Detection of climate change and climate variability signals in Colombia and the Amazon River basin through Empirical Mode Decomposition.

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INTRODUCTION

Several studies have reported evidences of climate change in Colombia. Hense et al., (1988) found increases in annual average temperatures of the troposphere between 200 and 700 hPa in Bogotá. Smith et al. (1996) performed statistical tests in order to detect trends and changes in the probability distribution function of hydrological records in Colombia, in terms of changes in the mean and variance. The works by Mesa et al. (1997) and Pérez et al. (1998) performed a suite of statistical tests searching for evidence of climate change on monthly records of hydro-climatic variables such as temperature (mean and minimum), dew point, vapor pressure, tank evaporation, precipitation, discharge and atmospheric pressure. Their results along with those of Ochoa and Poveda (2008) confirm the existence of statistically significant increasing trends in records of mean and minimum temperatures (in particular, positive trends of about 1°C in 20 years in minimum temperature records), concomitant with positive trends in relative humidity and evaporation throughout the country. Also, increasing long-term trends were identified for monthly records of minimum temperature in most of the country. The situation is critical along the Andes where eight glaciers disappeared in Colombia during the 20th century, and the remaining six are exhibiting rapid receding rates (Ceballos et al., 2006; Poveda and Pineda, 2009), which might contribute to their disappearance in the coming decades, and in turn will have strong implication for surface water-supply and on the ecological integrity of ecosystems below the snow line, including the fragile paramos (Poveda and Pineda 2009). In addition, significant decreasing trends have been identified in average monthly river discharges in the most important river basins of the country, namely those of the Magdalena and Cauca Rivers, which cross the country in a South-North direction and outflow into the Caribbean Sea. A mixing of increasing and decreasing long-term trends were also found (Mesa et al., 1997; Perez et al. 1998) in monthly records of precipitation throughout Colombia. Furthermore, these studies identified shifts in the phase and the amplitude of the annual and semi-annual cycles, of ample implications for diverse sectors such as hydropower, agriculture and human health among others.

On top of the aforementioned long-term trends, strong natural climate variability occurs in Colombia's hydro-climate. At inter-decadal timescales, significant quarterly correlations have been found between the Pacific Decadal Oscillation (PDO) with monthly records of average river discharges (Poveda et al., 2002). The interannual variability of rainfall in Colombia is mainly controlled by the effects of both phases of El Niño-Southern Oscillation (ENSO) (Poveda and Mesa 1997, Poveda et al 2001 and Poveda et al 2006). On seasonal timescales, central and western Colombia experience a bimodal annual cycle of precipitation with marked high-rain seasons (April-May and September- November) and low-rain seasons (December-February and June-August), mainly driven by the double passage of the intertropical convergence zone (ITCZ) (Eslava 1993; Mejía et al. 1999; León et al. 2000; Poveda et al. 2007, Álvarez et al. 2010). Some other factors such as the Chocó low level jet (Poveda and Mesa 2000), and other jets affect the seasonal cycle of Colombia. At intra-seasonal time scales, the westerly and easterly phases of the 40-50 day Madden-Julian oscillation (Poveda et al. 2005), and the dynamics of tropical easterly waves during the boreal summer-autumn are known to affect precipitation regimes over different regions of Colombia (Martínez, 1993). At shorter timescales, the diurnal and semi-diurnal cycles of maximum rainfall exhibits sharp differences even among nearby raingauges (Poveda et al. 2005), while exhibiting short persistence in time but fractal behavior in space (Hurtado and Poveda 2009) and maximum entropy at varying characteristic timescales (Poveda 2010). Thus, it is necessary to analyze the various hydro-climatic variables using powerful diagnostic tools that effectively contribute to the understanding of diverse phenomena and hydro-climatic variability modes, which influence simultaneously the South American hydro-climatology. It is also necessary to continue the search for evidences and signs of climate change in Colombia, with longer series of records than those used by Mesa et al., (1997) while using new and powerful statistical and mathematical methodologies.

