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RESEARCH ARTICLE

# Interannual variability of precipitation in Sri Lanka

**H.K.W.I. Jayawardene[1], D.R. Jayewardene[2] and D.U.J. Sonnadara[1*]**
[1] *Department of Physics, Faculty of Science, University of Colombo, Colombo 03.*
[2] *Department of Mathematics, Faculty of Science, University of Colombo, Colombo 03.*

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**Abstract:** Two different spectral analysis methods, the multitaper method (MTM) and the maximum entropy method (MEM) were applied to investigate the presence of low-frequency periodicities in precipitation records of 14 climatological stations in Sri Lanka. The spectral analysis revealed statistically significant periodicities in the range of 2 – 3 year and 3 – 6 year periods in all parts of Sri Lanka irrespective of the climatic variability. The 2 – 3 year band corresponds to the Quasi-Biennial oscillation (QBO), while the 3 – 6 year band corresponds to the *El-Nino*/Southern oscillation (ENSO) higher and lower frequency bands. Cross spectrum analysis showed statistically significant (at 5 %) coherencies for the Indian Ocean dipole (IOD) and Southern oscillation index (SOI) in the 2 – 3 year band and the 3 – 6 year band, respectively for most of the regions. Thus, it is concluded that the IOD and SOI play important roles as modulators of precipitation in Sri Lanka.

**Keywords:** ENSO, IOD, MEM, MTM, periodicities, spectral analysis.

## INTRODUCTION

In the tropics, especially in developing countries, the agriculture sector plays a crucial role in the economy. The impact of climate and climate variability on agriculture affects agricultural planning and productivity. Among the climatic parameters, precipitation plays a vital role in changing agricultural production. Focusing on Sri Lanka, strong links have been observed between the climate variability of the monsoon system and agricultural productivity (Panabokke & Walgama, 1974; Yoshino & Suppiah, 1983; Zubair, 2002). Both droughts and floods were found to contribute significantly to the reduction of rice yields, which is one of the principal crops of Sri Lanka. Inter-annual to decadal scale variability of precipitation has been known to cause a considerable strain on the economic progress of Sri Lanka where the main source of energy is hydropower. Thus, it is important to investigate the precipitation variability in Sri Lanka and its relationship to large scale climatic oscillations such as the *El-Niño*/Southern oscillation (ENSO) and the Quasi-Biennial oscillation (QBO).

The influence of the ENSO on Sri Lankan rainfall patterns has been reported by several researchers in the recent years. A relationship among the ENSO, rainfall and rice production for the two cultivation seasons during the last 50 years has been reported by Zubair (2002). A decrease in the annual stream flow of the Kelani River (a major river in the Western Province of Sri Lanka) during the *El-Niño* episodes and an increase during the *La-Niña* episodes have been reported (Zubair, 2003a). A similar behaviour due to the ENSO has been reported for the stream flow of the Mahaweli River, the longest river in Sri Lanka (Zubair, 2003b). Suppiah (1989, 1997) examined the influence of extreme phases of the Southern Oscillation phenomenon, *El Niño* and *La Niña* on the seasonal rainfall of Sri Lanka and found strong links between rainfall anomalies and the ENSO events. A recent analysis has revealed the influence of *El Niño* and *La Niña* events on seasonal rainfall (Malmgren *et al*., 2003). The study found significantly greater amounts of second intermonsoon (October-November) precipitation during *El Niño* years at most of the climate stations, and increased Southwest monsoon precipitation (May-September) during *La Niña* years at a few climate stations.

A recently discovered climatic oscillation is the Indian Ocean dipole (IOD), which is a coupled ocean-

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[*] Corresponding author (upul@phys.cmb.ac.lk)

atmospheric phenomenon in the Indian Ocean. Evidence has emerged that there is a possible connection between the IOD and inter-annual climate variability in several countries close to the Indian Ocean. The variance of the rainfall during the period October - December along the coast of Kenya and Tanzania showed a strong correlation with the sea surface temperature (SST) in the Indian Ocean, reflecting the role of IOD (Clark *et al*., 2003). Through a global climate simulation model, Ashok *et al*. (2001) have shown that the positive phase of the IOD tends to enhance the Indian monsoon rainfall. Zubair (2003c) reported that there is an impact of the IOD on the Sri Lankan Maha rainfall (September - December).

