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Trends of hydroclimatic intensity in Colombia

Oscar Mesa ^{1,*}, **Viviana Urrea** ^{1} **and Andrés Ochoa** ^{1}

[1] *Departamento de Geociencias y Medio Ambiente, Universidad Nacional de Colombia, Medellín, Colombia*

Correspondence*:
Oscar Mesa, Departamento de Geociencias y Medio Ambiente, Universidad
Nacional de Colombia, Carrera 80 # 64-223, 050041 Medellín, Colombia
ojmesa@unal.edu.co

ABSTRACT

Prediction of changes in precipitation in upcoming years and decades caused by global climate change associated with the greenhouse effect, deforestation and other anthropic perturbations is a practical and scientific problem of high complexity and huge consequences. To advance toward this challenge we look at the daily historical record of all available rain gauges in Colombia to estimate an index of the intensity of the hydrologic cycle (Giorgi et al., 2011). The index is the product of precipitation intensity and dry spell length. Theoretical reasons indicate that global warming should lead to increasing trends in either one of the factors or both. Our results indicate that there is no clear picture, there are gauges with positive and negative significant trends, and most of the gauges do not show a significant trend. We present the geographic distribution of results within regions and concerning the elevation in the Andes Cordillera. Results seem to agree with previous reports of total annual precipitation trends.

Keywords: Precipitation trends, Climate change, Colombia, Hydrologic cycle, dry spell length

1 INTRODUCTION

Predicting the effect of climate change on Colombia's hydrology, more specifically on precipitation, is not a small matter. To illustrate, only in the electricity sector recent studies for the Mining and Energy Planning Unit Macías and Andrade (2014) estimate that the impacts of the decrease in precipitation imply an increase in annual investment of US$ 290 million per year for the period 2013-2015.

But not only the impact is of magnitude, but the scientific problem of such prediction is also very complex, such models are not necessarily accurate. The focus of this work is the impact on precipitation, although global climate change impacts many more aspects such as temperature, sea level, coastal erosion, páramo ecosystem loss, vector-borne diseases, biodiversity, agriculture, and others.

Understanding the temporal-spatial variability of precipitation is a challenge of great importance due to the environmental, social, economic and cultural implications of the distribution of water resources in any country. On the other hand, the analysis of hydrologic processes under a climate change context, in addition to incorporating greater complexity to these processes, leads to the need to join efforts towards the understanding of national hydrology to manage the resource better. The broad objective of this work is to contribute to that challenging question, focusing on the use of precipitation information and mathematical and statistical techniques to identify and interpret evidence of climate change in Colombia.

Given the complexity of rainfall fields and the tropical climate in the rough topography derived by the Andes cordillera, rainfall records in Colombia are generally scarce, both because of their quality, missing data, length of the records and spatial coverage. Therefore, it is a unique challenge for Hydrology to predict the impact of climate change over Colombia rainfall at spatial and temporal scales suitable for critical applications. Among those applications, one can mention the planning for the sustainable development of the territory and its hydraulic resources, disaster prevention. Some of the theoretical questions are a better knowledge of the influence of macro-climatic phenomena like El Niño-Southern Oscillation (ENSO). In turn, a better understanding may allow better predictions.

2 PREVIOUS WORK

This short review has two parts. First, we present the main results of previous studies about climate change impact on Colombian rainfall trends. Then we briefly show the general context of how global warming impact precipitation.

Various works describe the climatology of the precipitation in Colombia (Snow, 1976; Oster, 1979; Eslava, 1993; Mesa et al., 1997; Mejía et al., 1999). The central control is the passage, twice a year, of the Inter-Tropical Convergence Zone that marks the rainy seasons of April-May and September-November in the Andes, and the seasons with the lowest rainfall in December-February and June. -August. The spatial distribution is marked by the sources of humidity in the Caribbean, the Pacific, and the Amazon, by the topography and prevailing winds. The inter-annual variability is controlled mainly by the phenomenon of ENSO in the tropical Pacific (Poveda and Mesa, 1997; Poveda et al., 2011).

Several studies have found evidence of climate change in Colombia using various statistical techniques with different record lengths (e.g. Smith et al., 1996; Mesa et al., 1997; Quintana-Gomez, 1999; Vuille et al., 2003; Ochoa and Poveda, 2008; Pabón, 2009; Cantor and Ochoa, 2011; Cantor, 2011; Carmona and Poveda, 2014; Hurtado and Mesa, 2015). In summary, these studies identify increasing trends in mean and minimum temperature records in a significant number of stations. Besides, they find mixed trends in precipitation, with a similar percentage of stations for each trend and 20% without a statistically significant trend for the set of considered series of up to 40 years of records. For precipitation stations with longer records, the majority (63%) shows an increasing trend and only 16% decreasing trend. A clear geographical pattern is not identified to locate areas with a particular trend, except in the Pacific plain that has the highest definite upward trend, explained by an increasing trend of the influence of moisture in the Pacific and the Chocó Jet.

These conclusions coincide with the IDEAM report, Mayorga et al. (2011), which analyzed 310 rainfall stations with monthly records in the period 1970-2010 using RCLIMDEX. This is a program developed by the CCl / CLIVAR working group (Climate and Ocean: Variability, Predictability and Change) part of the World Climate Research Program of the World Meteorological Organization and Unesco for the detection of climate change as a coordinated international effort to have indexes calculated with the same methodology that can be integrated internationally (Peterson, 2005). Of the 310 precipitation stations, 71 % show increasing trend, seven % without trend, 22 % decreasing trend. The conclusion related to the rising temperature is also confirmed, with an increase of 0.17 K per decade. It is essential to quote the report: “ ... the generalized increase in precipitation in the country is noticeable, highlighting the north-western zone (Antioquia and Chocó), Vichada, the Piemonte de Putumayo and the island of Providencia, where the most significant increase. The opposite occurs on the island of San Andrés, on the eastern slope of the

Eastern Cordillera (Arauca and Casanare) and in large areas of the Upper Cauca, where there is a decrease in precipitation. The largest decrease occurs in the south-west of the territory. ”

It is clear that the observed trends may be due to other causes besides increasing greenhouse gas global warming; deforestation and urbanization among others, not to mention observational issues.

Concerning the impact of deforestation, Salazar (2011) estimates through a numerical experiment that a possible drastic future change in coverage in the Amazon area would bring about a reduction in precipitation in Colombia of an order of magnitude of 300 mm/year.

The warming of the Colombian Andes has led to the complete extinction of eight tropical glaciers, and the six remaining snow-caps lose ice at accelerated rates (Rabatel et al., 2013). The páramos, unique and strategic ecosystems to supply water to several cities, including Bogotá and Medellín are also in danger by warming and other anthropogenic activities (Ruiz et al., 2008).