This study aims at detecting signals of climate change and climate variability in time series of hydro-climatic records using series of monthly rainfall, average river discharges and mean and minimum temperature records in Colombia and monthly rainfall stations in the Amazon basin. Also, time series of average monthly river discharges were selected on 10 Colombian river basins with gauging stations along their path. As many as possible series will be used to further continuing the studies of Mesa et al. (1997), Perez et al. (1998), and Ochoa and Poveda (2008). For estimation purposes statistical tools will be used, including the Empirical Mode Decomposition and the Hilbert-Huang Transform.

METHODS

The Empirical Mode Decomposition EMD

The Empirical Mode Decomposition (Huang et al., 1998, Huang and Wu, 2008) is a filtering process by which any data set can be decomposed into a finite number of Intrinsic Mode Functions (IMFs) which capture diverse oscillations of different periodicities embedded in the data. Each IMF must satisfy two basic conditions: (i) throughout the series, the number of extreme values and the number of zero crossings must be equal or different by one, (ii) the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero everywhere (Rao and Hsu, 2008). Also, unlike harmonic functions which exhibit constant frequency and amplitude, IMFs may have variable time-dependent amplitudes and frequencies. EMD is an adaptive method whereby the decomposition is derived exclusively from the data because it does not assume the existence of an a priori basis, e.g., the trigonometric functions of the Fourier transform. Thus, the decomposition based on local characteristics of the signal makes EMD applicable to nonlinear and non-stationary processes. In addition EMD works directly in the time domain.

The EMD process is based on the following assumptions: (i) the signal has at least two extrema (maximum or minimum values), (ii) the characteristic time scale is defined by the time lapse between the extrema. This shifting process contains the following steps: (Rao and Hsu, 2008):

1) Identify all extrema (maximum and minimum) of the signal *x(t).*
2) Connect these maxima with the cubic spline lines to construct an upper envelope *emax(t).* Use the same procedure for minima to construct a lower envelope *emin(t).*
3) Compute the mean of the upper envelope and lower envelope *m(t)=[emax(t)- emin(t)]/2.*
4) Calculate *d(t)=x(t)-m(t).*
5) Let *d(t)* be the new signal *x(t).* Follow the previous procedure again until *d(t)* becomes a zero-mean process according to some stopping criterion.
6) The zero-mean *d(t),* is designated as the first intrinsic mode function (IMF 1).
7) The IMF 1 is subtracted from the original signal and the residual is used as a new signal *x(t).* The sifting process is repeated to obtain the second IMF2.
8) Further IMF3, IMF4 and so on are obtained in a similar way. This process is stopped when the residual is a monotonic function having only one minimum or one maximum.

Modified Mann-Kendall Test for autocorrelated series of data

A common tool for detecting changes in climatological and hydrological time series is trend analysis. However, when time series exhibit a strong temporal autocorrelation, artificial trends may appear when they really do not exist or are not statistically significant. The Modified Mann-Kendall Test takes into account the autocorrelation among series (Hamed and Rao, 1998). The first step in applying the Mann-Kendall test for autocorrelated data is the estimation of the statistic, S:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_k),$$

Where,

$$\begin{aligned} sign(x_j - x_k) &= 1 \quad si \quad x_j - x_k > 0 \\ &= 0 \quad si \quad x_j - x_k = 0 \\ &= -1 \quad si \quad x_j - x_k < 0 \end{aligned}$$

The next step is to determine the variance of *S:*

$$V^*(S) = \frac{n(n-1)(2n+5)}{18} * \frac{n}{n_s^*} \, ,$$

with $$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} * \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\rho_s(i),$$

where *n* is the actual number of observations and $\rho(i)$ denotes the autocorrelation function of the ranks of the observations.

Then a standardized test statistic (Z) is estimated:

$$
\begin{aligned}
Z &= \frac{S-1}{\left[VAR(S)\right]^{1/2}} \qquad if \quad S > 0 \\
&= 0 \qquad\qquad\qquad\; if \quad S = 0 \\
&= \frac{S+1}{\left[VAR(S)\right]^{1/2}} \qquad if \quad S < 0
\end{aligned}
$$

Finally, a certain probability associated with Z (Z_{crit}) with a predetermined significance level is calculated. It is a probability threshold determined previous to the test (α=0.05, for a confidence level of 95%). Thus if the test statistic *Z* is smaller than the statistical Z_{crit} the identified trend is not significant.