Scientific studies leading to the extraction of low-frequency variability of precipitation patterns related to Sri Lanka are somewhat scarce in the literature. One of the early studies on extracting cyclic components in the precipitation time series was carried out by Suppiah & Yoshino (1984a; 1984b) using power spectrum analysis and filtering. Another investigation of temporal variability of the precipitation over Sri Lanka using a maximum entropy spectral analysis was carried out by Domroes (1996). An oscillatory behaviour of the monsoon rainfall over Sri Lanka and its relationships to SSTs in the Indian Ocean and ENSO was carried out recently by Malmgren *et al*. (2007). However, complementary studies are not yet available in the literature to compare and strengthen the findings of the earlier investigations.

In the present study, the concentration was on analyzing the time series of precipitation records to identify the influence of large scale atmospheric phenomena such as QBO and ENSO using two spectral analysis techniques; a nonparametric method, multitaper and a parametric method, maximum entropy method. The analysis was extended to identify the connection between the precipitation and two atmospheric indices, namely, the Southern oscillation index (SOI) and the Indian Ocean dipole (IOD).

## METHODOLOGY

For the present analysis monthly precipitation records from 14 stations having approximately 100 years of data or more were extracted from the published data records of Yoshino and Suppiah (1982). The stations are from different geographical regions and cover different climatic conditions that are experienced in Sri Lanka. The remaining data records were obtained directly from the Department of Meteorology, Sri Lanka. As the data from stations in the North-eastern part of Sri Lanka such as Jaffna, Mannar and Trincomalee consisted of missing values after 1980 due to the civil disturbances in the country, the length of the time series had to be truncated for these stations. Thus, the analysis in this study is based on annual precipitation data at 14 stations within the period 1869 to 1998. The length of data records together with the relevant station information (latitude, longitude and altitude) are given in Table 1. The spatial distribution of the selected weather stations is shown in Figure 1.

To identify ‘teleconnections’ between precipitation anomalies and large scale atmospheric variations such

**Table 1:** Summary of precipitation data used in this study together with information on the selected climatological stations

| | Station name | Period (years) | Latitude Nº | Longitude Eº | Altitude (m) | Length (years) |
|---|---|---|---|---|---|---|
| 1 | Colombo | 1869 - 1998 | 6.90 | 79.87 | 7 | 130 |
| 2 | Nuwara Eliya | 1869 - 1998 | 6.97 | 80.77 | 1895 | 130 |
| 3 | Rathnapura | 1869 - 1998 | 6.68 | 80.40 | 34 | 130 |
| 4 | Kandy | 1870 - 1998 | 7.33 | 80.63 | 477 | 129 |
| 5 | Galle | 1869 - 1993 | 6.03 | 80.22 | 13 | 125 |
| 6 | Anuradhapura | 1870 - 1998 | 8.35 | 80.38 | 93 | 129 |
| 7 | Badulla | 1869 - 1993 | 6.98 | 81.03 | 670 | 125 |
| 8 | Puttalam | 1869 - 1993 | 8.03 | 79.83 | 2 | 125 |
| 9 | Batticaloa | 1869 - 1993 | 7.72 | 81.70 | 3 | 125 |
| 10 | Kurunegala | 1885 - 1993 | 7.47 | 80.37 | 116 | 109 |
| 11 | Trincomalee | 1869 - 1986 | 8.58 | 81.25 | 79 | 118 |
| 12 | Mannar | 1870 - 1985 | 8.97 | 79.90 | 4 | 116 |
| 13 | Jaffna | 1871 - 1984 | 9.65 | 80.02 | 4 | 114 |
| 14 | Hambantota | 1869 - 1987 | 6.12 | 81.12 | 16 | 119 |