The heating means an increase of the air saturation vapor pressure according to the Clausius-Clapeyron equation. Overall, this increase is has been accompanied by an increase in evaporation and, therefore, in absolute humidity, to keep the relative humidity relatively constant (Stevens et al., 2013). A few series of tank evaporation and relative humidity confirm this observation for Colombia (Mesa et al., 1997). The consequences of this are essential to understanding the physical mechanisms associated with the impact of warming on precipitation and river flow.

Mesa et al. (1997) reports that a good part of the flow series in the Magdalena-Cauca basins have a decreasing trend. Recently, Carmona and Poveda (2014) confirm and reinforce this conclusion about the trends from their analysis of the same series with new years of observations and other series not analyzed in the initial work. The number of stations with a decreasing trend is higher than the number showing an increasing trend. The percentage that decreases varies from 61% to 100% depending on the length of the record, the first value for records of 25 years and the last for records over 50 years. Whereas, 0 to 34% of the analyzed streamflow gauges show an increase. The positive regional trend for the Atrato and San Juan flows coincide with areas of large increasing trends in precipitation.

Hurtado and Mesa (2015) developed a reanalysis of the precipitation field in Colombia, comprising 384 fields of monthly precipitation in the period 1975-2006 at a spatial resolution of 5 minutes of arc. For the reanalysis, they used records of 2270 rain gauges and various satellite-derived products for the most recent period. Then using Empirical Orthogonal Functions, Principal Component Analysis and statistical tests they looked for changes or trends. According to their results, both the Mann - Whitney mean change test and the simple t trend test indicate increasing precipitation trends mainly in the Pacific, Orinoco, and Amazon basin regions. In most of the Andean region, there are no changes or trends.

Another line of work has been the use of global climate models (GCM): Pabón (2005); Ruiz (2007, 2010); IDEAM-Colombia (2010). These models adequately represent the core of the physical processes, although not the totality, particularly rainfall, tropical convection, and topography. Besides, spatial resolution is not generally adequate for regional studies. In general, there is the possibility of correcting these deficiencies through the use of mesoscale models that have finer spatial resolution and better represent convective processes. This methodology, known as downscaling, has advanced, but it is not free of difficulties.

Ruiz (2010) and Pabón (2005) analyze the results of the low-resolution global models to conclude that “annual precipitation would be reduced in some regions and would increase in others. In the regions where there is a certain degree of coincidence in most of the models and current trends about an increase are: the North and Central Pacific, Middle Magdalena, Sabana de Bogotá, Sogamoso River Basins, Catatumbo, Arauca, Piedemonte Llanero, Central Orinoquia, Central Amazon and Amazonian piedmont. In those places the increase in rainfall compared with the typical period 1961-1990 could be between 10 and 15 % by 2050 and between 15 and 25 % for the year 2080. For the other regions, the study says that it is difficult to arrive at a concrete result since the different models present contradictory results". The results of the different IPCC models are available in http://www.climatewizard.org/. From there one can conclude that predicted change in rainfall for Colombia in scenario A1B for the average of the models indicate an increase of around ten % for all of Colombia, except the northernmost zone. If the models or scenarios are examined individually the general trend is the same, although the magnitudes vary. In general, for most of Colombia, they predict positive trends, except for the most northern part where they predict a decreasing trend.

Pabón (2005); Ruiz (2007, 2010); IDEAM-Colombia (2010) went beyond low-resolution models into higher resolution using the regional model PRECIS (Providing Regional Climates for Impacts Studies) of the United Kingdom and the global model GSM-MRI (Global Spectral Model) of Japan. The results obtained can be summarized by quoting the Colombian 2nd Communication: "The areas that on average, by the end of the 21st century, would have the greatest reductions in precipitation would be the departments of Huila, Putumayo, Nariño, Cauca, Tolima, Córdoba, Bolivar and Risaralda where the rains would be reduced close to 15% with respect to the 1971-2000 climatology. Likewise, it is possible that rainfall increases near 10%, in large areas of Chocó. From the point of view of the most pessimistic scenarios (A2, for example), the most significant reductions in rainfall throughout the 21st century would occur in Córdoba, Cauca, Bolívar, Caldas, Sucre, Valle, Antioquia, Nariño and Risaralda , where it would rain between 70 and 80% of the rainfall recorded during the period 1971-2000 (that is, reductions between 20% and 30%)."

However, some contradictions are striking. The minimum consistency required is that during the historical period the results of the models correspond to the observations. The trends in precipitation deduced from low-resolution global models do seem to be consistent with the trends observed in historical records. However, there is no consistency between the predictions of high-resolution models and low-resolution models. This single observation disqualifies their results of the high-resolution models.

Supported by these IDEAM results, UPME has analyzed the vulnerability of the Colombian electricity sector, which on average supplies 70% through hydro-electricity (ACON-OPTIM, 2013). The monthly flows that feed each reservoir were projected using the decreasing trends of precipitation. As expected, they found a generalized decrease for the three climate change scenarios analyzed (A2, B2, and A1B). It is worth mentioning the analysis they make of these results: "Although the results obtained coincide with reductions in the water supply of the reservoirs, in many cases the percentage changes in the monthly flows are exaggerated, reaching reductions greater than 50% of the current condition. Those values are considered unlikely considering that the recorded flow series do not show sufficient statistical evidence to demonstrate that there is any linear decreasing trend". Such studies give rise to policies and actions that have clear, practical consequences.

Urán (2015) carried out an analysis of the scaling between precipitation and temperature limited by the Clausius-Clapeyron using 86 stations of precipitation and 9 temperature stations over the Antioquia region of Colombia, with 15 minutes resolution. He also used rain derived from TRMM data (Tropical Rainfall Measure Mission) with rainfall intensities every 3 hours. He found that for temporal scales greater than 12 hours the trends are no longer significant trends. For the finer temporal scales trends become significant for extreme deciles of the distribution. He reports a close scaling due to the Clausius-Clapeyron relation limiting the intensification of precipitation following the ideas of O'gorman and Schneider (2009).

In response to global warming, the hydrological cycle also changes. A warmer atmosphere means more radiative cooling of the troposphere, which is a growing function of temperature. The highest infra-red radiation emission corresponds to the balance required to compensate for the greater radiation absorbed. To the extent that changes in cloudiness or the absorption of radiation by water vapor offset the necessary radiative cooling, changes in precipitation may occur. Regionally, the winds determine where there is an increase or a decrease. If the winds change little, compared to the humidity they transport, the wet regions import more water, and there could be more rain, while the dry ones could be drier (Mitchell et al., 1987; Soden and Held, 2006; Wentz et al., 2007).