Sen Test

This test is used to quantify the change in the magnitude of local slopes in time. This methodology requires equally spaced data and makes no assumptions about the statistical distribution of data (Sen, 1968). The slope is estimated as:

$$
m = \frac{X_{i+1} - X_i}{(i+1) - i},
$$

where *m* is the local slope between consecutive data X_{i+1} and X_i, at times $i + 1$, and i, respectively. Thus, the general slope of the studied series results from the average of the entire set of local slopes (Sen, 1968).

DATA

For estimation purposes, monthly series of rainfall (100 stations), average river discharges (42 stations), and temperature records in Colombia (37 stations), and 29 monthly rainfall stations in the Amazon Basin were used. Data for Colombia was obtained from Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). Rainfall stations in the Amazon Basin were provided by IDEAM, the Large-scale Biosphere Atmosphere Experiment in Amazonia (LBA) and by the Global Historical Climatology Network (GHCN). Stations with more than 25 years of data and well spatially distributed across the Amazon were selected. Also, time series of average monthly river discharges were selected on 10 Colombian river basins with gauging stations along their path.

RESULTS

The entire set of 208 time series was analyzed using the "DataDemon" software obtained from the National Aeronautics and Space Administration's (NASA). Figures 1 to 4 show results for the series of average monthly minimum temperature records at Olaya Herrera Airport in Medellin. Figure 1 shows the change in minimum temperature data over time. Figure 2 shows the IMFs resulting from the EMD process. Figure 3 shows both the original minimum temperature series along with the residual of its decomposition, pointing out the trend in the series. Figure 4 shows a detailed analysis of the residual, whereby a Mann-Kendall test confirms the trend in the series with a confidence level of 95%. The Sen Test estimated an increasing trend of 0.07 °C/year.

Figure 1 Monthly minimum temperature series, Olaya Herrera Airport, Medellín

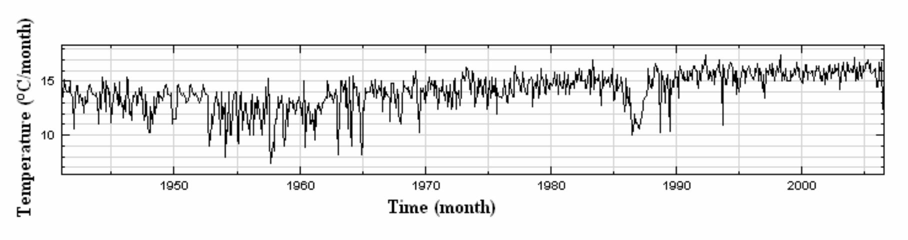


Figure 2 Intrinsic mode functions, Olaya Herrera Airport, Medellín

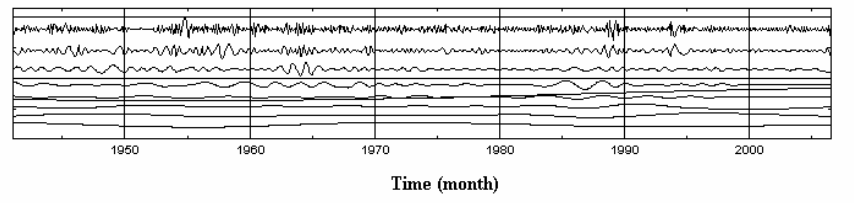


Figure 3 Monthly minimum temperature series superimposed with the residual IMF, Olaya Herrera Airport, Medellín

