was then performed to explore the oscillating characteristics of wind speed. Further, to examine the association between wind speed and rainfall patterns of Mannar and Southern Province weather stations, wavelet coherency analysis was performed. The analysis of Northern Province wind speed data revealed that Mannar has the highest wind speed in the region and has similar oscillating characteristics to that in Southern Province weather station. Wavelet coherency analysis further revealed that the maximum wind speed occurs during the dry seasons of the region.

Keywords: Wind speed, Renewable energy resources, Multiple Imputation, Wavelet analysis, Wavelet Coherency analyses

I Introduction

Due to ever increasing threat coming from traditional sources of electricity on environment and the concerns related to sustainability of fossil and nuclear fuel usage, renewable energy resources that are economically viable and environmentally acceptable have become an important research topic from both the environmental and economical points of view. According to the author in [4], a source can be considered as an ideal renewable energy resource if it is inexhaustible and does not lead to any significant disruption of existing environmental systems. Wind, solar, hydro, tidal, wave can be considered as few energy resources that are close to this ideal [4]. Among these possibilities, wind power has become one of the fastest growing renewable energy technologies all around the world as it gives kinetic energy free of charge and the cost calculation for energy production involves only the site development, equipment and maintenance costs [13].

Sri Lanka is an island just off the southeastern tip of India and is surrounded by the Indian Ocean, centered at approximately 81° east longitude and 7° north latitude. Due to this geographical position of Sri Lanka there are several locations in the country with high wind resources sufficient for cost-effective utility scale wind power plant developments. However due to the high cost involved with site development and related equipments for wind power plants, project feasibility assessment is vital prior to any development process [18].

Since Sri Lanka is a country with considerable amount of lands with high wind resources adequate for wind power plant developments, few local researches related to site screening had been done by the time the work of this research was started [11], [18]. However, almost all those projects had limited their attention only to southern coast, west coast or central part of the country. Due to the decades-old civil conflict in northern region of the country which last till 2009, no prior research related to the topic was found for the region even though it was introduced as one of the most favorable areas for wind resource potential by many literatures [9], [11], [18]. Since wind speed data for the region have now become available this study was in an attempt to analyze the wind speed characteristics of Northern Province of Sri Lanka using five year daily wind speed series for the years from 2010 to 2015.

Previous studies related to the topic have used statistical models based on normal, lognormal, Weibull and Reyleigh distribution functions to analyze the variation in wind speed data. Among them the two-parameter Weibull distribution function was recommended by many literatures as the most appropriate distribution function for wind speed analysis [3], [14], [16]. However, their inability in providing an insight into the non stationary behavior and oscillating characteristics of wind speed data over time, have limited the importance of those findings. According to the authors in [6], Wavelet Analysis is a powerful technique that can be used to overcome the limitations of those traditional methods as it allows to understand the oscillating characteristics of a given time-series. Therefore in this study, to fully understand the wind speed characteristics and their dynamic patterns, Northern Province wind speed data was more directly analyzed using Wavelet Technique.

The findings and recommendations of this study will be useful to update the country's existing profile of feasible locations of cost-effective utility scale wind power plants. Further it is hoped that the finding will stimulate further

research into this important phenomenon which enable continuous improvement and ensure the continued success of wind energy sector.

II Methodology

A. Study area and Data source

Authors in [18] have recommended National Renewable Energy Laboratory (NREL)'s wind atlas as a good starting point to locate areas for utility scale wind power plants. So following NREL wind atlas, Northern Province wind speed data was analyzed and compared with the three regions southern coast, west coast, and central part of Sri Lanka which were introduced by NREL wind atlas as regions of high wind potential.

