Trends in rainfall and temperature in the Peruvian Amazon-Andes basin over the last 40 years (1965-2007).

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Abstract

The hydroclimatology of the Peruvian Amazon-Andes basin (PAB) which surface corresponds to 7 % of the Amazon basin is still poorly documented. We propose here an extended and original analysis of the temporal evolution of monthly rainfall, mean temperature (Tmean), maximum temperature (Tmax), and minimum temperature (Tmin) time series over two Peruvian Amazon-Andes basins (Huallaga and Ucayali) over the last forty years.

This analysis is based on a new and more complete database that includes 77 weather stations over the 1965-2007 period and we focus our attention on both annual and seasonal meteorological time series. A positive significant trend in mean temperature of 0.09°C per decade is detected over the region with similar values in the Andes and Rainforest when considering average data. Though, a high percentage of stations with significant Tmean positive trends are located over the Andes region. Finally, changes in the mean values occurred earlier in Tmax (during the 1970s) than in Tmin (during the 1980s).

In the PAB, there is neither trend nor mean-change in rainfall, during the 1965-2007 period. However, annual, summer and autumn rainfall in the southern Andes presents an important interannual variability that is associated with the sea surface temperature (SST) in the tropical Atlantic Ocean while there are limited relationships between rainfall and ENSO events. On the contrary, the interannual temperature variability is mainly related to ENSO events.

Key words: Amazon basin, hydroclimatology, rainfall and temperature trend, climate change, Peru, ENSO, Atlantic SST.

INTRODUCTION

This paper presents an analysis of recent climate changes over the Peruvian Amazon-Andes basin (PAB) based on a new extended climatological database.

The PAB is located in the western part of the Amazon basin and is very contrasted, being limited by steep and tall (up to 6000 m a.s.l.) mountain ranges to the west and by relatively flat lowland plains to the East (80 m a.s.l.). Though changes in physical, geochemical and biologic parameters may be progressive in between, two regions are usually distinguished topographically by the 500 m a.s.l isohypse not only by Peruvian geographers and naturalists (Pulgar-Vidal, 1998 and Brack and Mendiola, 2004) but also by international organisms such as UNESCO (2006): the Andes (~ over 500 m a.s.l.) and the Rainforest (~ below 500 m a.s.l.).

Trends studies in the Amazon basin mainly focus on the Brazilian region (Marengo et al., 1998, Costa and Foley, 1999, Marengo, 2004 among others); while few studies are dedicated to the PAB. The last ones are often based on a small number of stations and on observations regarding short periods of time. For instance, Gentry and Lopez-Parodi (1980) identified significant rainfall decrease in 3 out of 8 PAB weather stations during the 1970-1978 interval (compared to the 1961-1969 reference period) and associated these differences with deforestation. Their results were then discussed by Nordin et al. (1982) who found positive water levels trends in Iquitos and Pucallpa stations during the 1955-1979 and 1957-1981 periods respectively. More recently, comprehensive studies have been realized in the Andean regions of PAB in the mark of glacier evolution. Vuille and Bradley (2000) using the Global Historical Climatology Network data show a warming trend in the tropical Andes of 0.10–0.11 °C per decade between 1939 and 1998, and of 0.32–0.34 °C per decade between 1974 and 1998 that corresponds to a tripling of the warming rate during the last 25 years.

Vuille et al. (2003), based on in situ and Climate Research Unit (CRU) data collected over the 1950-1994 interval, put in evidence similar trends in temperature and a non-significant rainfall trend over the PAB, the only exception being southern Peru where there is a general tendency toward slightly drier conditions.

In our contribution, we will focus our attention on two large and representative basins of the PAB region: the Ucayali and Huallaga basins (figure 1).Studying the high mountains of the Ucayali basin (i.e. the Mantaro basin), IGP (2005) outlines a decreasing rainfall trend of 3% per decade over the 1964-2003 interval, a positive trend of 0.2°C per decade for maximum temperature and no trend for minimum temperature during the 1965-2002 interval. Espinoza et al. (2006) describe a 8.3% per decade downward trend in mean rainfall over the 1970-1997 period in the Peruvian-Ecuadorian Amazon basin using 237 rainfall stations; this trend is corroborated by a similar one in the discharge of the Amazonas River at Tamshiyacu . Haylock et al. (2006) also identify a downward trend in annual precipitation for the 1960-2000 period in a meteorological station located in the Ucayali basin. In fact, strong rainfall and runoff diminution in western Amazonas are related to high values during the 1970s and to the extreme low values documented in the last decades (e.g. 1998; 2005 and 2010 drought c.f. Espinoza et al., 2011).