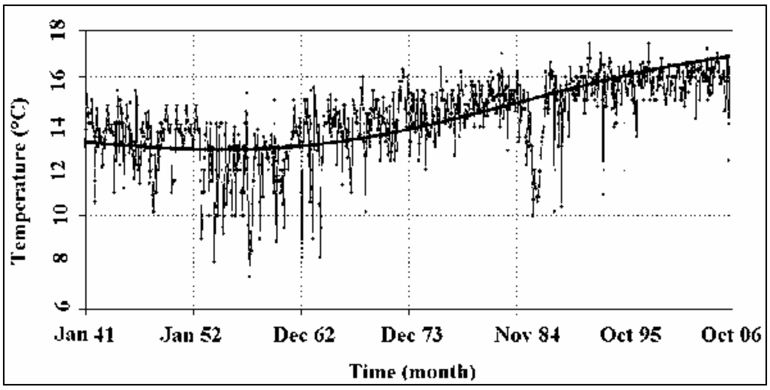
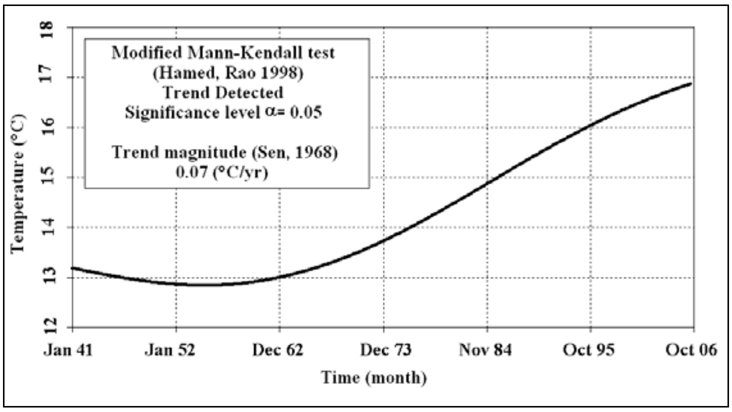


Figure 4 Residual IMF, Olaya Herrera Airport, Medellín



Results obtained for the studied variables and series at gauging stations with record lengths of 25, 30, 40 and 50 years, respectively, in Colombia and the Amazon River basin, are shown in Tables 1 to 5. Thus, the percentage of stations with increasing, decreasing and no trend was obtained for all the variables.

Table 1 Colombian stations with over 25 years of records.

Variable	**Number of stations**	**Increasing trend**	**Decreasing Trend**	**No trend**
Rainfall	100	41%	44%	15%
River discharge	42	33%	62%	5%
Mean Temperature	22	32%	59%	9%
Minimum Temperature	15	87%	7%	7%

Table 2 Colombian stations with over 30 years of records.

Variable	**Number of stations**	**Increasing trend**	**Decreasing Trend**	**No trend**
Rainfall	99	41%	43%	15%
River discharge	41	34%	61%	5%
Mean Temperature	22	32%	59%	9%
Minimum Temperature	15	87%	7%	7%

Table 3 Colombian stations with over 40 years of records.

Variable	**Number of stations**	**Increasing trend**	**Decreasing Trend**	**No trend**
Rainfall	64	42%	42%	16%
River discharge	8	25%	63%	13%
Mean Temperature	21	29%	62%	10%
Minimum Temperature	7	71%	14%	14%

Table 4 Colombian stations with over 50 years of records.

Variable	**Number of stations**	**Increasing trend**	**Decreasing Trend**	**No trend**
Rainfall	19	63%	21%	16%
River discharge	1	0%	100%	0%
Mean Temperature	17	24%	71%	6%
Minimum Temperature	4	75%	25%	0%

Table 5 Monthly rainfall trend results, Amazon basin.

	Years of records	**Number of stations**	**Increasing trend**	**Decreasing Trend**	**No trend**
Rainfall Amazon basin	25	17	29%	53%	18%
	30	13	38%	54%	8%
	40	8	50%	50%	0%
	50	8	50%	50%	0%

Tables 1 to 4 evidence that Colombian monthly rainfall series exhibit no clear trend pattern given the similarity of percentages of rain-gauges having increasing and decreasing trends. This finding confirms previous results with shorter time series reported by Mesa et al. (1997) and Ochoa and Poveda (2008).