Giorgi et al. (2011) introduce a new measure of hydroclimatic intensity (HY-INT), which integrates metrics of precipitation intensity and dry spell length. The responses of these two metrics to global warming are deeply interconnected. They found clear increasing trends of HY-INT in global and regional climate models. Depending on the region, the increase in HY-INT is due to an increase in precipitation intensity, dry spell length, or both. They also examined late twentieth-century observations and concluded that they also exhibit dominant positive HY-INT trends, providing a hydroclimatic signature of late-twentieth-century warming. Precipitation intensity increases because of increased atmospheric water holding capacity. However, increases in mean precipitation need increases in surface evaporation rates, which are lower than for atmospheric moisture. Global warming increase potential evapotranspiration which may probably result in an increase in actual evaporation, or evapotranspiration in plants, only if adequate moisture is available. So potentially there is more drying, but in drought situations part of any extra energy goes into raising temperatures, thereby amplifying warming over dry land. This feedback leads to a reduction in the number of wet days and an increase in dry spell length.

3 STUDY AREA AND DATA

We analyzed data from 1706 sites in the whole territory of Colombia, 1062 in the Andes region. The other sites are in the Amazon (77), the Caribbean 398, the Orinoco (91) and the Pacific (78) regions. Data comprise daily time series of rainfall amount. Since the method requires no missing data (Section 4) we trim the series to the common period between 1970 and 2014. We also fill the missing data with data from the CHIRPS (Funk et al., 2015) data-set. A condition for this filling was that the percentage of missing days did not exceed 30%. Otherwise, the whole year is missing. The authors tested the performance of CHIRPS in Colombia in previous studies (Urrea et al., 2019; Urrea, 2017; Urrea et al., 2016). Of the original IDEAM dataset, we dropped for our analysis all the stations with more than 50% missing data in the common period and others that do not pass a minimum quality check. The final data-set has 1629 stations.

Figure 1 shows the IDEAM the rain gauge network. The network covers a range of elevations from sea level in the Caribbean and Pacific coasts to 4150 meters above sea level in the Andes. Notice also the low density of the gauge network in the Amazon and Orinoco regions.

Colombian climate is tropical, mean annual temperature is high, above 25°C at sea level, the diurnal range of temperature exceeds the annual range, and the annual range is minimal, less than 5°C (Snow, 1976). Precipitation is abundant in comparison with any other place in the world. There are places of the Pacific coast with perennial rain with mean annual totaling 12200 mm. Over the Orinoco and Amazon basins in Colombia, the mean annual precipitation varies from 2000 to 7000 mm per year. In the Caribbean coast the average is of the order of 1500 mm, but to the north, there are places with near 300 mm/year. In the Andean region mean annual precipitation ranges from 1000 to 3000 mm/year.

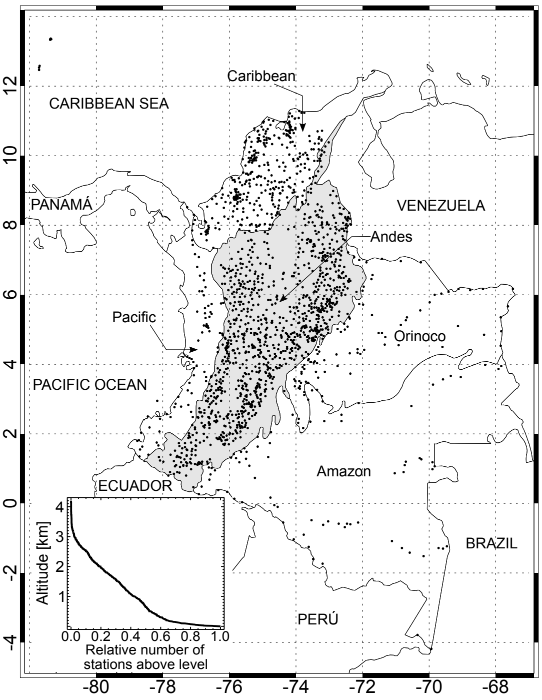

Figure 1. Location of the IDEAM rain gauge network that was used in this work. The bottom left graph shows the vertical distribution of the rain stations. The map also shows the five natural regions of Colombia (IGAC, 1997).

Atmospheric moisture is transported toward Colombia by the trade winds from the Caribbean sea, the Atlantic ocean through both Amazon and Orinoco basins that themselves contribute with recirculating moisture. Also from the Pacific ocean, westerly winds contribute to the massive convergence of moisture over Colombia. The migration of the inter-tropical convergence zone and three low-level jet streams (Chocó, Caribbean, and South America) are part of the complex circulation given rise to that high precipitation (Poveda et al., 2014).

4 METHODS

Hydroclimatic intensity (Giorgi et al., 2011) is evaluated using the HY-INT indicator

$$\text{HY-INT} = \text{INT} \times \text{DSL}, \tag{1}$$

where INT and DSL are mean intensity during wet days and mean dry spell duration for each year in the record. In both cases, one works with scaled variables using the respective inter-annual mean as scale factor (Giorgi et al., 2011). Therefore the long-term average of both INT and DSL are 1.

We also evaluate the trends of P, the total annual precipitation for each year; and LW, the average length of a wet spell in each year. We also counted the number of wet and dry days in each year as well as the number of dry and wet spells in each year.

Also, we constructed an extreme indicator of the hydrologic cycle generalizing (Giorgi et al., 2011) ideas. For that, we computed the maximum daily intensity for each year (INTX) and the maximum dry spell length for each year (DSLX). In other words, for this proposal instead for the average of the corresponding variable for each year, we take the maximum. Their product gives the HY-INTX indicator of the strength of the hydrologic cycle.

For each year in the record we computed each one of the variables mentioned above. Therefore for each gauge and each variable, we have a time series. We then proceed to evaluate the existence of trends in those time series for each gauge.

4.1 Trend analysis

We use the Mann-Kendall test (Mann, 1945; Kendall, 1955) for autocorrelated data (Hamed and Ramachandra-Rao, 1998) to evaluate the existence of trends in the time series, and the Sen's slope estimator (Sen, 1968) for calculating the magnitude of the trend. A summary of these techniques follows. More details in the cited references.