Climate Data for Northern Province were adopted from the observations of three weather stations; Jaffna (Latitude: 9.65, Longitude: 80.01, Altitude: 3), Mannar (Latitude: 8.98, Longitude: 79.91, Altitude: 3), Vavuniya (Latitude: 8.75, Longitude: 80.5, Altitude: 98). These data were analyzed and compared with the data received from three weather stations of the three provinces: Southern Province (Latitude: 6.11, Longitude: 81.13, Altitude: 20), North Western Province (Latitude: 8.03, Longitude: 79.83, Altitude: 2) and Central Province (Latitude: 6.96, Longitude: 80.76, Altitude: 1880). Total rainfall (in millimeter), average wind speed (in Km/h) and maximum sustained wind speed (in Km/h) of the six weather stations from January 1, 2010 to September 30, 2015 were used as the study data. Here the 'total rainfall' refers to the daily rainfall amount for a particular day which was collected over a period of 24 hours. 'Average wind speed' refers to the mean wind speed of the day. 'Maximum sustained wind speed' refers to the maximum one minute average wind speed recorded by an anemometer located 10 meters above the surface for a given day [10].

B. Missing Data imputation

Missing data represents a general problem when dealing with environmental data and it has been extensively reviewed in [15]. The main sources of missing data mechanisms considered in this study were reading invalidations; collapses of measurement instruments; and maintenance incidents. Therefore following the guidance of authors in [12], the wind speed and rainfall data were analyzed assuming missing at random mechanism. Since single imputation methods does not consider the uncertainty in the imputations [17], multiple imputation by chained equations method, implemented in 'mice' package in R was used to perform the imputation. Five complete datasets were generated by imputing five values for each missing record in the six data sets. They were then aggregated by averaging the five imputed values of each missing record and the resulted complete data set of each weather station was used for further analysis.

C. Wavelet Analysis

Wavelet analysis has become a powerful tool in handling non-stationary time series [2]. Thus to explore the oscillating characteristics of Northern Province wind time series data, continuous wavelet transform, which decomposes the time series into time and frequency component was performed. Morlet wavelet was used as the mother function. High frequency periodicities of the time series in the time-frequency domain was quantified using the thickness variations of the wavelet power spectrum [8]. To quantify the statistical significance of the computed patterns, Montecarlo simulation was used. All wind time series were decomposed and the trend was suppressed prior to wavelet transformation. 'Biwavelet' package in R was used to perform the analysis.

D. Wavelet Coherency analyses

Wavelet Coherency analysis is a method of analyzing the coherence and phase lag between two non stationary time series [7]. Thus to examine the association between rainfall and wind speed; and the period (in week) the coherency occurs between them, Wavelet coherency analysis was performed [6]. The 'biwavelet' package in R was employed to compute both wavelet cross spectrum and rough information on the phase difference between the two time series. Colors in the wavelet cross spectrum indicate the strength of the coherence. Reddish areas within solid black lines represent the statistically significant areas (threshold of 5% confidence interval) [5]. The direction of the arrows in the wavelet cross spectrum indicate the degree to which the two time series are in phase. If two time series move together at a particular scale, the phase difference between the two series will be equal to zero. Arrows point to the right in the wavelet cross spectrum indicate the positive correlation between the two time series and the opposite is true for negatively correlated time series. Furthermore, arrows pointing up indicate that the first time series leads the second by 90 degrees (one fourth of the cycle at that period), and opposite is true for the arrow pointing down [1].

III RESULTS

The wind resource in Sri Lanka is driven by four wind seasons: northeast monsoon (from December to February), first inter-monsoon (March and April), southwest monsoon (from May to September), and second inter-monsoon (October and November) [18].

