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Rain gauge derived precipitation variability over Virginia and its relation with the El Nino southern oscillation

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Abstract

The El-Nino/Southern Oscillation (ENSO) Phenomenon has a strong impact on local and regional scale climate through strong teleconnections affecting the coupled ocean-atmosphere and even land system. Recent studies have pursued the effects of such periodic events on different climatological and meteorological parameters. This study focuses on ENSO impact on local precipitation patterns. We study the precipitation patterns derived from gauge stations over Virginia, USA. Forty years of the Hourly Precipitation gauge Data (HPD) jointly developed by the National Climatic Data Center (NCDC) and the Forecast Systems Laboratory (FSL) at five gauge locations in Virginia are considered. High frequency random noise at each station is removed through wavelet decomposition. A Morlet wavelet basis function is then fitted to the non-seasonal data to derive the interannual and longer periodic signals. Three to five years' cycles are observed in the anomaly signal in keeping with the 2–8-year period of ENSO signals reported in the literature. An Empirical Mode Decomposition (EMD) is also applied to the data set. The signal is found to correlate reasonably well with the Southern Oscillation Index (SOI) with a correlation coefficient of 0.68 at a confidence level of 95% for the stations. Cross-spectral coherency and phase analysis reveals a strong physical link between precipitation and ENSO. One of the major outcomes of this study is that ENSO may strongly affect local precipitation.

Keywords: ENSO; Precipitation; Wavelets; EMF

1. Introduction

Ropelewski and Halpert (1986, 1989), found that the Great Basin in the western United States and the Gulf of Mexico in the southeast are significantly affected by El-Nino/Southern Oscillation (ENSO). Joyce (2002); has carried out an EOF analysis of the precipitation and temperature data over the eastern United States and found the leading Principal Component of wintertime precipitation to be significantly correlated with Southern Oscillation Index (SOI). He has concluded that the relative sensitivity of different climatic parameters to different climatic indices may vary over time over the eastern United States. We have examined hourly precipitation data collected over 2000 gauges over the US using time series analysis techniques. This work reports on our initial analysis of gauge data at five stations in Virginia.

2. Data

The data for our time series analysis are the HPD produced jointly by the NCDC and the Forecast Systems Laboratory (FSL). The Tipping-bucket (TB) gauge stations used in our case measure the rainfall volume or the rainfall rate. TB gauges have been corrected for under catch due to loss of water during time of tip. The rain data undergo extensive gross error and consistency checks at FSL before being incorporated into a randomly accessible compressed data archive developed at FSL. Fig. 1 shows the location of the five gauge stations used in this study from the 38 gauges in Virginia. Monthly mean SOI dataset is obtained from the climatic datasets maintained by the Climate Research Unit, of the University of East Anglia. SOI values are calculated

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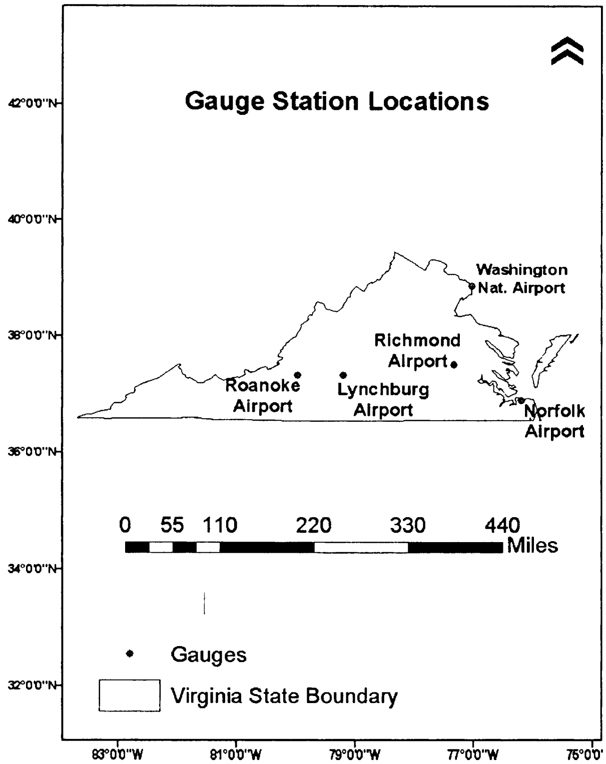

Fig. 1. The base map showing the distribution of the five gauge stations.

as a difference between the standardized Sea Level Pressure of Tahiti and Darwin in Australia.