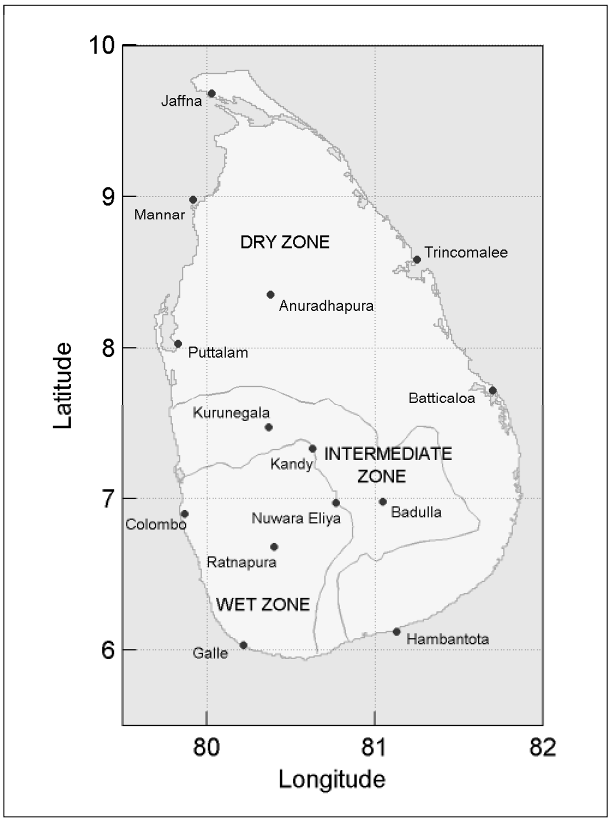

**Figure 1:** Spatial distribution of the selected weather stations. The demarcation between the commonly identified climate zones (Wet zone, Dry zone and Intermediate zone) is also shown.

as ENSO and QBO, two weather indices, namely, the SOI and IOD were selected. The SOI and IOD have been identified by many authors as being responsible for the monsoon anomalies observed in the Indian Ocean region (Suppiah, 1997; Ashok *et al*., 2001; Malmgren *et al*., 2003; Zubair *et al*., 2003c). In this study, the SOI values were obtained from the Climate Research Unit, School of Environmental Science, University of East Anglia (*www.cru.uea.ac.uk*), while the IOD values were obtained from the Frontier Research System for Global Change (*www.jamstec.go.jp*).

In order to extract the periodicities of precipitation records, power spectra were calculated for annual precipitation values of each station and two weather indices separately using the multitaper method (MTM) and the maximum entropy method (MEM) described by Ghill *et al*. (2002).

The MTM employs multiple orthogonal data tapers to extract the periodicities in a given time series spectra. The tapers are designed such that they lead to independent estimates of the time series spectra. The optimal tapers or 'eigen tapers' are a discrete set of eigen functions, which solve the variational problem by minimizing spectral leakage outside the frequency band with half bandwidth equal to $pf_R$, where $f_R = (N\times\Delta t)^{-1}$ is the Rayleigh frequency, $\Delta t$ is the sampling frequency and $p$ is a suitably chosen integer. Averaging over a (small) ensemble of spectra obtained by this procedure yields a better and more stable estimate than Fourier techniques (Rajagopalan & Lall, 1998).

The choice of the bandwidth $2pf_R$ and the number of tapers $K$ represents a compromise between the spectral resolution and the variance. In practice, only the first $K = 2p$-1 tapers provide usefully small spectral leakage. For climate records with a typical length of a few hundred points, the choice $p = 2$ and $K = 3$ offers a reasonable frequency resolution for resolving distinct climate signals and the benefit of reduced variance (Ghill *et al*., 2002). Longer datasets permit the use of a greater number K of tapers, while maintaining a desired frequency resolution. The multitaper estimates frequency resolution is $\pm\, pf_R$.

Red noise is often used to describe the noise in spectra of most climatic and hydrological time series records (Ghill *et al*., 2002). The simplest statistical model for a discrete finite red noise series is the autoregressive (AR) process of order 1. All peaks are tested for significance relative to the null hypothesis of a red noise background. The ratio of the magnitude of the spectral estimate to the local magnitude of the continuum, which is distributed as chi-square divided by degrees of freedom, was used to estimate the confidence intervals. If $K$ is the number of tapers used in the multitaper spectrum analysis, then the corresponding degrees of freedom of the test statistic is $2K$.

The MEM yields a higher resolution than the MTM in cases where the time series length is short. Instead of trying to estimate the power spectral density directly from the data, the MEM 'models' the data as the output of a linear system driven by white noise. The most commonly used linear system model is the autoregressive (AR) process of order $M$. The choice of order $M$ determines the quality of the spectrum. To find the best approximating model or reasonable $M$, the Akaike information criteria (Cavanaugh, 1997) was used. It is based on minimizing the residual of a least squares fit between the AR approximation and the original series.