Also, temperature and rainfall fluctuations both depend on large-scale ocean-atmospheric indexes, such as the Southern Oscillation Index (SOI) in the Pacific Ocean and the SST in the Atlantic Ocean in many regions of tropical South America (Aceituno, 1988; Marengo, 1992 and more recently Ronchail et al., 2002, Marengo and Camargo, 2008, Espinoza et al 2009, Yoon and Zeng, 2010, Marengo et al. 2011a, Marengo et al. 2011b) and specifically in Peru (Tapley and Waylen, 1990; Rome-Gaspaldy and Ronchail, 1998, Kane, 2000; IGP, 2005, Espinoza et al. 2009 and Espinoza et al. 2011).

This study present the first detailed regional climate of a poorly documented region of the Amazon basin, in order to estimate rainfall trends and means change in rainfall and temperature. This analysis is then related statistically and physically to large-scale ocean-atmospheric indexes fluctuations, such as the Southern Oscillation Index (SOI) in the Pacific Ocean and the SST in the Atlantic and Pacific Ocean, in order to explain the climate variability. In particular, we aim to complement former works, especially the study by Vuille and Bradley (2000), Vuille et al. (2003), or Espinoza et al. (2009), but using a significantly higher number of rainfall stations than this last author (58 gauges here) also including, temperature station data (48 stations).

DATA AVAILABILITY AND METHOD

Our study focuses on the two main basins of Peru that are part of the Amazon basin: the Huallaga basin, with 75% of its total area located in the Andes region and 25% located in the Rainforest region, and the Ucayali basin, with 50% of its total area located in each region. Basins areas are respectively 89 654 km^2 and 350 287 km^2 (Fig. 1a), and the sum of both basins area corresponds to almost 7% of the entire Amazon basin. Basins subdivision is based on the Digital Elevation Model (DEM) provided by the National Aeronautics and Space Administration (NASA) through the Shuttle Radar Topography Mission (SRTM). SRTM data is available at 3 arc second (~ 90m resolution). A detailed description of this DEM can be found in Farr et al. (2007).

This study is based on data from 77 conventional meteorological stations (Table 1), included in the Peruvian National Meteorology and Hydrology Service SENAMHI network. Among the 77 weather stations, 58 stations provide rainfall data and 48 temperature data; 24 stations are located in the Huallaga basin and 53 are located over the Ucayali basin. Fig. 1b shows the spatial distribution of the 77 stations in the PAB region.

Rainfall and temperature (i.e. mean (Tmean), maximum (Tmax) and minimum (Tmin) temperature) data are available at monthly resolution from January 1965 to December 2007. A procedure for quality analysis in temperature data is first applied following the methodology developed by Vuille et al. (2000). After a visual detection of suspect outliers in monthly plots, box plot graphics are computed for suspect months; doubtful temperature values are those that exceed the third quartile plus three times the interquartile range. Suspect outliers values are compared to values of the corresponding period in nearby stations (over similar physiographic zone). The data is discarded only if a mismatch is detected through both criteria. Missing values including discarded data represent less than 5% of the total database. Missing values were filled by a multiple correlation method based on nearby geographical stations data. Rainfall data over the 1965-2003 period are validated using the Regional Vector Method (Hiez, 1977 and Brunet-Moret, 1979, Espinoza et al., 2009). The interpolation of the climatic variables is based on Kriging method through Hydraccess software (Vauchel, 2005). One should note that a high percentage of stations are located over the Andes region (44 for rainfall and 37 for temperatures) when compared to the Rainforest region (14 for rainfall and for 11 temperatures) and this may produce over or underestimation of rainfall or temperature when we focus on specific geographical zones, but this asymmetry does not affect the forthcoming local scale analyses.

As rainfall series are not always normally distributed, two statistical distribution-free tests are used in this work to identify trends and mean-changes in climate series (Robson et al., 2000):

- The Mann-Kendall (MK) non parametric trend test (Mann, 1945 and Kendall, 1975) described by Burn and Elnur (2002) as the most commonly used for detecting trends in climatic variables.