It is a measure of the large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific. El Nino (La Nina) episodes are associated with prolonged periods of negative (positive) SOI values, coinciding with abnormally warmer (cooler) ocean waters across the eastern tropical Pacific.

3. Methodology

Monthly mean rainfall obtained from hourly precipitation is detrended using climatological values and the resultant time series anomaly is corrected for high frequency noise through wavelet decomposition at level 2. We select a threshold, given in Eq. (1), and apply it to the detailed coefficients for each level from 1 to 2.

$$\mathrm{thr} = \sqrt{2 \times \log(n)} \times s, \tag{1}$$

where s is an estimate of the noise level and n is the number of months.

We perform a wavelet reconstruction using the original approximation coefficients of level 2 and the modified detailed coefficients of levels from 1 to 2. Level 2 is used to focus on interannual changes as the use of level 3 bears the possibility of missing some cycles of interest. ENSO signals are known to have a periodicity of 3–8 years; hence a low pass Butterworth filter is applied to the time series to highlight interannual signals by removing high frequencies for all periods less than 1 year. Morlet wavelet basis function is then fitted to the data to derive the interannual and longer-term signals. The time series is zero padded before doing the wavelet transformation to reduce the wavelet power near the edges and to avoid wrap-around effects (Torrence and Compo, 1998).

Empirical Mode Decomposition (EMD) of the time series has been carried out to extract precipitation components from the five stations. The EMD is more adaptive and suitable for even non-linear and non-stationary signal (Liang et al., 2000). EMD coupled with the Hilbert transform has been reported to work better in depicting the local time scale instantaneous frequencies than wavelet and FFT (Huang et al., 1998). Its advantage lies in its totally adaptive nature as it has no fixed basis functions and forms its own basis functions depending on the signal itself. Relevant harmonics have been extracted through EMD to calculate the matrix of intrinsic mode functions (IMF). Two sets of time series plots are obtained between the raw station data and SOI and between their corresponding IMFs.

4. Results and discussion

Wavelet power spectrum plots of the five stations (see Fig. 2) reveal the existence of a signal having a period ranging from 3–6 years corresponding to the ENSO period of 3–8 years. The white curves in the plots identify the region of the wavelet spectrum in which edge effects become important and is defined here as the e-folding time, given by Eq. (2) for the autocorrelation of wavelet power at each scale, namely;

$$\tau_s = \sqrt{2}s, \tag{2}$$

where τ_s is the e-folding time and s is the wavelet scale.

This e-folding time is chosen so that the wavelet power for a discontinuity at the edge drops by a factor e^{-2} and ensures that the edge effects are negligible beyond this point. The peaks within these regions have been reduced in magnitude due to the zero padding. Thus, it is unclear whether the decrease in power beyond that edge is a true decrease in variance or an artifact of the padding (Torrence and Compo, 1998). The thick contour lines represent the 95% confidence level for the corresponding red-noise spectrum, which is modeled following Gilman et al. (1963). The red noise model is a univariate lag-1 autoregressive process, whose normalized Fourier power spectrum is calculated through Eq. (3)