Figure 1: Weekly average wind speed pattern in (A) Jaffna (Lat.: 9.65, Long.: 80.01), (B) Mannar (Lat.: 8.98, Long.: 79.91), (C) Vavuniya (Lat.: 8.75, Long.: 80.5), (D) Southern Province (Lat.: 6.11, Long.: 81.13), (E) North Western Province (Lat.: 8.03, Long.: 79.83), (F) Central Province (Lat.: 6.96, Long.: 80.76)

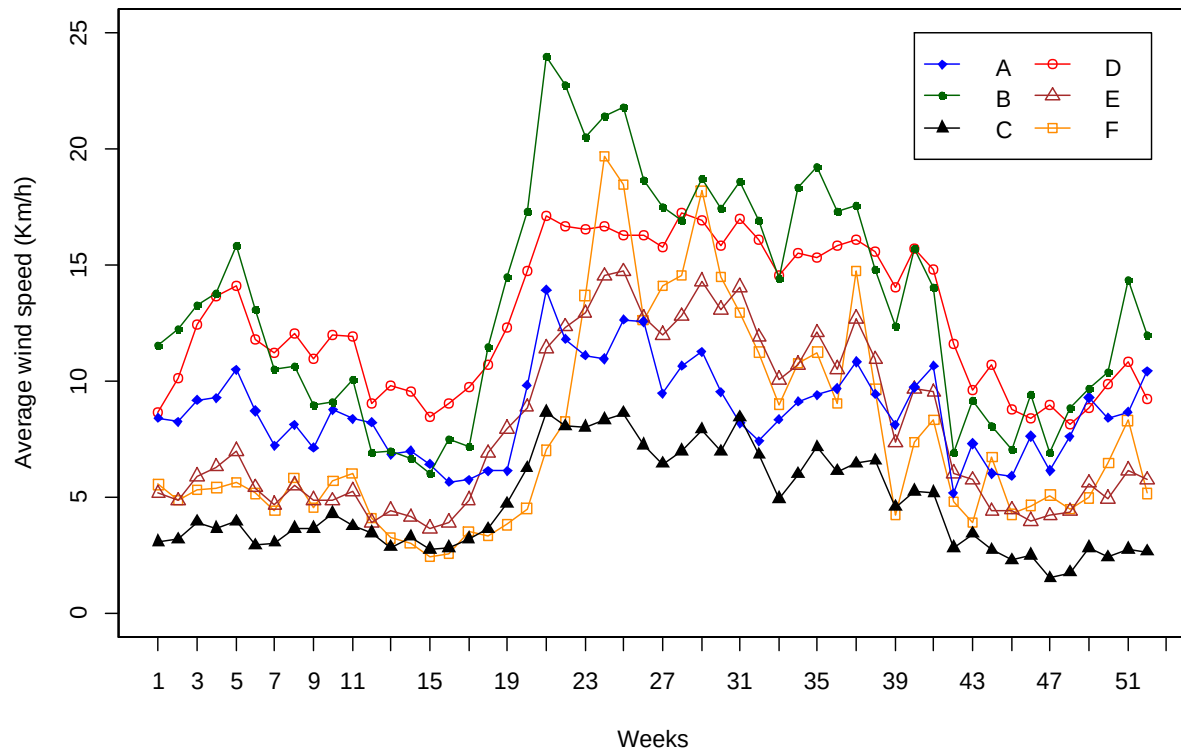


Figure 1 demonstrates the changes in weekly average (mean) wind speed in the six weather stations. Similar wind pattern can be observed in all the six weather stations with highest values between mid May to September (21th week and 41th week) which represent the general southwest monsoon season of the country. Compared to other four sites, Mannar weather station and Southern Province weather station have the highest average wind speed both in southwest and northeast monsoon seasons. Among them the southwest monsoon wind is stronger in Mannar weather station than that in Southern Province weather station and the opposite is true during the northeast monsoon season. In all the six cases inter-monsoon winds are generally low. On the whole the wind regime in Vavuniya weather station is very much weaker than that of other weather stations.

All weekly average wind speed time series are presented in the left panel of Figure 2, and results from the wavelet analysis are given in the middle and right panels, respectively. An annual cycle (52 weeks) is apparent in all the six weather stations with additional components of variability at shorter periods.