- the Pettitt (PT) non-parametric test (Pettitt, 1979) for mean-change detection in temporal series.

The significance level (α) is assumed to be the probability that a test detects non-null trend or mean-changes when none is present (Robson et al., 2000). In this study, the null hypothesis in statistical tests is rejected for α equal 0.05 (i.e. statistical significance at the 95% level). Temporal series are averaged over five periods: the year from January to December, austral summer (December-January-February noted DJF), autumn (March-April- May noted MAM), winter (June-July-August noted JJA) and spring (September-October-November noted SON).

Several regional climatic indexes were used: the monthly Southern Oscillation Index (SOI) that is the standardized pressure difference between Tahiti and Darwin, monthly SST data (1965–2007) for the northern tropical Atlantic (NATL, 5–20°N, 60–30 °W) and the southern tropical Atlantic (SATL, 0–20 °S, 30 °W–10 °E). The difference between the NATL and SATL is computed to feature the SST gradient in the Atlantic basin. All these indexes are from the Climatic Prediction Centre of the US National Oceanic and Atmospheric Administration. Then, the coefficients of correlation between climate time series and the index of the SOI, or the SST difference (NATL-SATL) are computed and the stations with significant correlations (α equal to 0.05) highlighted. Climate variability is also analyzed using the 2.5 x 2.5 degree resolution horizontal and vertical winds and humidity data from NCEP–NCAR reanalysis (Kalnay et al., 1996) to describe the atmosphere characteristics. These data were obtained from the NOAA data server. The vertically integrated water vapor flux is derived from the specific humidity and the horizontal wind between the ground and 300 hPa (Peixoto and Oort, 1992).

Since both basins are characterized by highly heterogeneous climatic conditions, the climatic evolution will be analyzed at a regional scale but distinguishing the Andes (over 500 masl) and the Rainforest (under 500 masl) and, we also provide a more local scale analysis.

REGIONAL CLIMATE

Most rainfall is produced by convection in the PAB region (Garreaud et al., 2003) and the moisture origin is predominantly the Atlantic Ocean and the Amazon basin (Fuenzalida and Rutllant, 1987; Vuille et al., 1998; Chaffaut et al., 1998; Garreaud, 1999; Garreaud et al., 2003; Vizy and Cook, 2007).

Annual cumulative rainfall is very high in the north and the centre of PAB, especially in the lowland regions with about 2235 mm/year (table 2). Rainfall decreases toward the western and southern mountainous regions (about 1025 mm/year), but local maximum and minimum rainfall due to topography and to the exposition of the stations are noticeable on figure 2. In particular, very high annual rainfall is recorded in valleys opened in the direction of North and therefore oriented toward the humid trade winds (for example 4160 mm/year are recorded in Aguaitia station in the Pachitea valleys on the high Ucayali, or along massive relief with a northward exposure). These values contrast with less rainy annual cumulative data over regions such as the high Huallaga valley located on a lee side and is consequently protected from moist air advection. This is consistent with Espinoza et al. (2009) who also found high rainfall gradients over this zone with for instance 6000 mm/year recorded at the San Gabán station and 530 mm /year recorded at the Paucartambo station , almost 110 km apart.

Rainfall tends to decrease when altitude increases but this relation appears as non linear (Figure 3c). Abundant rainfall at low altitude is related to the release of high quantity of water vapour over the first eastern slope of the Andes. On the contrary, annual rainfall is often less than 1000 mm per year above 500 meters. Similar results showing the absence of linearity between rainfall and altitude and the presence of a rainfall peak at low altitude have been described in the Amazon basin as a whole by Johnson (1976), Figueroa and Nobre (1990) and Espinoza et al. (2009) who find a peak at around 1000 masl. In Equator, the peak is located at around 700-800 masl by Laraque et al. (2007), as in Venezuela (Pulwarty et al. 1992) or Bolivia (Roche et al. 1990, Guyot 1993) but a little higher, around 1200masl, in the Zongo valley in Bolivia (Ronchail and Gallaire 2006). These altitudes that strongly depend on the location of the rain gauge stations are generally lower than that the value proposed by Bookhagen and Strecker (2008) using TRMM data, i.e. 1300 masl.