$$p_k = \frac{1-\alpha^2}{1+\alpha^2-2\alpha\cos(2\pi k/N)}, \tag{3}$$

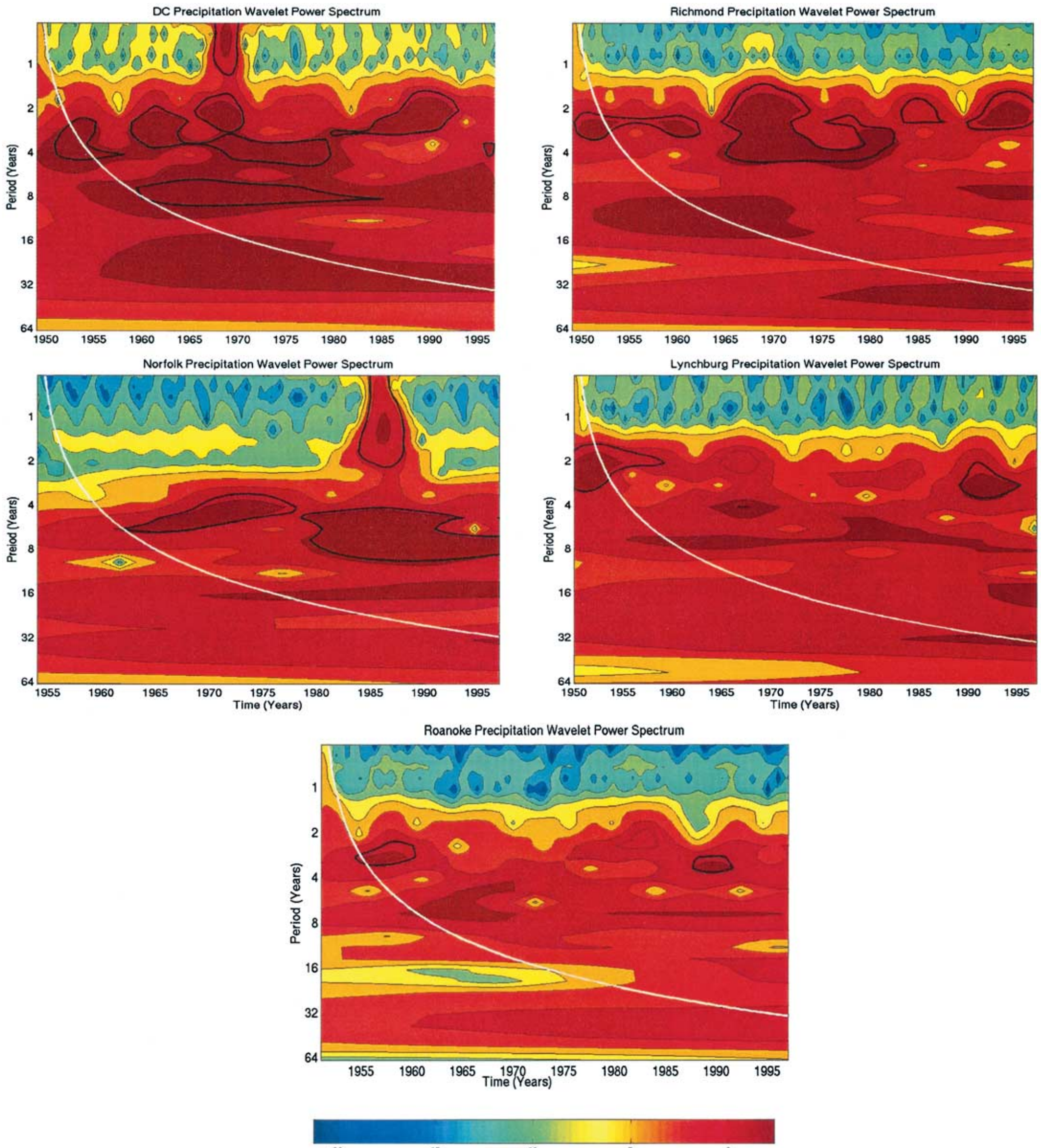

Fig. 2. The wavelet power spectrum plots from five stations in Virginia. Scale below shows blue as the lowest power, graduating to red having the highest power.

where $k = 0, ..N, N/2$ is the frequency index and α is the lag-1 autocorrelation calculated for each station.

A high frequency component is prominent in the Washington, DC and Norfolk stations representing large scale flooding events, where the signal over Norfolk is associated with Hurricane Gloria in September of 1985. It is interesting to note that both events are during La Nina years, conforming to the view that more hurricanes form during La Nina years rather than El Nino years in the Atlantic Ocean (Bove et al., 1998). As such, the strong ENSO effect on precipitation seen in the stations here may have been caused by increased rainfall associated with hurricanes, which themselves are tied to La Nina years.

The different EVIFs identified for each gauge through EMD are observed and the one showing similar period with respect to SOI has been selected in each case and identified as the principal ENSO component. Correlation values are reported for the IMFs of the gauge precipitation and the SOI data. The plot of the respective component of SOI and precipitation against each other shows a strong lagged correlation of six months over most of the stations especially during the ENSO events of 1982–1983, 1991–1992 and 1997. This observation could not be extended due to the lack of data.