The null hypothesis of the Mann-Kendall test is that the data come from independent and identically distributed random variables (iid) and hence no long-term trend exists. When the data are iid, the statistic S,

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i), \tag{2}$$

has asymptotic normality with mean zero and variance $\operatorname{Var}[S]$

$$\operatorname{Var}[S] = \frac{n(n-1)(2n+5)}{18} - \frac{1}{18} \sum_{j=1}^{m} t_j(t_j - 1)(2t_j + 5). \tag{3}$$

In Eq. 2 n is the sample size, x_t is the value of the time series at time t, and $\operatorname{sgn}(x_j - x_i)$ is defined by

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if} \quad x_j - x_i > 0, \\ 0 & \text{if} \quad x_j - x_i = 0, \\ -1 & \text{if} \quad x_j - x_i < 0. \end{cases} \tag{4}$$

The sum in the last term of Eq. 3 accounts for the reduction in variance due to the existence of tied ranks (Hamed, 2008). In Eq. 3 m is the number of groups of tied ranks and t_j is the number of ranks in group j.

The standardized test statistic Z is calculated by

$$Z = \begin{cases} \frac{S-1}{\sqrt{\operatorname{Var}[S]}} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \frac{S+1}{\sqrt{\operatorname{Var}[S]}} & \text{if } S < 0. \end{cases} \tag{5}$$

The null hypothesis of no trend is rejected if $|Z|$ exceeds the value $|Z_{1-\alpha/2}|$ of the standard normal distribution for a given significance level α.

The result of Mann-Kendall test is sensitive to autocorrelation in the data. Positive autocorrelation increases the probability of rejecting the null hypothesis when it is true, and negative autocorrelation increases the probability of not rejecting the null hypothesis when it is false. This effect occurs because of a bias in the estimation of $\operatorname{Var}[S]$. Hamed and Ramachandra-Rao (1998) suggested the empirical formula in Eq. 6 for calculating $\mathrm{Var}[S]$ in the presence of autocorrelation.

$$\mathrm{Var}[S_{ac}] = \mathrm{Var}[S] \times \left[1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\rho_s(i)\right] \tag{6}$$

where $\rho_s(i)$ is the auto-correlation function of the ranks of the observations.

The Sen's non-parametric method (Sen, 1968) estimates the long-term linear trend slope of a time series as the median value of the slopes between all pairs of points in the series. For $N = n \cdot (n-1)/2$ pairs of data in the series, the N slopes, Q, are calculated as shown in Eq. 7. The median of Q is the Sen's slope estimator.

$$Q_i = \frac{x_j - x_k}{j - k}, \quad i = 1, 2, \ldots N; \quad 1 \leq j \leq n-1; \quad j \leq k \leq n. \tag{7}$$

4.2 The HY-INT trend

Even though HY-INT is not a linear function of INT and DSL, the long-term trend slope of HY-INT is a function of the trend slopes of INT and DSL. Equivalently, one can estimate it from the time series of HY-INT. Taking the time derivative of Eq. 1 one gets

$$\frac{d\text{HY-INT}}{dt} = \text{INT}\frac{d\text{DSL}}{dt} + \text{DSL}\frac{d\text{INT}}{dt}. \tag{8}$$

And because all the variables are scaled, what one needs is the logarithmic derivative

$$\frac{1}{\text{HY-INT}}\frac{d\text{HY-INT}}{dt} = \frac{1}{\text{DSL}}\frac{d\text{DSL}}{dt} + \frac{1}{\text{INT}}\frac{d\text{INT}}{dt}. \tag{9}$$

Therefore the temporal trend slopes satisfy

$$m_{HY-INT} = m_{INT} + m_{DSL}. \tag{10}$$

5 RESULTS

Neglecting data autocorrelation in trend analysis increases the probability of error in the Mann-Kendall test result (Kulkarni and von Storch, 1992; von Storch, 1995). We compared the results of the classic MK test and the MK test for autocorrelated data proposed by Hamed and Ramachandra-Rao (1998) in our 1629 series data set, and conclude that ignoring the auto-correlation may lead to false trends of the order of 20% of the gauges, and false no trends in of the order of 10% of the gauges.

Table 1 presents in each row the four elements of the confusion matrix for the Mann-Kendall test that does not take into account auto-correlation in comparison with the one that does. We take this last one as the correct method for the comparison. The most significant error (from 18 to 25%) comes from false trends. However, there are also errors due to false no trends (from 11 to 15%). As a result, the accuracy (total number of hits) is between 60 and 71%. It is always recommended to take into account the auto-correlation of the series to evaluate the significance of trends.

We also considered the possible implication of the definition of the year. Besides the calendar year, we considered a hydrology year starting on April 1st. The idea was that the end of the calendar year might

Table 1. Confusion matrices for the evaluation method of the significance of the trends for each of the indicated variables without taking into account auto-correlation. For the purpose of the illustration the Mann-Kendall test with auto-correlation is considered the true one.

Variable	true trend	false trend	false no trend	true no trend
	R-R	R-NR	NR-R	NR-NR
	Number of gauges (Percentage of the total number of gauges)			
P	45 (3%)	293 (18%)	180 (11%)	1111 (68%)
INT	116 (7%)	400 (25%)	245 (15%)	868 (53%)
DSL	62 (4%)	316 (19%)	184 (11%)	1067 (66%)
HY-INT	108 (7%)	393 (24%)	212 (13%)	916 (56%)