Testing the significance of the MEM has been carried out with the two-time red noise background. Only the frequency values, which are two times higher than the red noise can be taken as statistically significant at the 5 % level.

In order to determine the coherent frequencies between precipitation and other climatic indices, namely, the Southern oscillation index (SOI) and the Indian Ocean dipole index (IOD), spectral coherence between the series were computed. To test whether the given two series have any relationship between each other, the estimated values in the coherence spectrum were compared to a confidence level. The 'null hypothesis' that the true squared coherence is zero at a considered frequency can be tested at a level of significance P by comparing the estimated values in the squared coherence spectrum with the value $1- P^{2(v-2)}$, where $v = 2K$ is the number of degrees of freedom associated with the spectral estimates (Jarvis & Mitra, 2001).

## RESULTS AND DISCUSSION

The secular trend was removed from the data records by subtracting the linear trend values. To obtain the background spectrum, the lag one autocorrelation was computed for the detrended time series. The Rayleigh frequency $f_R$ varies between 0.008 and 0.009 cycles/year, which correspond to maximum and minimum lengths (130 and 109 years) for the selected data series. Thus, the frequency resolution $pf_R$ for the present work where $p = 2$, is better than ± 0.02 cycles/year for all stations.

Results for the MTM and MEM for six selected stations are shown in Figures 2 and 3, respectively.

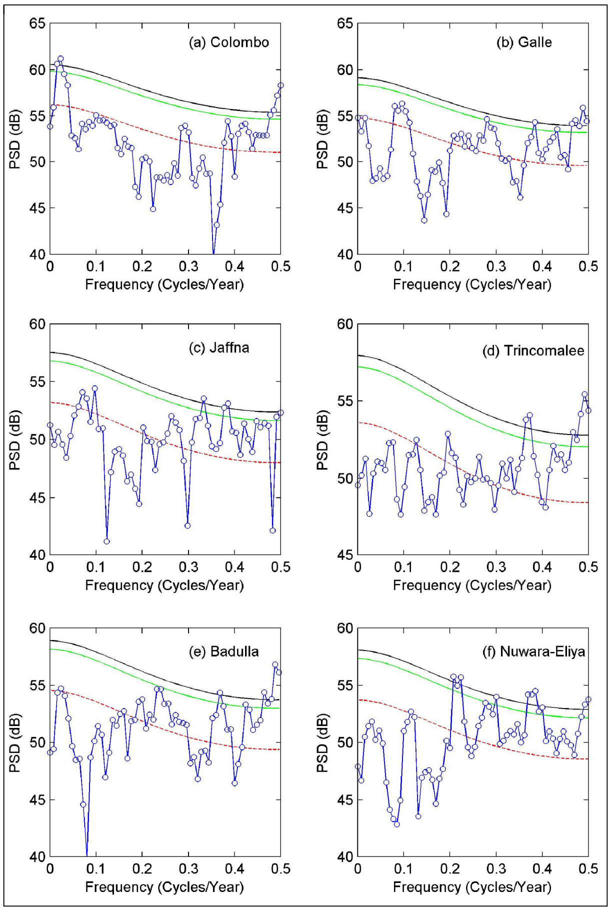

**Figure 2:** Power spectral density obtained by MTM for (a) Colombo; (b) Galle; (c) Jaffna; (d) Trincomalee; (e) Badulla and (f) Nuwara-Eliya with the bandwidth parameter $p = 2$, and tapers $K = 3$. The estimated red noise background and associated 90 % and 95 % confidence levels are shown by the smooth curves, from the lowest to the highest.