However, a detailed analysis of those rainfall stations with over 50 years of records allows us concluding that there are more stations with increasing trends than with decreasing or no trends at all (Table 4). With respect to monthly mean river discharges and mean temperature records, the number of stations with decreasing trends exceeds that of increasing trends, regardless of the series length. Besides, stations with increasing trends in monthly minimum temperatures outnumber those with decreasing trends for all record lengths from 25 to 50 years. Results for monthly rainfall records in Amazonia (for raingauges having between 25 and 30 years of records) evidence that stations with decreasing trend exceed (53% and 54%) that of increasing trends (29% and 38%). Nevertheless, for raingauges having more than 40 years of records, the percentage of stations with increasing and decreasing trend is the same (Table 5). Figures 5 to 7 show the spatial distribution of stations exhibiting increasing (red) decreasing (blue), and no trends (green), with the diameter of the circle being correlative to the magnitude of the trend.

Figure 5 Rainfall trend analysis results

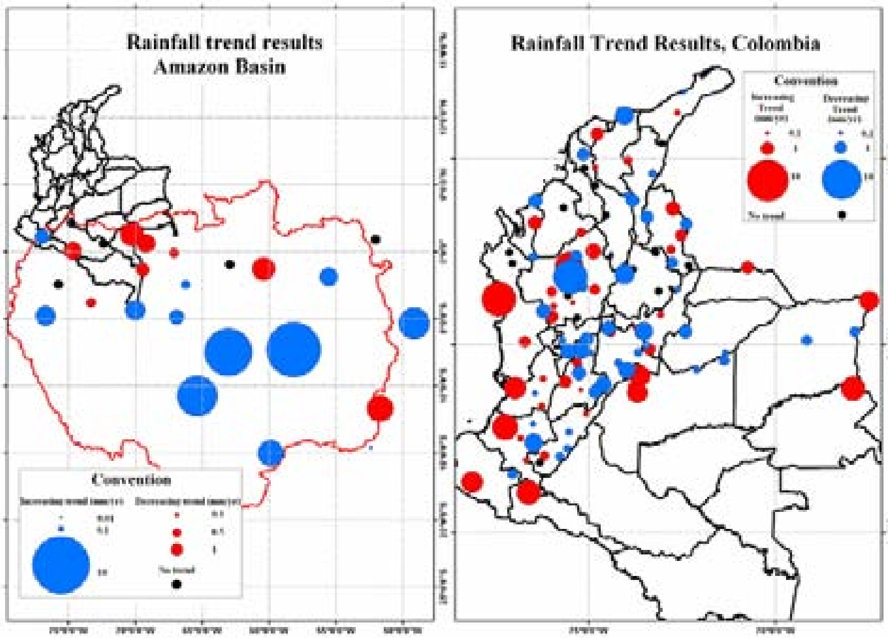


Figure 6 Temperature trend analysis results

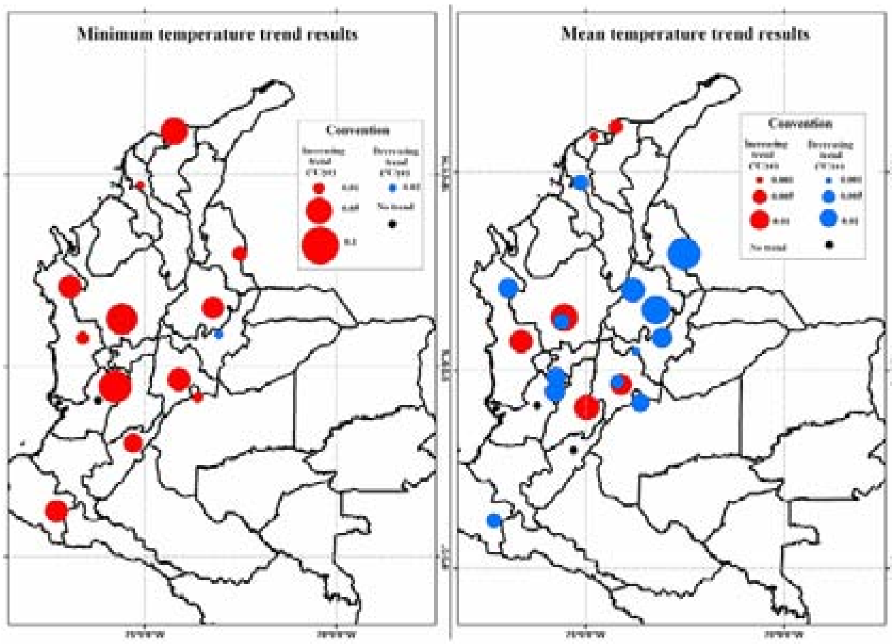
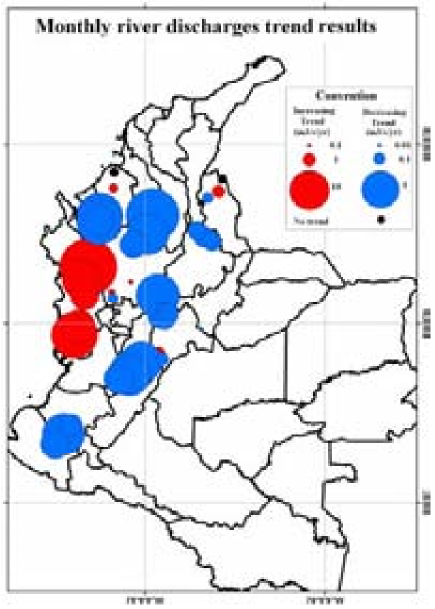


Figure 7 Monthly river discharges trend analysis results



Tables 1 to 4 and Figures 5 to 7 reveal that, in general, most discharges and mean temperature stations exhibit decreasing trends, while minimum temperature records show increasing trends. No distinctive pattern was found in rainfall series, since the number of stations with increasing and decreasing trend is similar. A regional analysis in Colombia show that the highest increasing trends in rainfall and monthly mean river discharges are witnessed on stations located on the low lying regions of the Pacific coast. No other clear-cut regional pattern in the distribution of trends is observed throughout Colombia. In the Amazon River basin, the highest (decreasing) trend magnitudes are located in the central and south-eastern parts of the region. Figures 5 and 7 show the spatial coherence between results