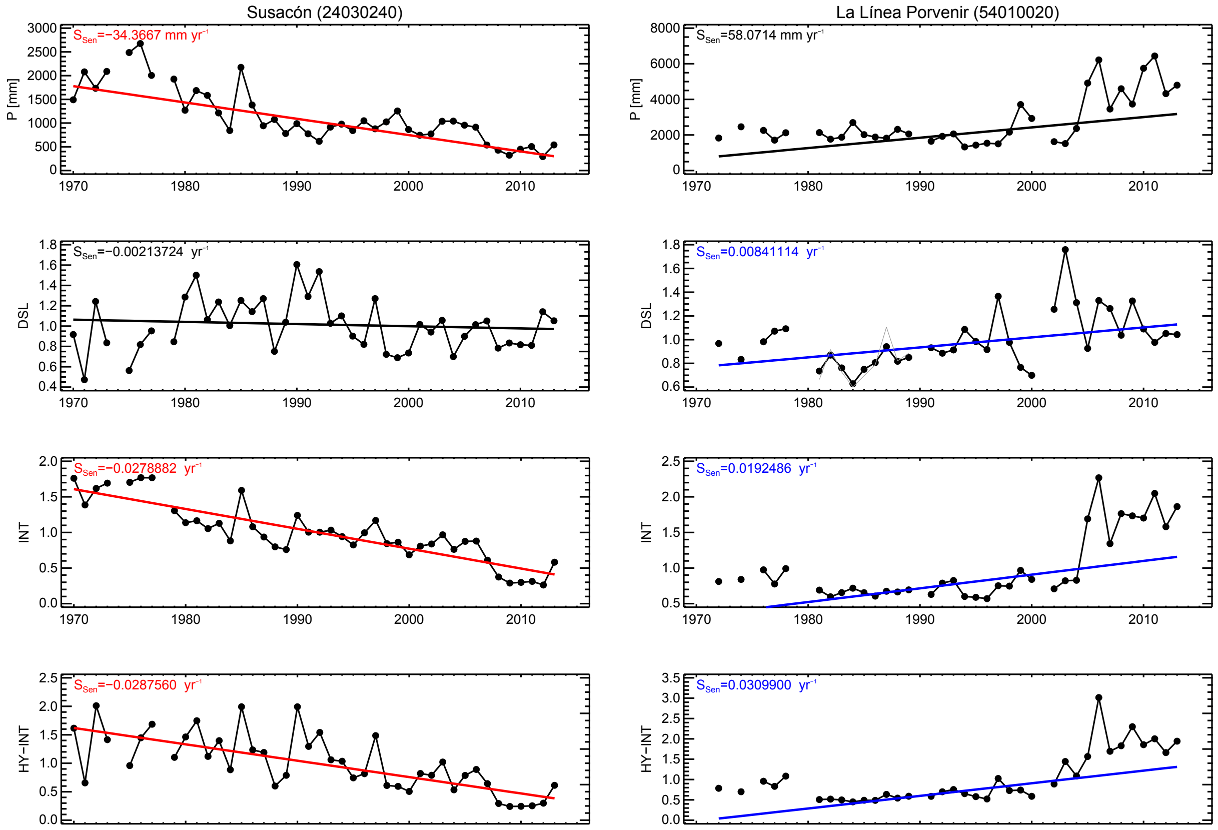

Figure 2. Two examples of trend analysis for (top to bottom) P, DSL, INT and HY-INT for two representative stations. Left: Susacón in Boyacá, at 2550 masl. Right: La Línea El Porvenir in Risaralda, at 1955 masl.

split the longest dry spell. Because the dry season usually starts in mid-December and ends in March in Colombia. However, as we show below, the dominant fact for the significant trends is an increase in the number of wet days (70%), not the length of the dry season.

Figure 2 illustrates two of the 1629 cases of the trend analysis. Notice the treatment of the missing years that may come for any missing day. For the Susacón gauge in the left part of the Figure, the trends in P, INT, and HY-INT are decreasing and statistically significant. However, the trend in DSL is not. For La Línea El Porvenir station in the right side of the Figure DSL, INT, and HY-INT have significant positive trends, whereas P has an increasing non statistically significant trend.

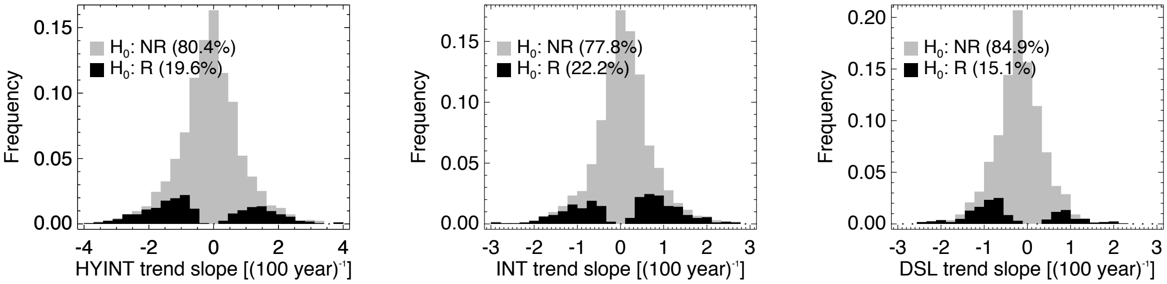

Figure 3. Histograms of the HYINT (left), INT (center) and DSL (right) trend slopes of the 1629 rain gauges used. Non significant trends (H_0: Stationary hypothesis not rejected, NR) in grey and significant trends in black (H_0: Stationary hypothesis rejected, R).

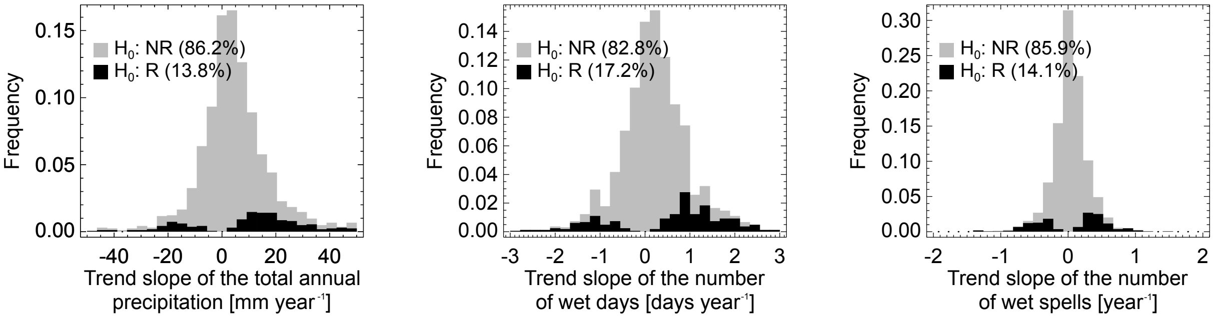

Figure 4. Same as Figure 3 for the trend slope of the total annual precipitation (left), the number of wet days in the year(center) and number of wet spells in the year(right).

Table 2 summarizes the results of the trend analysis for the 1629 stations and the more relevant variables. The first observation is that only a minority of the stations show significant trends. Among the variables, INT shows the largest percentage of significant trends, but only reaching a 22.2% of the stations. The least percentage is for the variable DSLX with only 9.3%. A second observation is that the extreme variables do not show a larger percentage of significant trends in comparison with the corresponding average variables: For INTX the percentage is 9.3 in comparison with 22.2 for INT. Similarly, for DSLX is 9.3 in comparison with 15.1 for DSL; and for HYINTX is 9.4, whereas for HY-INT it is 19.6. Among the stations with statistically significant trends, the analysis of positive and negative trends is interesting. There is a clear majority among the significant ones for positive trends for P, the number of wet days, LW, Number of both dry and wet runs, INTX, and INT. Similarly, there is a majority of a significant negative trend for DSLX, HYINTX, number of dry days, DSL, and HY-INT.