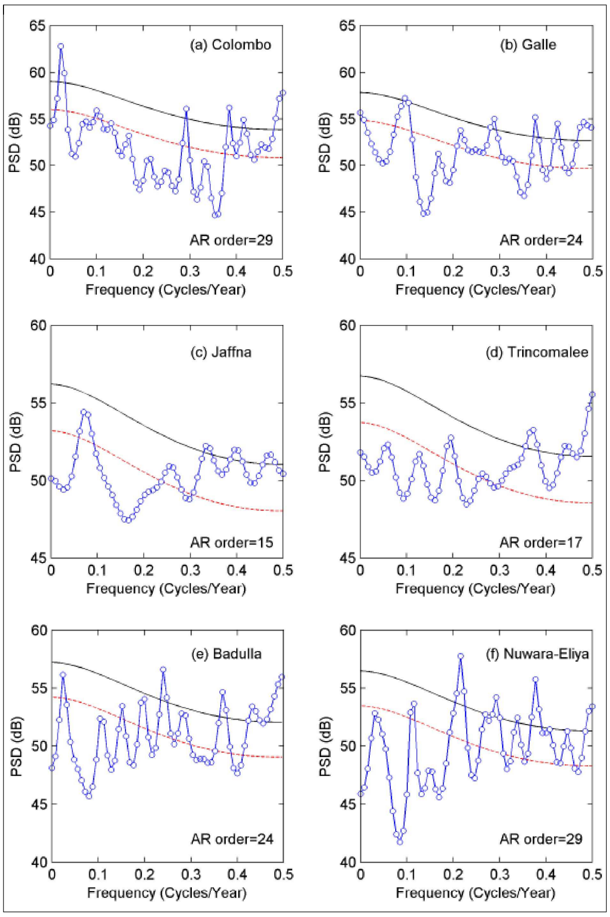

**Figure 3:** Power spectral density obtained by MEM for (a) Colombo; (b) Galle; (c) Jaffna; (d) Trincomalee; (e) Badulla and (f) Nuwara-Eliya with best approximating AR model orders. The estimated red noise background and associated 95 % confidence levels are shown by the smooth curves, from the lowest to the highest.

The bottom dashed line is the null continuum related to red noise background, and the top solid line represents the 95 % confidence level. It is interesting to note that both MTM and MEM spectrums apparently show quite similar spectral patterns. However, the power spectrum of the MEM is much smoother and sharper than that of the MTM. A recent study with synthetic data has shown that although MEM is an excellent method for finding periodicities, it is poor in evaluating the magnitude of spectral peaks (Rigozo *et al*., 2005). The MTM performs better in extracting frequencies and amplitudes of signals, especially at low periodicities. Thus, the significance of spectral peaks of the MTM was tested at 90 % and 95 % confidence levels while MEM was tested at the 95 % level.

For Colombo (Figure 2a and Figure 3a), consistent with the MTM spectrum, the MEM spectrum recognizes two highly significant peaks; one centered at f = 0.023 cycles/year (43.3 year period) and another at f = 0.5 cycles/year (2.0 year period). These two signals are significant at the 5 % level. Since the half bandwidth corresponds to 0.0154 cycles/year for the Colombo station, periods greater than 65 years should be considered as associated with long-term trends. Given the fact that both the MTM and MEM are not accurate at finding longer periods (Rigozo *et al*., 2005), the 43.3-year period could be considered as associated with the long-term trend. Although the MEM spectrum shows three other peaks with periods at 2.4, 2.6, and 3.4 years significant at 5 % level, they are not significant at 10 % level in the MTM spectrum. Therefore, the cycle with period 2.0 years can be considered as the most dominant periodicity in the Colombo precipitation time series.

The results obtained from the spectral analysis using both MTM and MEM for all stations together with the SOI and IOD are summarized in Table 2. As described in the methodology section, testing the significance of the peaks have been carried out relative to the null hypothesis of a red noise background corresponding to each data series. The peaks that are underlined under MTM are significant only at the 10 % level. All the other peaks are significant at the 5 % level. The results are grouped under three frequency bands, namely, 2 – 3, 3 – 6, and greater than 6 years.

The activity in the 2 – 3 year band is usually associated with the Quasi-Biennial Oscillation and the high frequency end of ENSO. The 3 – 6 year band is usually associated with ENSO and the 6 – 9 band is presumed to reflect the nonlinear interaction between QBO and ENSO. The band with periods greater than 10 years reflects the decadal scale variability (Rajagopalan *et al*., 1998).