Mannar weather station (Figure 2, B I-III) exhibits similar behavior to that in Southern Province weather station (Figure 2, D I-III). In addition to the clear annual cycle, 14 – 26 week strong oscillating cycle was also detected for both weather stations, throughout the entire period under consideration. Further, for the three regions: D) Southern Province, (E) North Western Province and (F) Central Province, 4 to 8 week discontinuous cycle was observed with substantial heterogeneity in the relative strength of the cycle. Out of the three weather stations considered in Northern Province, a similar pattern was observed only in Jaffna weather station. In Jaffna and Central Province weather station these discontinuous cycle was most pronounced during the period that aligned with the general southwest monsoon season of the country.

According to the above analyses, out of the three weather stations considered in Northern Province, Mannar had the highest wind speed throughout the year and the corresponding wind pattern was quite similar to that of Southern Province weather stations. So to gain further insight, climate data obtained from Mannar weather station was further analysed using Wavelet coherence analysis and the result was compared with Southern Province wind regime. Under this the association between wind speed and the rainfall was more directly analysed. In each case, the phases of the two time series were also analysed to gain information about the possible delay in the association (Figure 3).

For both Mannar (Figure 3b) and Southern Province weather stations (Figure 3d), the cross wavelet power spectrum of weekly average wind speed (de-trended) and weekly average rainfall (de-trended) reveals a significant (p value < 0.05) annual cycle for the full length of the study period. Phase analysis further reveals that rainfall series leads wind speed series by 90 degrees in both stations. This highlights the fact that the maximum wind occurs during the dry seasons of the two regions. Further, a significant coherence was also detected at 26 – 30 week (sub annual) periodic band for Mannar weather station.

Figure 2: Wavelet analyses of average wind speed time series with weekly data across 6 weather stations: (A) Jaffna (Lat.: 9.65, Long.: 80.01), (B) Mannar (Lat.: 8.98, Long.: 79.91), (C) Vavuniya (Lat.: 8.75, Long.: 80.5), (D) Southern Province (Lat.: 6.11, Long.: 81.13), (E) North Western Province (Lat.: 8.03, Long.: 79.83), (F) Central Province (Lat.: 6.96, Long.: 80.76). For each station, the left panel shows the seasonal and trend decomposition of weekly average wind speed time series. The top graph corresponds to weekly average wind speed from 1st January 2010 to 30th September, 2015; second graph illustrates the trend cycles of weekly average wind speed; third graph represents seasonal cycles of weekly average wind speed and the bottom graph corresponds to the random (residual) components. The middle panel shows the wavelet power spectrum of weekly average wind speed (de-trended). The shading represents increasing spectrum intensity, from blue(white) to red (black); the black lines show the statistically significant areas (threshold of 5% confidence interval); and the white curve delimits the cone of influence (region not influence by edge effects). Finally, the right panel corresponds to the mean wavelet power spectrum.