for estimated trends in monthly rainfall and discharges records in Colombia. In particular, an increasing trend was found in flows for the rivers Atrato and San Juan, coinciding with an increasing trend in rainfall records for those stations located nearby the Pacific Ocean. This result prompted us to analyze the possibility of a trend in moisture advection to the region by the winds of the Chocó low level jet (Poveda and Mesa, 2000). The series was obtained from the NCEP-NCAR Reanalysis Project (Kalnay et al., 1996). The presence of a significative increasing trend in the Chocó low level jet series, of about 0.0002 $[(kg_{water} / m^3_{air})*(m/s)]$ per month, was confirmed.

This study included 59 gauging stations in common with that of Mesa et al. (1997), with around 10 years more of records. We found that out of the 19 rainfall stations in common, 7 revealed the same trend in both studies (increasing or decreasing), 10 stations that in 1997 did not exhibit a trend in this study they do so, and the only station that exhibited a trend in the 1997 study, nowadays it is not statistically significant. Only one station showed a different trend in both studies (located above 2000m) positive in 1997 and negative in 2010. With respect to river discharge stations from the 6 common stations among the two studies, 2 had the same trends in both studies while 4 of them did not have any trend in 1997 but now in 2010 they do. From the 20 common stations of mean temperature, 14 had the same trend in 1997 and 2010, 4 did not have any statistically significant trend in 1997 and now they do, 1 had a trend in 1997 but now it is not statistically significant and only one station had a different result in both studies. Finally, from the 14 common stations of minimum temperature, 11 had the same trend, 3 showed no significant trend in 1997 and in 2010 they do and 1 station that had a trend in 1997 and in 2010 it does not. Table 6 presents the comparison between the studies of Mesa et al. (1997)and the current study (Carmona & Poveda, 2011) showing the percentage of stations with same trend, no trend in 1997 but trend in 2011, trend in 1997 but no trend in 2011 and different trend in both studies.