Only 40% of the significant HY-INT stations have a positive trend, even though one of its factors, INT, has a majority of positive trends (57%) among the significant ones. However, that percentage reduces to 43% among the ones with significant HY-INT trend. The other reason is the sign of the trends in DSL, 69.1% negative among significant DSL trends. This percentage only is reduced to 61% when one considers stations with significant HY-INT trend. Besides, the histograms of the slopes of the trends in Figure 3 illustrate well this point. Therefore for Colombia's humid climate HY-INT, the indicator proposed by Giorgi et al. (2011) to measure the strength of the hydrologic cycle, only makes sense partially concerning INT, but not for dry spells. Because, they are not increasing in length significantly, not even among the small number of stations with significant trends that on the contrary are getting shorter for the average dry run and more so for the extreme ones.

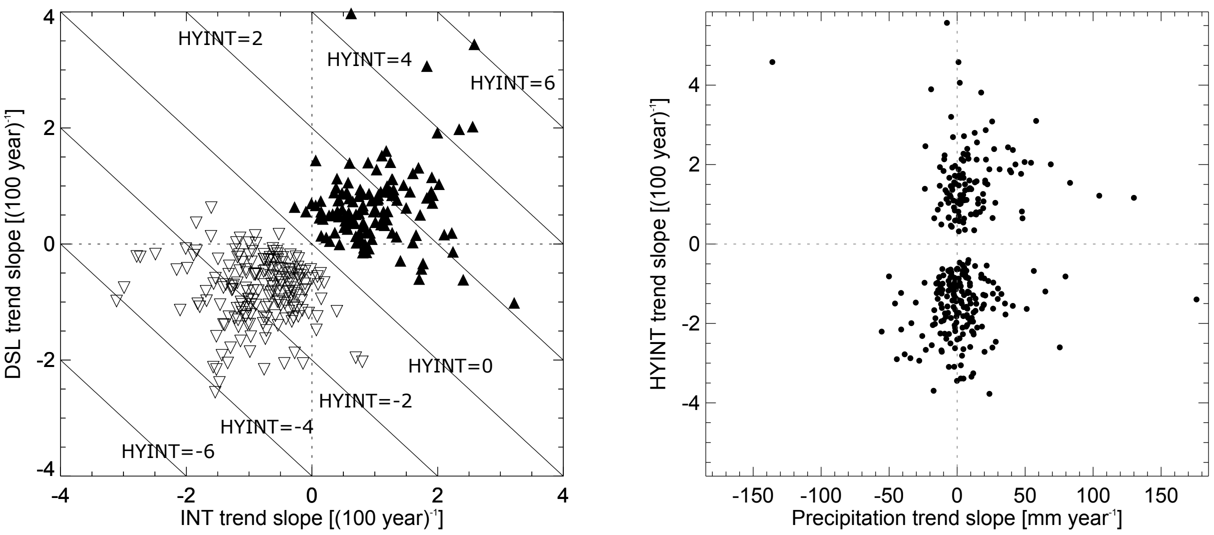

Figure 5. Left: Dispersion diagram of the DSL trend slope vs. INT trend slope for all stations with significant HY-INT trend slope. Notice that because of Eq 10 the trend slope of HY-INT is the sum of the trend slopes of INT and DSL. This equation explains the slanted iso-lines for the HY-INT trend slope. Right: Dispersion diagram of the HY-INT trend slope vs. precipitation trend slope for all stations with significant HY-INT trend slope

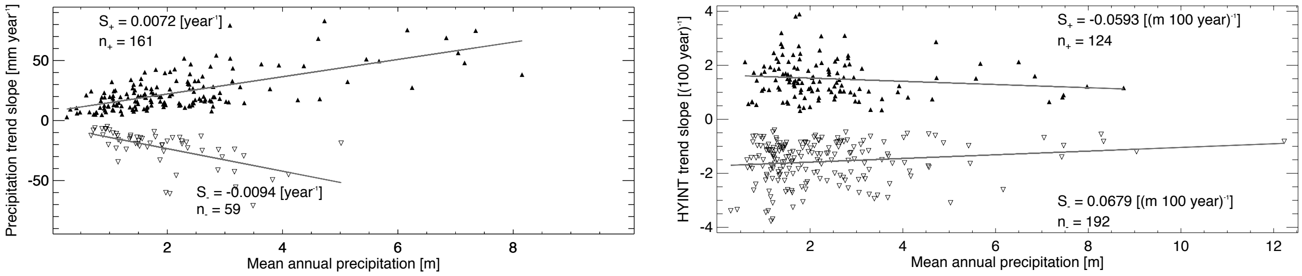

Figure 6. Precipitation trend slope vs. mean annual precipitation (A) and HY-INT trend slope vs. mean annual precipitation (B) for the stations with significant trend. n_+ and n_- are number of stations with positive (negative) slope. S_+ and S_- are the corresponding slopes.

Figure 4 shows the histograms of the trend slopes for P, the number of wet days and the number of wet spells. Again, the majority of the stations do not have significant trends. However, among the significant ones, there is a clear majority of positive trends.

Figure 5 allows further analysis of the result about HY-INT discussed above. Notice that almost all stations with positive trend slope for HY-INT have positive trend slopes for both INT and DSL. Conversely, almost all with negative trends for HY-INT have negative trends for INT and DSL. Therefore, most of the points in the figure are in either the first or the third quadrant (89%). Of the 320 stations with a significant trend in HT-INT, 124 and 170 do not have significant trends for INT and DSL respectively.

Figure 5 also shows the relation between the trend slopes for P and HY-INT. There are two groups of stations also, depending on the sign of the HY-INT trend. However, among both, there are positive and negative trends in P.

For the significant trends, the magnitude of the trends seems to be related linearly with P, see Figures 6A and 6B. This tendency is more clear for the P trend than for the HY-INT trend. The magnitude of the P

Table 2. Basic statistical analysis of the significant trends of the different variables using the calendar year and taking into account autocorrelation: P: Total Annual Precipitation, INT: averaged scaled intensity on wet days, DSL: averaged scaled dry run length; HYINT=INT× DSL; N stands for number; LW: averaged scaled length of wet runs. In addition extreme variables are computed for the hydrologic year (April 1st to March 31): INTX: the maximum daily intensity; DSLX: the maximum dry run length; HY-INTX=INTX× DSLX; and LWX: The maximum wet run length. Column symbols: N Rej is the number of stations for which the null hypothesis of no trend was rejected; % Rej/T is the percentage of total stations that rejected the test; N Positive is the number of stations with significant positive trend; and finally % Pos/Rej is the percentage of those with positive trend among the ones with significant trend.