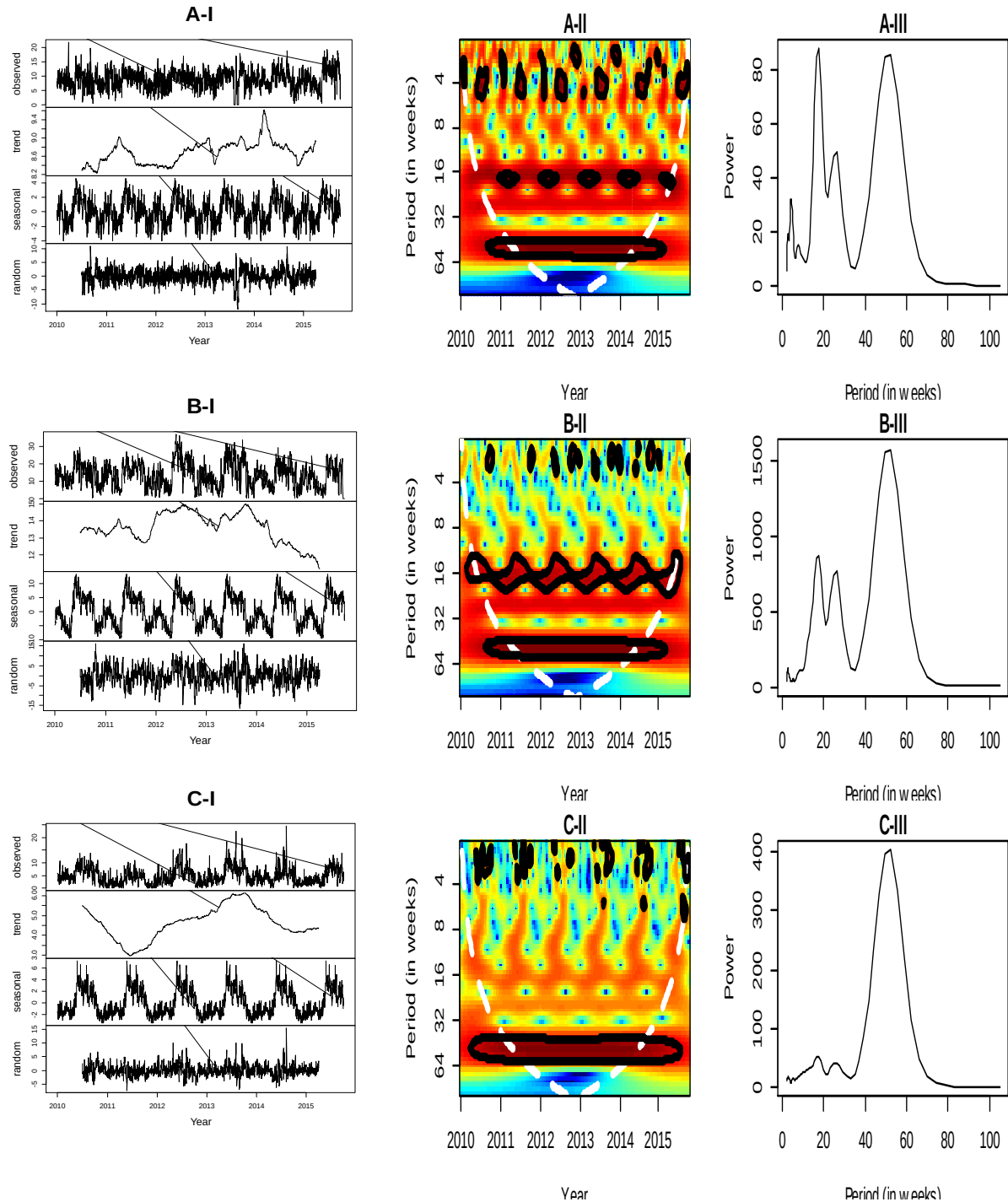