Seasonal rainfall values in the whole region of study represent around 38%, 28%, 11%, and 24% of the annual values considering summer, autumn, winter and spring respectively (table 2). Two regimes coexist over the Huallaga and Ucayali basins (see Espinoza et al., 2009). The first one is a south tropical and mountainous regime with a dry season from May to September and a wet season from December to March (Figure 4c). The marked seasonality is related to the warming of the continent and to the onset of the South American Monsoon System (SAMS) that drives water vapour toward the Amazon basin in austral summer and to its demise in winter (Zhou and Lau, 1998). These features are also coupled in the Andes together with the presence of the upper level Bolivian High and of easterly winds that allow the uplift of moisture from the Amazon towards the upper Andes (Garreaud 1999). The second regime is observed in low and northern regions close to the Equator. It corresponds to a lower impact of the onset and of the demise of the SAMS and to a quasi-permanent heating and moisture availability that explain less rainfall seasonality with a very rainy period from January to April and a drier one from June to October (Figure 4e).

The temperature spatial fluctuations appear in direct relationship with elevation and highlight an east –west and north-south gradients not directly related to latitude. The highest temperature values (more than 25°C for the mean annual temperature) are recorded along the eastern boundaries with Brazil while the lowest are measured in the south-western and southern high Andes. The most severe spatial gradients correspond to Tmin fluctuations and temperature is much lower in the Andes during the night than during the day (Figure 2c and

2d, figure 4c and table 2). This leads to a more pronounced temperature gradient considering Tmin (about -0.54°C per 100 m, figure 3d) than Tmax variations (about - 0.48°C per 100 m, figure 3c). The stronger Tmin temperature gradient may be related to the important radiative drop in temperature in the Andes, especially in winter, where the sky remains often clear whereas it is always somewhat cloudy in the lowlands (figure 4d). On the contrary, the differences in nebulosity may explain that Tmax data differ less between Andes and lowlands. These differences in nebulosity also explain that temperature daily amplitude is lower in the lowlands (about 10° C) than in the Andes (about 15° C) (figures 4d and 4f).

The Tmax and Tmin variables do not significantly vary during the year in the lowland (Figure 4f) and the annual amplitude (about 1°C) is much lower than the daily amplitude, as usually observed in tropical regions (Table 2). This is also observed for Tmax flucutations in the Andes. Indeed, in austral summer, the rainy season, the nebulosity avoids an intense radiation and temperature elevation, while, on the contrary, in winter which is the dry season, the lack of nebulosity allows a good solar irradiation and heating. However, the highest Tmax values are observed in October and November, after the sunny but "cold" winter and before the rainy and cloudy season. The annual amplitude of Tmin is more pronounced in the Andes (about 4°C) than in the lowlands (about 1.5°C), because of the different radiative characteristics that have been commented before. All, these results are consistent with less cloud cover density in the Andes than in the lowlands and during winter than during summer, and finally during night time than during day time.

TEMPORAL TRENDS IN PRECIPITATION AND TEMPERATURE

The existence of trends and mean-change in temperature records at regional scale, over the 1965-2007 interval, is examined using Mann Kendall and Pettitt respectively with a statistical significant level of 0.05. Results are reported in table 3 and the time series are plotted in the figure 5.

Regional rainfall series exhibit no trend. This is in accordance with Vuille et al. (2003) results that indicates that annual precipitation in the Andes of Peru during the 1950-1994 interval, 5 stations out of 42 (2) highlight significant increase (decrease) in the annual precipitation in the Andes of Peru during the 1950-1994 interval.

Annual Tmean time series exhibit in large majority positive significant trends over the whole region. The +0.09°C per decade trend value obtained for Tmean time series is similar to the value found by Vuille et al. (2003) for the eastern slopes of the Andes and it is in accordance with Bradley et al. (2009) who find an upward trend in the freezing line height (+0.1 °C per decade).

In the Andes, Tmax time series exhibit strong significant trends in summer (0.15°C/decade) and in spring (0.13°C/decade) while they are much lower considering Tmin fluctuations. In the Rainforest, Tmax increases only during winter. Tmin time series exhibit significant positive trends over the Rainforest region during all the seasons, but this positive trend is much more pronounced in summer (0.15°C/decade).