**Table 2:** Comparison of results from the spectral analysis by the MTM and MEM. The peaks that are underlined under MTM are significant only at 10 % level. All the other peaks are significant at 5 % level.

| | Series name | MTM | | | MEM | | |
|---|---|---|---|---|---|---|---|
| | | Period (years) 2 – 3 | Period (years) 3 – 6 | Period (years) >6 | Period (years) 2 – 3 | Period (years) 3 – 6 | Period (years) >6 |
| 1 | Colombo | 2.0 | | 43.3 | 2.0, 2.4, 2.6 | 3.4 | 43.3 |
| 2 | Nuwara Eliya | 2.0, 2.5, 2.6 | 3.3, 4.5, 4.8 | | 2.0, 2.7 | 3.0, 3.4, 4.6 | |
| 3 | Rathnapura | 2.0, 2.2, 2.3 | 3.3, 3.6 | | 2.0, 2.2 | 3.5 | |
| 4 | Kandy | 2.0, 2.6 | 3.3, 3.5 | | 2.0, 2.2, 2.6 | 3.4 | |
| 5 | Galle | 2.0, 2.1, 2.6 | 3.6 | | 2.1, 2.4, 2.7 | 3.5 | 10.4 |
| 6 | Anuradhapura | 2.0 | | | 2.1, 2.6 | 3.7 | |
| 7 | Badulla | 2.0, 2.2, 2.7 | | | 2.0, 2.3, 2.7 | 4.0 | |
| 8 | Puttalam | 2.0, 2.3 | 3.0, 3.6 | | 2.0, 2.3, 2.7 | 3.0, 3.6 | |
| 9 | Batticaloa | 2.0 | 3.2, 3.4 | | 2.1 | 3.2 | |
| 10 | Kurunegala | 2.7 | 3.3, 3.6, 5.4 | | 2.5 | 3.4 | |
| 11 | Trincomalee | 2.0, 2.1, 2.7 | | | 2.0, 2.3, 2.7 | | |
| 12 | Mannar | 2.0, 2.8 | | | 2.0, 2.8 | | |
| 13 | Jaffna | 2.0, 2.6 | 3.0 | | 2.1, 2.5 | 3.0 | |
| 14 | Hambantota | 2.1, 2.3 | 3.0 | | 2.0, 2.3 | 3.0 | |
| 15 | SOI | 2.8 | 3.5 | 6.2, 6.8 | | 3.6 | 6.8 |
| 16 | IOD | 2.1 | 5.1 | | 2.1, 2.7 | 3.0, 5.2 | |

Most stations show a 2 – 3 year cyclical variability (at least one significant peak within the band) under the MTM and MEM at 5 % level. Batticaloa shows a 2.0-year cycle significant only at 10 % level for the MTM spectral analysis (for MEM this is significant at the 5 % level). Except for Trincomalee and Mannar, all the other stations show cycles within the 3 – 6 year band significant at 5 % level for the MEM spectral analysis. In the MTM results, 50 % of the stations (Colombo, Ratnapura, Galle, Anuradhapura, Badulla, Trincomalee and Mannar) do not show peaks at the 3 – 6 year band significant at 5 % level and most of these stations (Colombo, Anuradhapura, Badulla, Trincomalee and Mannar) are not significant even at the 10 % level. The Galle station showed a peak significant at 5 % level at 10.4 cycles/year for the MEM analysis but this is not significant at 10 % level for the MTM analysis. From all time series records, only Colombo showed a 43.3 year long cycle significant at 5 % level.

To identify the correlation of periodic components of the precipitation series with key climate indices such as the SOI index and the IOD index, coherence spectrums were computed using cross-spectral analysis of the MTM spectra with each of the weather indices and summarized in Table 3. All periods shown are the most dominant peak in each of the coherent spectrums that are significant at 5 % level. If the precipitation records are strongly modulated by the large scale weather indices, then the dominant peak in the spectra must occur at a period representative of the weather indices. MEM was not considered for estimating the coherence spectrums due to its weakness in evaluating the amplitudes of the signals correctly. Figures 4 and 5 show the squared coherence spectrums obtained for six selected stations for both weather indices.

**Table 3:** Results of the cross-spectral analysis between monthly precipitation and selected weather indices. All spectral peaks shown are the positions of the most dominant peaks, which are significant at 5 % level.