Variable	N Rej	% Rej/T	N Positive	% Pos/Rej
P	225	13.8	165	73.3
INT	361	22.2	206	57.1
DSL	246	15.1	76	30.9
HY-INT	320	19.6	128	40.0
N Wet Days	281	17.2	200	71.2
N Dry Days	282	17.3	80	28.4
LW	286	17.6	183	64.0
N Wet Runs	229	14.1	134	58.5
N Dry Runs	235	14.4	144	61.3
INTX	148	9.3	85	57.4
DSLX	148	9.3	29	19.6
HYINTX	149	9.4	39	26.2
LWX	228	14.4	146	64.0

trend slope increases with precipitation irrespective of the sign. Whereas for the HY-INT case, positive trend slope decreases with P and the negative slope increases.

As expected from the small number of stations with significant trends, the space distribution does not seem to show any pattern. Maps in figure 7 show in the location of each station the sign of the trend in HY-INT, INT, DSL, and P. Nevertheless, Table 3 shows that though the percentage of stations with a significant trend is small, there is a majority of positive trends for total annual precipitation overall (73%) and an overwhelming majority in the Pacific (94%) and Caribbean (91%) regions. These results accord with previous studies for the Pacific region. For the Caribbean region, the results show a trend in the opposite direction to the predictions of GCM's (see section 2).

Bearing in mind that only a fraction (10 to 20%) of the stations show statistically significant trends, among the significant ones the Pacific region exhibits differences with the overall behavior. For the HY-INT variable, the percentage of significant trends is 32% whereas overall is only 20% and the percentage of increasing trends goes from 40% (overall) to 50%. For the INT variable, the corresponding figures go from 57% to 74%. Similarly, for the number of wet spells, the percentage of increasing trends among the significant ones goes from 59% overall to 67% for the Pacific region. For the number of wet days in the year, the percentage of significant trends is 27% whereas overall is only 17%. Moreover, for DSLX the significant negative trends go from 80% to 93%. Together with the observation about total annual precipitation, these changes indicate that the region tends to a more humid condition.

For the rest of the regions, the significant trends in HY-INT are not notably different from the total. Except for the Orinoco region that we analyze below.

Besides the changes in P mentioned above, for the Caribbean region, the percentage of increasing trends among the significant trends differs from the overall in the number of wet spells (59% overall vs. 76%) and

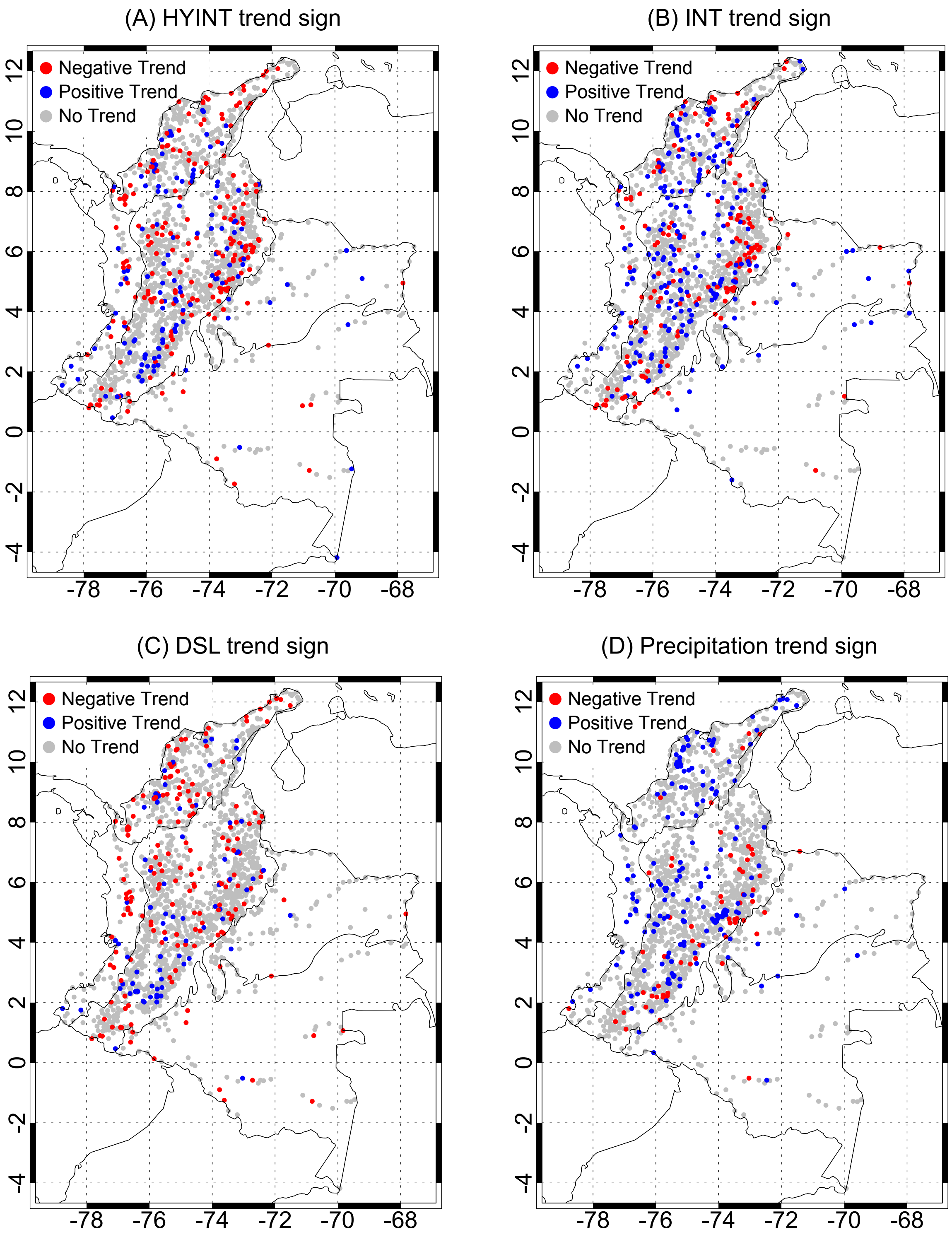

Figure 7. Maps of the trend sign for HY-INT (A) and INT (B), DSL (C) and P (D). Significant positive (increasing) trends in blue, negative (decreasing) trends in red and no significant trends in gray.

the INT variable (57% overall vs. 63%). With the caveat of the low number of stations with statistically significant trends, these results also point in the direction of a wetter region.

For the Amazon region, the variables with different behavior than the overall are in the decreasing trends of DSL (69% overall vs. 92%) and DSLX (80% overall vs. 94%). That means that the lengths of dry spells are getting shorter.