Moreover, the temperature variability in the Rainforest (table 3) is quasi systematically characterized by changes at the end of the seventies and the beginning of the eighties (+0.15 ºC of anomaly in 1981-1995 comparing to -0.2º C in the 1965-1980 for Tmax), while over the Andes, changes are not systematically synchronized and occur during the mid-seventies as well as latter on (+0.04 ºC anomaly during the 1981-1995 comparing to -0.2º C in the 1965-1980 for Tmax). This is partly in accordance with Vuille and Bradley (2000) who find a change in the mid-seventies for mean temperature in the Andes.

After this regional analysis, we propose a systematic analysis of the data from the 77 stations in order to highlight localized effects over this region.

Based on the Mann-Kendall test, figure 6 highlights the spatial distribution of stations with significant positive or negative trends in mean annual, summer, autumn, winter and spring rainfall. For all seasons, there are very few stations with a significant trend (see also table 4).

The spatial distribution of stations with significant trends in Tmean time series is depicted in Figures 7a, b, c, d and e. The number of stations that exhibit significant Tmean trends corresponds to 40 to 50% of the stations (~ 22 stations out of 48 stations), distributed all over the two basins (Table 4). Significant trends are mainly positive and their spatial distribution appears as similar when considering annual or seasonal series. They are widely spread in summer as they are put in evidence in 27 out of 48 stations (22 out of 37 in the Andes and 5 out of 11 in the Rainforest).

Positive trends are also observed in Tmax (17 out of 48 stations) and are also more frequent in summer (19 out of 48 stations), especially in the Andes, while they are less frequent in winter (9 out of 37 stations) (Figures 7f, g, h, i and j and table 4). In the Rainforest region, a few cases of negative trends are observed, especially in summer and winter. Similar remarks can be applied to Tmin but with a smallest percentage of positive trends in the whole region in winter (11 out of 48 stations) (Figures 7k, l, m, n and o).

Table 5 reports the percentage of stations with significant mean-change in rainfall and temperature time series, classified on four time intervals: 1965 to 1970, 1971 to 1980, 1981 to 1990 and 1991 to 2007. Mean-changes consisting in decreasing rainfall, are observed in a few stations (about 10%), mainly during the 1981-1990 interval in the Andes and during the 1991-2007 interval for annual series in both regions.

Tmean and Tmin time series exhibit significant mean-change mostly over the 1981-1990 interval (in about 30% of the stations) and also latter on, during the last period, for Tmin. On the other hand, mean-change in Tmax time series occurred sooner, mostly during the seventies (in 30% of the stations) and during the eighties. These different timings for Tmax and Tmin may be related to the diminution in humidity observed by Vuille et al. (2003)

during the second half of the XXth century. Indeed, a diminution in humidity favors insolation and day time temperature elevation while it acts in an opposite way during the night.

RELATION BETWEEN RAINFALL AND TEMPERATURE AND LARGE-SCALE OCEANIC INDEXES

The coefficients of correlation between rainfall or Tmean time series and the SOI, or NATL-SATL are computed and the stations with significant correlations (α equal to 0.05) are depicted in figure 8 and figure 9.

Rainfall appears as positively correlated with SOI in a small number of stations of the southern Ucayali basin (Andes region) especially during the rainy season, at the peak of El Nino events (see Fig. 8a, summer rainfall). These results suggest that rainfall is less abundant during El Niño events and more abundant during La Niña, in accordance with many authors who find that during El Nino, the western upper level circulation is reinforced, disturbing and reducing the uplift of moisture from the Amazon basin to the Andes (Aceituno, 1988; Tapley and Waylen, 1990; Rome-Gaspaldy and Ronchail, 1998; Vuille et al., 2000; Vuille et al. 2003; Silva et al. 2008; Lagos et al 2008, Espinoza et al., 2009, Lavado et al., 2012, Espinoza et al., 2012). However, in spring, this relationship is reversed in some intra-Andean stations of the extreme south of the studied region with more rainfall during El Niño events and less rainfall during La Niña events (see Fig. 8a spring rainfall). This signal has also been reported in the lowlands of Bolivian Amazon basin (Ronchail and Gallaire 2006) and is typically observed in the La Plata basin (see Aceituno, 1988 and many others since then).