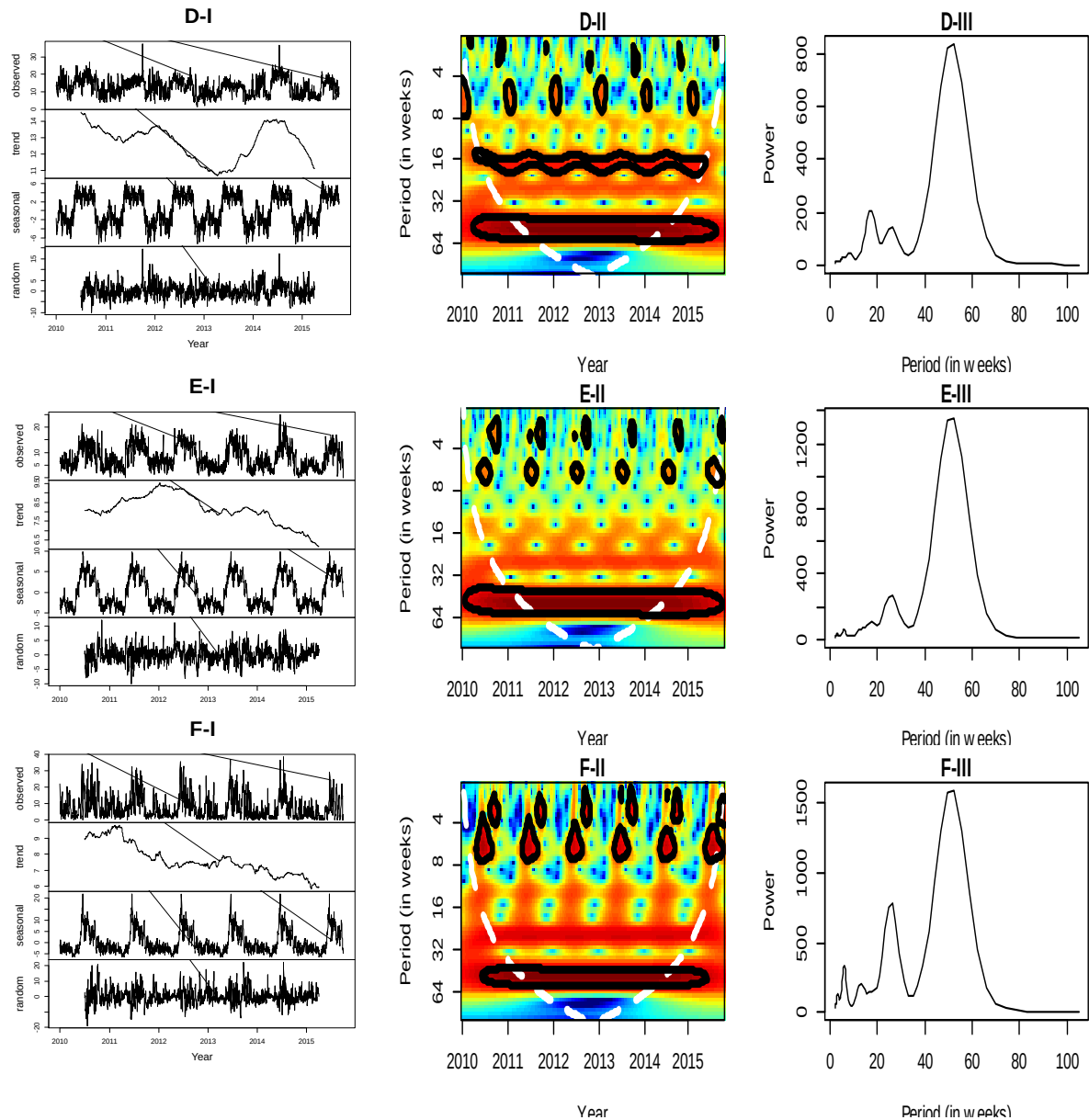