Table 1 shows the maximum correlation coefficients and their corresponding lags for each of the 10-year periods (except the last period that has been taken as 11 years) and for each of the stations going back from 1997. The most recent period of 1987–1997 comes out to be the one to be most affected by ENSO. This effect is seen to be uniform over all the stations. This suggests a

Table 1
The compilation of the correlation coefficient values at the lag where highest correlations are obtained for the five gauges

Stations	Periods				
	1950–1997	1957–1966	1976–1967	1977–1986	1987–1997
DC	0.25, 0	−0.57, 0	−0.51, 0	−0.15,0	0.69, 0
Richmond	0.16, 6	−0.55, 6	−0.33, 6	−0.11, 6	0.76, 6
Norfolk	−0.1, 6 from 1954	−0.33, 6	0.47, 6	0.47, 6	−0.56, 6
Lynchburg	0.48, 3	0.13, 0	0.27, 6	0.47, 6	0.82, 0
Roanoke	−0.1, 6 from 1951	0.20, 6	−0.65, 0	0.58, 6	0.84, 0

change in the precipitation pattern with respect to ENSO in the last decade or so for the geographical area around Virginia. In Table 1 we have omitted the first data periods of each station as that varied between the different data stations.

Assuming a decorrelation time of nine months for the SOI, the effective number of independent samples for a 10 and 45-year periods are 14 and 60, respectively. Correlation coefficients above 0.52 and 0.25 are significant at the 95% level (Bendat and Piersol, 1971). It therefore seems that there is significant correlation between SOI and monthly rainfall for Washington DC and Lynchburg for the whole time period and for all five stations in the last decade.

Fig. 3 shows the respective time series of de-noised gauge data and SOI for the whole period and IMF plots for the period 1987–1997. Putting together Fig. 3 with Table 1, makes it quite obvious that rainfall pattern in