The Orinoco region has few stations and much fewer significant trends. Among those the variables HY-INT, number of wet days, and the number of wet spells show notorious differences in the percentage of increasing trends with the countrywide numbers: 40 vs. 55%, 71 vs. 47%, and 59 vs. 64% respectively (Off each pair the first figure is for the whole country and the second one is for the region).

The Andes region has a substantial number of all the stations in the country, and therefore for all the variables, the behavior of each trend is close to the one of the whole country, except for the number of wet spells. For that variable, the percentage of positive trends among the significant ones is only 46% whereas the country average is 59%. This reduction is possible because for the other four regions the percentage increases.

Table 3. Regional summary of the trends of rain gauges for Total Annual Precipitation and HY-INT. Column symbols as in Table 2

Region	N Rej	% Rej/T	N Positive	% Pos/Rej
		Total Annual Precipitation		
Amazon	8	11	6	75
Andes	133	13	85	64
Caribbean	57	15	52	91
Orinoco	9	10	5	56
Pacific	18	24	17	94
Total	225	14	165	73
		HY-INT		
Amazon	16	21	5	31
Andes	188	19	74	39
Caribbean	81	21	31	38
Orinoco	11	13	6	55
Pacific	24	32	12	50
Total	320	20	128	40

Figure 8 shows the distribution of the record length of all the stations coding with gray the ones corresponding to a significant trend in HY-INT. The percentage of stations with significant trend out of the total number of stations in each record length bin does not change significantly except at the tails. In other words, the probability that the HY-INT trend of a given station is statistically significant is pretty much uniform as a function of the record length. This observation indicates that for the set of rain gauges analyzed the record length does not explain the lack of significant trends. On the contrary, the reason for the limited number of significant stations with significant trend needs other explanation.

We also looked into the possible dependence of trend slopes on latitude, longitude, elevation, and seasonality of the annual regime of precipitation. However, there were not any pattern worth mentioning.

6 DISCUSSION

Our results about the trends in annual precipitation agree in some way with the previous studies reported in Section 2 that considered rain gauges: Increasing trends prevail over decreasing trends among the

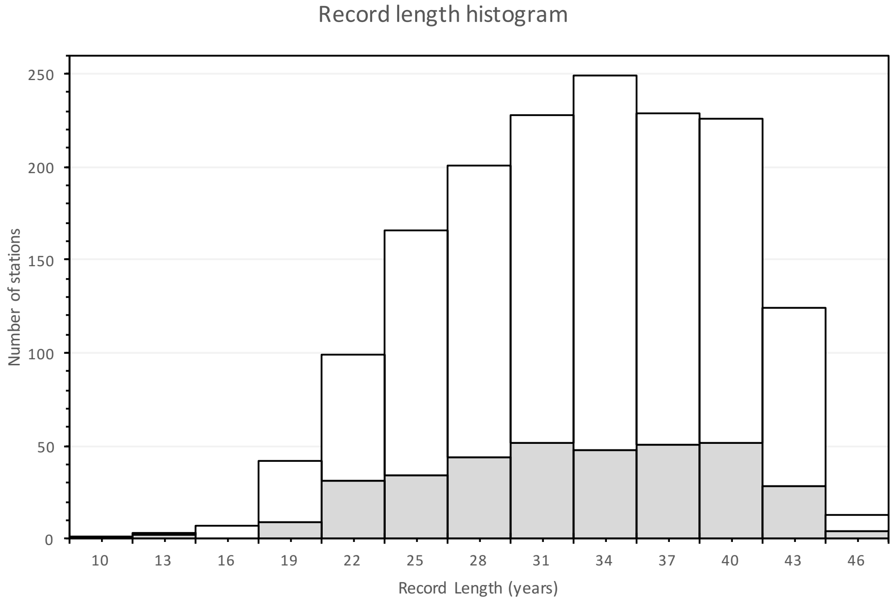

Figure 8. Histogram of the the record length (number of complete years) of the 1629 rain gauges used in this study. Stations with significant trend for HY-INT in gray.

statistically significant ones. However, we found a large number of stations with no significant trends. Probably the number of stations we considered explain these differences.

The principal result of this work is that the existing records of precipitation in the rain gauge network of Colombia do not show a clear signal of statistically significant trends. Only approximately 20% of the gauges present significant trends. This observation is valid for all the variables we studied, even with a lower percentage of significant trends for some of the variables. Given the overwhelming evidence of global climate change, this result claims for an explanation.

Also, the lack of a space pattern for the trends in the Andes is another evidence that is striking. The few stations with significant trends are mixed in space with nearby gauges with no significant trend or even significant trend of the opposite sign.

One possibility is to blame short records. Although one wishes to have longer records, this does not seem to be a good explanation. The percentage of significant trends out of the number of gauges in a given bin of record length remains approximately constant.

One factor that may play a role is the irregularity of the precipitation field.

The humid tropical climate of Colombia is probably a factor for the explanation. However, (Stevens et al., 2013) has argued that changes in precipitation need to be coupled with changes in the global circulation. The sole increase in absolute moisture is not sufficient to change the amount of precipitation, at least in an average sense. In that sense, there are no reports of changes in the trade winds or the low-level jets that bring moisture to Colombia, except for the Chocó jet.

The issue of changes in ENSO due to climate change is a big area of debate, see for instance Kohyama and Hartmann (2017). Some argue that with global warming ENSO could become more frequent and intense, but others that it could become weaker or more located on central rather than eastern Pacific. The effect of ENSO over Colombia is to produce dryer weather. Therefore the issue is very relevant to elucidate the effects of climate change over Colombian precipitation. In that sense, our results seem to suggest that ENSO is not becoming more intense or frequent. Also, the fact that majority of significant trends for total annual precipitation is positive for the Pacific region accords with the nonlinear ENSO warming suppression and a possible strengthening of the Chocó jet.

Other result is about the HY-INT index of Giorgi et al. (2011) to quantify the intensity of the hydrologic cycle. For many parts of the globe, it may be true that rainfall intensity and dry spell length are deeply interconnected. However, our results suggest that it is not the case for a humid tropical climate like Colombia's. At least for the few gauges with significant trends the two factors in the definition of HY-INT, rainfall intensity and dry spell length do not necessarily go together. For instance, of the 57% (205 out of 361) of the station with significant INT trend have a positive trend; but of those, 45% have positive DSL trend and 55% negative one (92 and 113 respectively).

We wanted to complement HY-INT, the indicator of the intensity of the hydrologic cycle, by defining an extreme version, HYINTX, the product of the maximum daily rainfall times the maximum dry spell length. For Colombia, this indicator did not give any good results. Even they were weaker than the original HY-INT indicator. One reason for this failure seems to be that dry spell length tends to decrease even though the trend in maximum intensity is positive.

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