Tmean time series appear as negatively correlated with SOI, especially at annual time scale and during summer and autumn seasons, in a large number of stations located in the central and northern Andes region. Tmean values are higher during El Niño events and lower during La Niña events as previously shown by various authors (Aceituno 1988, Vuille et al., 2003, among others.). Therefore, as the impact of ENSO on temperature is particularly strong in the Andes, the observed Tmean significant positive increase (figure 7) over the region may be associated with the stronger frequency of El Niño events since the end of the seventies (Trenberth and Hurell, 1994) together with a change in Pacific Decadal Oscillation (Mantua et al. 1997) (see Fig. 9a). It may also be related to the global warming due to the greenhouse gas concentration increase in the terrestrial atmosphere. Thought, using a model approach, Vuille et al. (2003) shows that a great part of the temperature elevation is due to the change in ENSO during the second half of the 20th century.

Rainfall time series appear as negatively correlated with NATL-SATL SST in a large number of stations located in the southern and south-western Andean regions of the Ucayali basin. Rainfall is more abundant when NATL SST is low compared to SATL SST and significant correlation between these variables is observed at annual time scale, in summer and in autumn (Figure 8b).

The SST and the water vapor flux differences between seasons with positive NATL-SATL anomalies and negative NATL-SATL anomalies are reported in figures 10a and 10b for DJF and figures 10c and 10d for MAM. They clearly show that when the northern tropical Atlantic is warmer than the southern (figures 10a and 10c), the water vapor flux anomaly is oriented toward the center of the Amazon basin and the Atlantic, meaning that the PAB receives a lower quantity of water vapor than usually and explaining a reduction in rainfall (Figure 10b and 10d). This has been also commented by Marengo et al. (2011a and 2011b) and Espinoza et al (2011) about recent hydrological extreme events in the Amazon basin.

In consequence, NATL-SATL SST fluctuations appear to be a more decisive forcing for rainfall fluctuation than SOI in the upper Andean basins of the Amazon in Peru. This is in accordance with Espinoza et al. (2011) who explain the recent extreme droughts in the Peruvian Amazonas River (1995, 1998, 2005 and 2010) and with Silva et al. (2008) for the

1970-2004 interval in the Mantaro Valley. Though, it is in opposition to what was concludes by Vuille et al. (2000) during the 1960-1990 interval.

The annual, summer and autumn Tmean fluctuations appear as positively correlated with NATL-SATL SST in the Andes. Temperatures are higher when the northern tropical Atlantic Ocean SST is warmer than usual and the southern tropical Atlantic Ocean SST is colder than usual (see Fig. 9b). This may be the result of drought and clear sky during warm event in the northern Atlantic that favor high temperature during the daytime.

However, considering the percentage of stations with significant correlation, SOI seems to have the most important influence on mean temperature fluctuations compared to NATL-SATL SST, in the Andes region, over the Huallaga and Ucayali basins.

CONCLUSIONS

The present contribution provides some information about the spatial variability of rainfall and temperature in the different regions of the Peruvian Amazon-Andes basin (PAB). This work also documents climate changes during the last 43 years (1965-2007).

A clear positive temperature trend is put in evidence over the last 40 years whereas no clear trend in rainfall is highlighted. The mean warming over the global region, Andes and rainforest, is about +0.09°C per decade and concerns about half of the stations. This estimation is close to the 0.10-0.11°C increase per decade reported by Vuille et al. (2003) for the 1939-1998 interval on the eastern slopes of the tropical Andes. It is higher than the estimations of the global warming (~ 0.07 °C per decade over the last 100 years, Christensen et al., 2007). The strongest increases occurred in summer. They are more pronounced in Tmax in the Andes and in Tmin in the Rainforest (1.5°/decade in both cases). Moreover, this elevation of temperature coincides with a change in the Pacific Decadal Oscillation in the mid-seventies and a change in the frequency of El Niño events (Trenberth and Hurell, 1994), which influence the temperature, especially in the Andes regions. In any case, these changes in temperature will have important consequences for eastern Andes glaciers and for communities located in high altitudes that rely on glacier-fed water (IGP, 2005 and Bradley et al., 2006).