| | Station Name | SOI | | IOD | |
|---|---|---|---|---|---|
| | | Period (Years) | Lag (Years) | Period (Years) | Lag (Years) |
| 1 | Colombo | 3.3 | 1.4 | 6.7 | 0.3 |
| 2 | Nuwara Eliya | 2.5 | -0.3 | 2.2 | 0.5 |
| 3 | Rathnapura | 2.5 | -1.1 | 3.7 | -1.0 |
| 4 | Kandy | 3.3 | 0.7 | 2.3 | 0.4 |
| 5 | Galle | 3.7 | 1.0 | 3.6 | -1.3 |
| 6 | Anuradhapura | 3.9 | -0.5 | 2.0 | 0.6 |
| 7 | Badulla | - | - | 2.1 | 0.0 |
| 8 | Puttalam | 3.2 | 1.3 | 5.4 | 0.2 |
| 9 | Batticaloa | 8.3 | 3.9 | - | 0.1 |
| 10 | Kurunegala | 2.9 | -1.5 | 2.2 | 0.2 |
| 11 | Trincomalee | 10.7 | -4.0 | 2.2 | 0.4 |
| 12 | Mannar | 3.0 | -1.3 | 2.3 | 0.1 |
| 13 | Jaffna | 5.2 | 2.0 | 2.1 | -0.4 |
| 14 | Hambantota | 3.8 | 1.6 | 2.2 | 0.0 |

Spectral analysis of annual precipitation at most of the stations showed statistically significant peaks with periods of 3 – 4 years (Table 2). The SOI time series also showed a significant cycle within a period of 3 – 4 years. Cross-spectral analysis of SOI and annual precipitation at most stations (10 out of 14 stations) revealed maximum coherencies, which are significant at 5 % level within the period 2.5 – 3.9 years supporting the link between precipitation in Sri Lanka and the SOI (Table 3). Trincomalee, Batticaloa and Jaffna, which are located in the Northern and Eastern parts of Sri Lanka showed maximum coherencies at 10.7, 8.3 and 5.2 years, respectively. In addition, Badulla which is located in the Eastern slope of the central highlands did not show coherency with the expected frequency band significant at 5 % level.

The spectral analysis showed statistically significant cycles of 2 – 3 years in the precipitation data of most stations (Table 2). As the periodicity of the quasi-biennial cycle ranged from 2.0 to 2.7 years, the 2-3 cyclical variation that appeared in precipitation spectrums does not clearly highlight the association between the IOD and precipitation in Sri Lanka. The IOD time series showed a significant cycle within a period of 2.1 years. The cross spectrum analysis showed links between the precipitation records in all stations with the IOD index (9 out of 14 stations showed statistically significant coherencies at 5 % level in the 2.0 – 2.3 year band - see Table 3). Badulla and Hambantota are synchronous with the IOD event, which is indicated by near zero phase lags at the period of 2.1 – 2.2 years with maximum coherence. Galle and Rathnapura showed maximum coherencies significant at 5 % level at 3.6 and 3.7 year periods, respectively. Colombo and Puttalam had maximum coherencies significant at 5 % level at longer periods (6.7 to 5.4 years, respectively). Batticaloa did not show a coherency with the expected frequency band significant at 5 % level.

## CONCLUSION

Two different methods, the multitaper spectral analysis and the maximum entropy spectral analysis were applied to investigate whether there are any cyclic patterns in the