Table 6 Comparison between studies of Mesa et al. (1997) and Carmona & Poveda (2011)

Variable	**Stations in common**	**Same Trend (%)**	**Trend in 1997 No trend in 2011 (%)**	**No trend in 1997 Trend in 2011 (%)**	**Different trend (%)**
Mean temperature	20	70	5	20	5
Minimum temperature	14	79	7	21	0
Rainfall	19	37	5	53	5
River discharge	6	33	0	67	0

CONCLUSIONS

Results of trend detection in hydro-climatological signals demonstrate the power of the Empirical Mode Decomposition to extract a residue from the data, which represents a trend in the series over time. This could be noted by overlaying it with the observed time series. It was found that most discharge and mean temperatures series exhibit a decreasing trend, whereas the minimum temperature series have, almost unanimously, an increasing trend. On the other hand, a general result could not be found in rainfall series since the number of stations with increasing and decreasing trend was similar. However, it was established that the maximum trend magnitudes in rainfall series are located in the Colombian Pacific region (increasing trends), whereas towards the rest of the country no clear spatial pattern could be recognized. Also a consistent result between trends in rainfall and discharges in the Pacific region was found. These series exhibit increasing trends coinciding with a rising trend estimated in the Chocó Low level Jet series which represents moisture advection into this particular area. In the Amazon basin the maximum trend magnitudes were found in the basin's central and south-eastern region. Even though most series of monthly minimum temperature show increasing trends there is a series that exhibited a decreasing trend. This particular series is located in a station above 2000m and the trend could possibly be attributed to "Ground Frost". Results from previous works (Mesa et al., 1997, Ochoa and Poveda, 2008), carried out using other methodologies were confirmed with EMD. In most series analyzed in both studies trends remain. Some series that showed trends in 1997 do not exhibit them in this study with more than 10 years of records which may be an indication that these stations may be affected more by long-term periodicities and climate variability, than by climate change. On the other hand, stations that did not exhibited a trend in 1997 showed trends in this study, which could be an indicative of climate change. However studies should be carried on to determine if these trends persist with time, disappear, or are part of longer-term periodicities. This evidence of environmental change (climate change coupled with deforestation and changes in land use) should be incorporated into plans for environmental change adaptation in Colombia, as well as in water resources planning.

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ABSTRACT

The hydro-climatology of Colombia exhibits significant signatures of climatic change and also strong natural climate variability at a broad range of time scales from interdecadal and interannual all the way through intra-diurnal. Signals of long-term trends and of natural climate variability are detected in Colombia and the Amazon River basin using long series of monthly rainfall (100 stations), average river discharges (42 stations) and mean and minimum temperature records (37 stations) in Colombia. In the Amazon basin 29 monthly rainfall stations were studied. Stations with more than 25 years of data and well spatially distributed across Colombia and the Amazon were selected. Also, time series of average monthly river discharges were selected on 10 Colombian river basins with gauging stations along their path. For estimation, the Empirical Mode Decomposition (EMD), is used as a filtering process whereby a time series is decomposed into a finite number of intrinsic mode functions (IMFs), assuming that at any given time, many simple oscillatory modes of different frequencies coexist in a time series, where the residual represents the general trend of the series over time. The statistical significance of the trend in the EMD residuals are tested through the Mann-Kendall test for autocorrelated series and the magnitude of the trends are quantified by the Sen test. Results show that most monthly river discharges series exhibit decreasing trends, whereas the minimum temperature series show increasing trends. Results on precipitation are inconclusive as monthly records exhibit a mixed pattern of increasing and decreasing trends. However, it was established that the maximum trend magnitudes in rainfall series are located in the Colombian Pacific region (increasing trends), whereas towards the rest of the country no clear spatial pattern could be recognized. Also a consistent result between trends in rainfall and discharges in the Pacific region was found. These series exhibit increasing trends coinciding with a rising trend estimated in the Choco Low level Jet series which represents moisture advection into this particular area. In the Amazon basin the maximum trend magnitudes were found in the basin's central and south-eastern region.