There is neither trend in rainfall, nor mean-change in the PAB during the 1965-2007 interval. Only 10 % of the stations at regional scale exhibit a mean-change characterized by a decrease in rainfall, since the eighties in the Andes and the nineties in the rainforest. As Espinoza et al. (2006) and recently Lavado et al. (2012) find a strong decrease in rainfall and discharge in the downstream Amazonas River basin at Tamshiyacu, it seems that other Peruvian basins, such as the northern Marañón basin, may also reflect the signal of rainfall diminution.

However, rainfall also fluctuates at interannual time scale and this variability, at least in the southern part of the Ucayali basin, is poorly related to ENSO but essentially associated in summer and at the end of the rainy season with the SST gradient variability in the tropical Atlantic. As Vuille et al. (2000) did not find the same results for the 1960-1990 interval, it can be noticed that the relationships between rainfall and oceanic indicators may vary through time. This work opens to promising future developments for the comprehension of climate features in the PAB.

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Table 1 Characteristics of the stations: Name, Code reported in figure 1b, Geographical location, basin and measured variables at the weather stations. (R: Rainfall; T: Temperature.)

Weather Station	Code	Latitude (°S)	Longitude (°W)	Altitude (m a.s.l.)	Basin	Variable
Cerro De Pasco	1	-10.694	-76.254	4260	Huallaga	R
Yanahuanca	2	-10.491	-76.508	3170	Huallaga	R
San Rafael	3	-10.322	-76.169	2600	Huallaga	R,T
Huanuco Cayhuayna	4	-9.966	-76.237	1947	Huallaga	R,T
Chavin	5	-9.586	-77.176	3160	Huallaga	R
Tingo Maria	6	-9.288	-76.000	686	Huallaga	R,T
Aucayacu	7	-8.600	-75.934	600	Huallaga	R
Sihuas	8	-8.567	-77.650	2716	Huallaga	R
Tocache	9	-8.184	-76.500	508	Huallaga	R,T
San Marcos	10	-7.322	-78.169	3200	Huallaga	R
Juanjui	11	-7.175	-76.734	280	Huallaga	R,T
Augusto Weberbauer	12	-7.152	-78.491	2536	Huallaga	R
Bellavista	13	-7.051	-76.559	247	Huallaga	R,T
Sauce	14	-6.694	-76.203	620	Huallaga	R
El Porvenir	15	-6.593	-76.322	230	Huallaga	R,T
Tarapoto	16	-6.513	-76.372	282	Huallaga	T
Lamas	17	-6.424	-76.525	920	Huallaga	R,T
Navarro	18	-6.356	-75.779	190	Huallaga	R
Chachapoyas	19	-6.203	-77.881	2490	Huallaga	T
Rioja	20	-6.034	-77.169	880	Huallaga	T
Moyobamba	21	-6.000	-76.967	860	Huallaga	R,T
San Ramon	22	-5.949	-76.085	184	Huallaga	R
Jamalca	23	-5.898	-78.237	1200	Huallaga	R
Yurimaguas	24	-5.894	-76.118	187	Huallaga	R,T
Caylloma	25	-15.184	-71.767	4420	Ucayali	T
La Angostura	26	-15.180	-71.649	4150	Ucayali	R,T
Yauri	27	-14.817	-71.417	3927	Ucayali	R
Pampahuasi	28	-14.484	-74.250	3650	Ucayali	R
Santo Tomas	29	-14.399	-72.089	3253	Ucayali	R
Chalhuanca	30	-14.393	-73.179	3358	Ucayali	R
Sicuani	31	-14.254	-71.237	3574	Ucayali	R,T
Combapata	32	-14.100	-71.433	3464	Ucayali	T
Paucaray	33	-14.051	-73.644	3250	Ucayali	R
Acomayo	34	-13.917	-71.684	3160	Ucayali	R,T
Paruro	35	-13.768	-71.845	3084	Ucayali	T
Andahuaylas	36	-13.657	-73.371	2866	Ucayali	R,T
Vilcashuaman	37	-13.644	-73.949	3590	Ucayali	R
Ccatcca	38	-13.610	-71.560	3729	Ucayali	T
Granja Kcayra	39	-13.557	-71.875	2360	Ucayali	R,T
Curahuasi	40	-13.553	-72.735	2763	Ucayali	R,T
Cusco	41	-13.537	-71.944	3399	Ucayali	T
Paucartambo	42	-13.324	-71.591	3042	Ucayali	R,T
San Rafael	43	-13.321	-74.169	2600	Ucayali	R
Urubamba	44	-13.311	-72.124	2863	Ucayali	R,T
Tunel Cero	45	-13.254	-75.085	4700	Ucayali	R