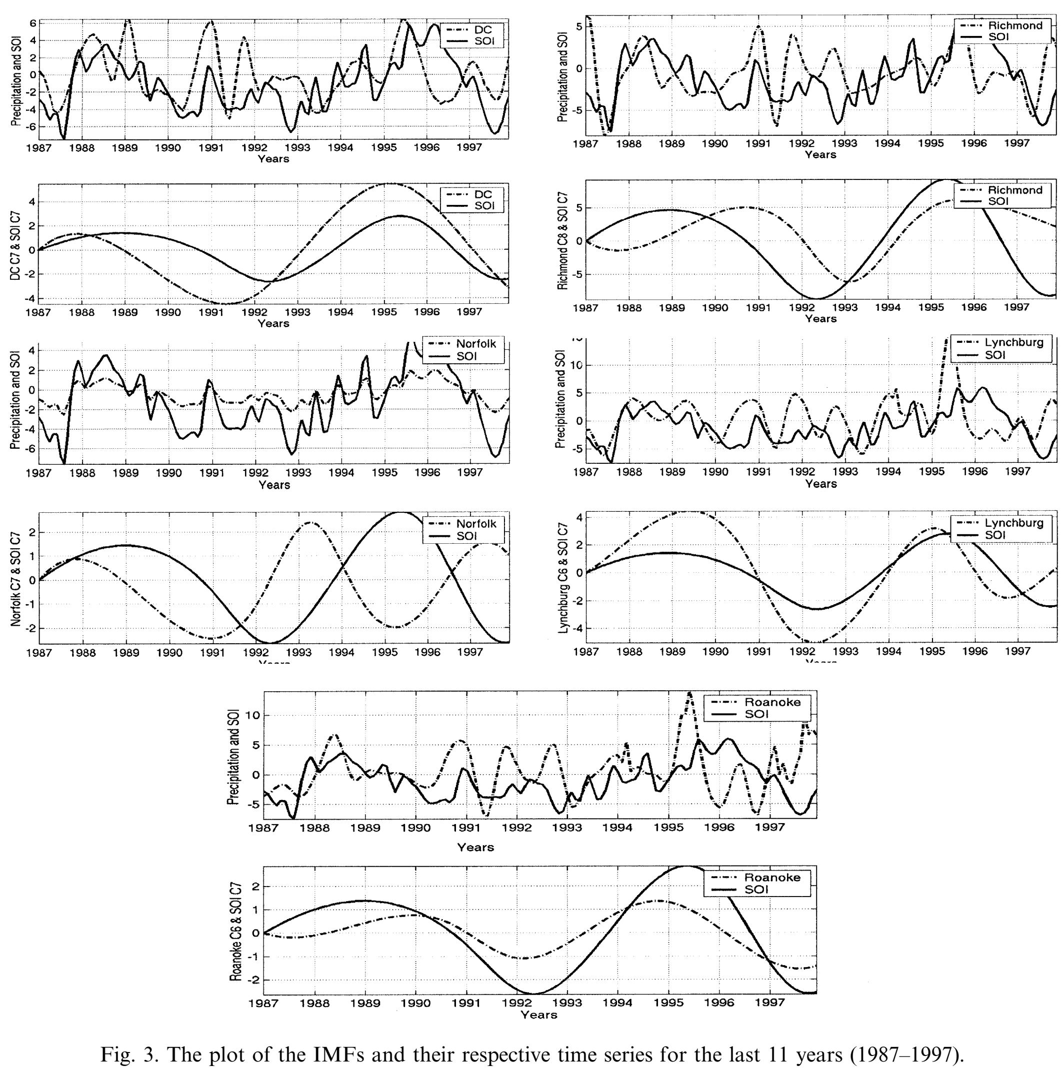

Fig. 3. The plot of the IMFs and their respective time series for the last 11 years (1987–1997).

Table 2
Coherency and phase values obtained for rainfall at the five gauges versus SOI at 95% confidence level (dominant periods are shown in bold)

Stations	Parameters		
	Periods (years)	Coherence	Phase (degrees) for dominant periods vs. lag (months)
DC	5.34, **3.56**, 2.66	0.29, **0.96**, 0.58	0.059°/0
Richmond	**3.56**, 2.66	**0.52**, 0.89	4.27°/6
Norfolk	**5.34**	**0.48**	4.14°/6
Lynchburg	**2.66**	**0.96**	1.87°/3
Roanoke	**3.56**, 2.66	**0.98**, 0.67	4.2°/6

the state of Virginia and the surrounding areas in the eastern part of USA have significant relation with the ENSO. This relation has fluctuated over their entire data span but is seen to remain more or less constant and uniformly significant for the last 11 years.

A cross-spectral, coherency and phase analysis between the rain fall data and the ENSO time series provides further insight regarding the possible physical link between precipitation and ENSO. The degree of coherency and phase difference between them in accordance with the obtained time lags from the EMD analysis are shown in Table 2.

5. Conclusion

Our work focuses on a specific region of the eastern coast in terms of 40 years of rain gauge station data. This is the first work of its kind that takes an in-depth look at the precipitation pattern in the eastern coast and its relation with ENSO. Several interesting observations are made in this regard that shed some light on the way precipitation pattern has behaved in terms of ENSO for the past 40 years. The relation of precipitation with ENSO seems to vary within the pilot area. This is found from the behavior of stations near the coast as they show a more consistent relation with ENSO in terms of their lag effect with respect to ENSO, more than those further inland that show a varying relationship. This may be explained by the presence of other competing effects at local scales, as these sites are not far from each other but have different local conditions (e.g., topography, weather, etc.). The cross-spectral coherency analysis supports the teleconnection pattern between ENSO and regional rainfall, consistent with the wavelet results. The phase analysis reveals the consistency between the phase difference angles (degrees) between the rainfall and the SOI data and their corresponding time lags (months) obtained from the correlation analysis of their IMFs. It is interesting to note that the relationship with ENSO might be mediated through the effects of tropical storms, which are known to be substantial rainfall producers. The limited sample examined here does not allow us a complete validation of this hypothesis but we expect significant variations from the coastal to the inland stations as suggested here. The last 11 years from 1987–1997 turn out to be the most affected by ENSO for all the stations irrespective of their locations. This result is quite significant with regard to earlier work by (Sarkar and Kafatos (2002)). They found significant change in behavior of NDVI patterns with respect to ENSO before and after 1988 while studying the NDVI pattern over the Indian sub-continent. Such result may suggest a possible global teleconnection pattern. The results show that ENSO has effects over the eastern coast, which though not as dominant as over the western coast, still has distinct signature.

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