Figure 2 continues

Figure 2 (continued)



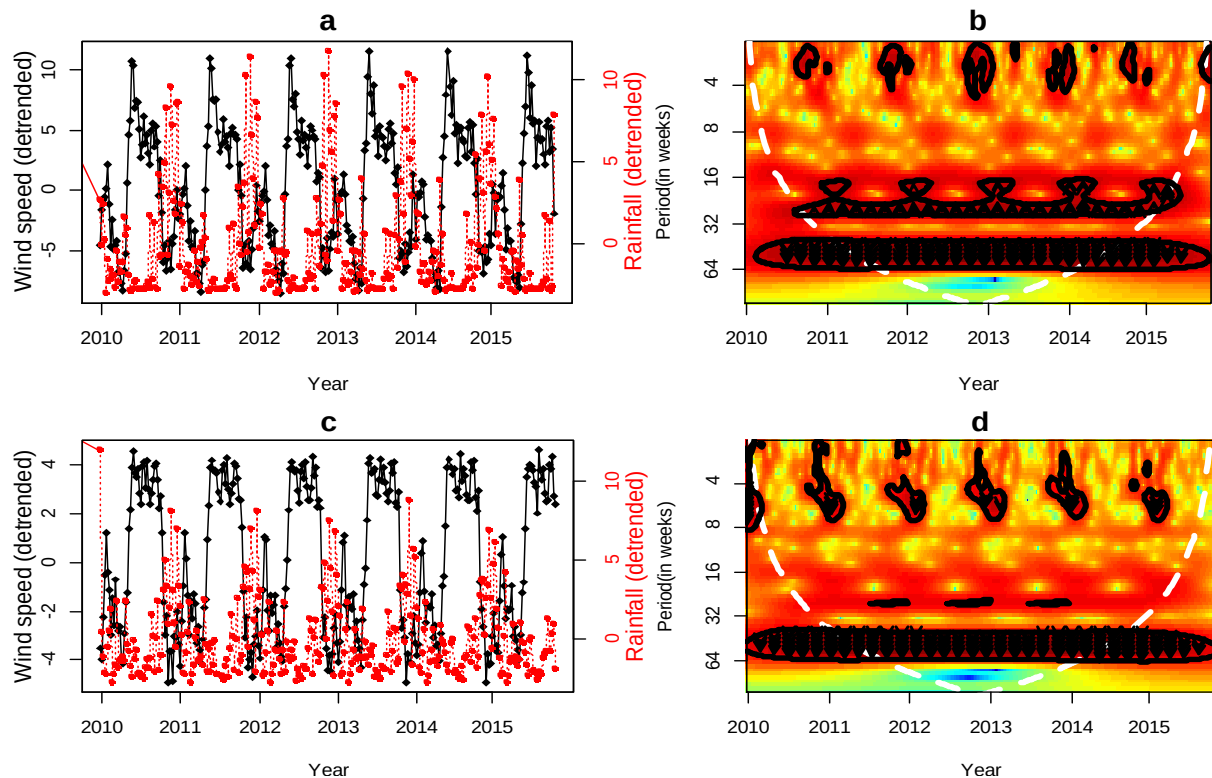
IV Discussion

Due to decades old civil conflict in the northern region of Sri Lanka, which last till 2009, no prior researches related to wind speed characteristics for the region was found. This study was therefore conducted to analyze the wind speed characteristics of Northern Province of Sri Lanka. Wind speed patterns of the region were analyzed and compared with the data obtained from three weather stations in southern coast, west coast and the central part of Sri Lanka. Authors in [18] had identified these three regions as regions with near-term potential for cost-effective utility scale wind power plant development.

In this study, missing data were imputed using multiple imputation method. The particular method was selected over single imputation methods, as it considers not only the relations within the data set but also the uncertainty of the imputations. To identify the oscillating characteristics of the wind speed time series wavelet analysis was used taking Morlet wavelet as the mother function. From the analysis it was found that the wind speed time series in Mannar weather station is similar to Southern Province weather station. The overall wind pattern in both regions follows the general monsoon wind climate in Sri Lanka, which is characterised by the south west monsoon (from May to September) and Northwest monsoon (from December to February). Southwest monsoon wind in Mannar was found to be stronger than Southern Province weather station. To examine the possible linkage of wind speed and rainfall of Mannar weather station and Southern Province weather station, their wavelet cross spectrums were inspected. High coherencies in both comparisons were detected for the 1 year periodicity. The phases of weekly average wind speed and weekly average rainfall of the two weather stations were also analysed to gain information

about the possible delay in the relationship between the two series. The analysis revealed that the maximum wind occurs during the dry season of the two regions. So wind power could be expected to help in mitigating electricity constraints during dry seasons. Further it is hoped that the findings of this study will help the researchers move this field forward.

Figure 3: Wavelet coherence between weekly average wind speed and weekly average rainfall in (a, b) Mannar (Lat.: 8.98, Long.: 79.91) and (c, d) Southern Province (Lat: 6.11, Long.: 81.13). Left panel shows the time series plots (detrended) of weekly average wind speed (black solid line) and weekly average rainfall (red dotted line). Right panel shows wavelet coherence



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