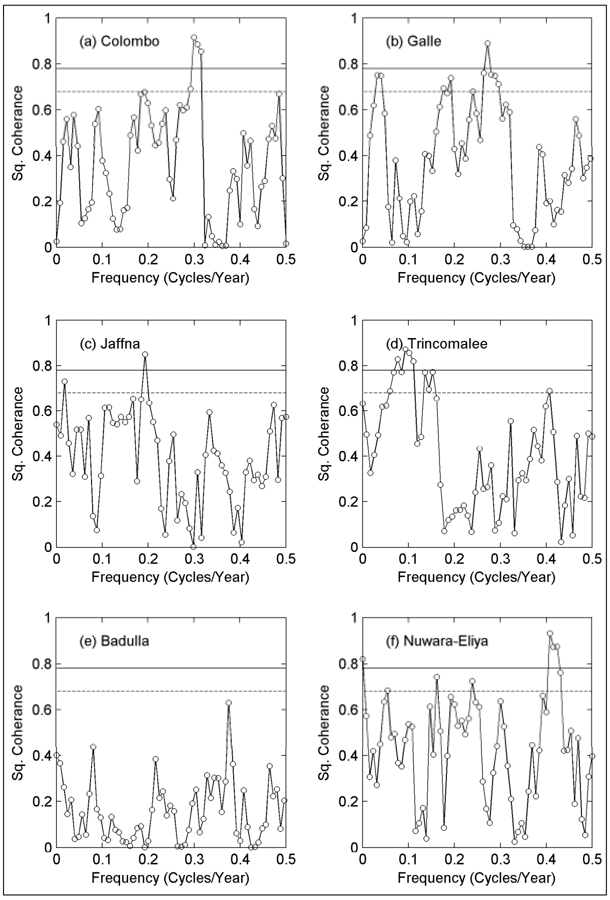

**Figure 4:** Coherence spectrums for annual precipitation and SOI for (a) Colombo; (b) Galle; (c) Jaffna; (d) Trincomalee; (e) Badulla and (f) Nuwara-Eliya. The two lines represent the 90 % and 95 % confidence limits from the lowest to the highest.

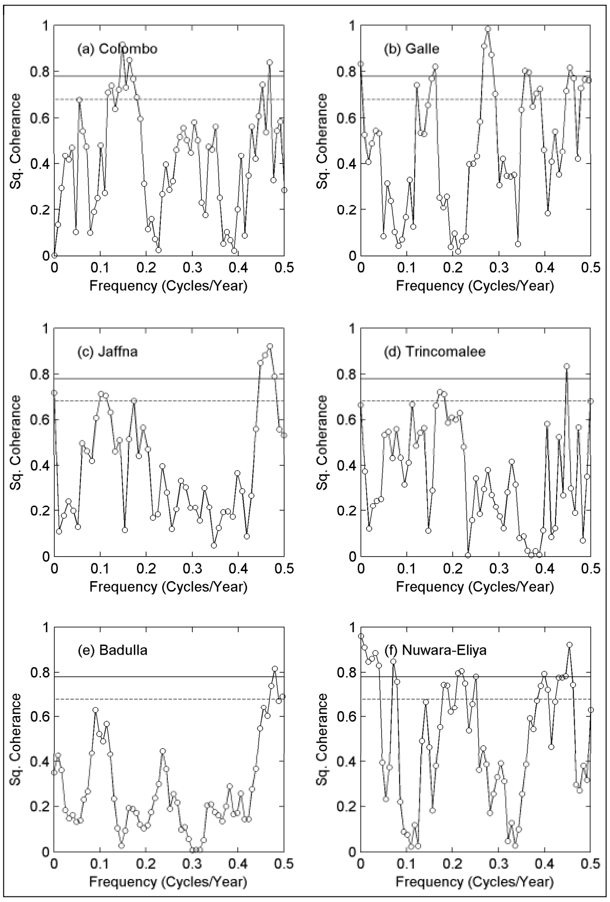

**Figure 5:** Coherence spectrums for annual precipitation and IOD for (a) Colombo; (b) Galle; (c) Jaffna; (d) Trincomalee; (e) Badulla and (f) Nuwara-Eliya. The two lines represent the 90 % and 95 % confidence limits from the lowest to the highest.

Sri Lankan precipitation. The spectral analysis revealed strong signals in the range of 2 – 3 year period and 3 – 4 year period. The 2-3 year band is consistent with the influence of the quasi biennial oscillation (QBO) and the Indian Ocean dipole (IOD).

The *El-Niño* Southern oscillation (ENSO) is consistent with the range of 3 – 4 years and most stations showed significant peaks for both the single and the cross spectral analysis, supporting the link between the precipitation in Sri Lanka and the SOI.

Interestingly, the influence of the Indian Ocean dipole (IOD) was identified through cross spectral analysis. Most of the stations showed significant associations between precipitation and the IOD with a few months lead or lag in the band of 2 – 3 years. Thus, the IOD also plays an important role as a modulator of precipitation in Sri Lanka. Further studies may reveal the way IOD acts on Sri Lankan precipitation if one considers the relationship with other weather elements such as air temperature, humidity and sea surface temperature.

The spectral analysis work discussed above utilized the amount of precipitation received at each station annually. Instead of annual precipitation, future studies could be focused on seasonal precipitation, which may show a better teleconnection with the large scale climatic oscillations. In addition, precipitation amounts could fluctuate rapidly due to local influences. Also, nonlinearity in the generation of precipitation as a function of atmospheric flow may affect the precipitation amounts more than the precipitation occurrences. Further studies can be carried out by analyzing the cyclic variations using the occurrence of precipitation instead of amounts.

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