Machu Picchu	46	-13.167	-72.546	2563	Ucayali	R,T
Wayllapampa	47	-13.068	-74.220	2500	Ucayali	T
La Quinua	48	-13.034	-74.135	3232	Ucayali	R,T
Lircay	49	-12.983	-74.729	3150	Ucayali	R,T
Quillabamba	50	-12.856	-72.692	990	Ucayali	R,T
Huancavelica	51	-12.779	-75.034	3676	Ucayali	T
Paucarbamba	52	-12.467	-74.567	3000	Ucayali	R
Pilchaca	53	-12.406	-75.085	3570	Ucayali	T
Laive	54	-12.252	-75.355	3990	Ucayali	R,T
Huayao	55	-12.034	-75.339	3308	Ucayali	R,T
San Lorenzo	56	-11.850	-75.384	300	Ucayali	T
Jauja	57	-11.779	-75.474	3322	Ucayali	R,T
Comas	58	-11.745	-75.118	3300	Ucayali	R
Ricran	59	-11.542	-75.525	3500	Ucayali	R
Marcapomacocha	60	-11.405	-76.325	4479	Ucayali	R,T
Tarma	61	-11.389	-75.695	3000	Ucayali	T
Huasahuasi	62	-11.254	-75.627	2737	Ucayali	R
Satipo	63	-11.220	-74.627	607	Ucayali	R
Puerto Ocopa	64	-11.136	-74.254	788	Ucayali	T
San Ramon	65	-11.117	-75.334	904	Ucayali	T
Pichanaky	66	-10.966	-74.830	547	Ucayali	R
Sepa	67	-10.817	-73.284	307	Ucayali	R
Oxapampa	68	-10.593	-75.390	1814	Ucayali	T
Pozuzo	69	-10.051	-75.559	798	Ucayali	T
Aguaytia	70	-9.034	-75.508	338	Ucayali	R
Tournavista	71	-8.932	-74.711	185	Ucayali	R,T
Pucallpa	72	-8.384	-74.576	160	Ucayali	R,T
Contamana	73	-7.353	-75.006	185	Ucayali	R,T
Juancito	74	-6.034	-74.867	150	Ucayali	R,T
Requena	75	-5.043	-73.836	128	Ucayali	R,T
Genaro Herrera	76	-4.900	-73.650	132	Ucayali	R
Tamshiyacu	77	-4.003	-73.161	141	Ucayali	R

Table 2 Mean (1965-2007) seasonal climate values for the entire zone, the Andes region (under 500 m a.s.l.) and the Rainforest region (above 500 m a.s.l.). Tmax.: Maximum Temperature; Tmin.: Minimum Temperature; Tmean.: Mean Temperature.

		Rainfall (mm)	Tmean (°C)	Tmax. (°C)	Tmin. (°C)
Total	Anual	1296.2	17.6	24.1	11.1
	Summer	490.7	18.2	23.9	12.5
	Autumn	357.3	17.7	23.9	11.5
	Winter	138.5	16.5	23.9	9.0
	Spring	309.7	18.1	24.8	11.4
Andes	Anual	1024.9	15.2	22.0	8.4
	Summer	427.4	15.9	21.6	10.1
	Autumn	275.6	15.3	21.7	8.8
	Winter	86.9	13.9	21.8	6.0
	Spring	235.0	15.8	22.7	8.8
Rainforest	Anual	2235.3	25.7	31.4	20.1
	Summer	709.7	26.0	31.4	20.6
	Autumn	640.0	25.7	31.0	20.4
	Winter	317.4	25.1	31.1	19.1
	Spring	568.3	26.1	32.0	20.2

Table 3 Rainfall and temperature linear trends (over the 1965-2007 period). Significant trends values using Mann-Kendall test (α at 0.05) are with asterisks (**). Values between brackets are years of mean-change using Pettitt test (α at 0.05).
Tmax.: Maximum Temperature; Tmin.: Minimum Temperature; Tmean.: Mean Temperature.

		Rainfall mm/decade	Tmean. °C/decade	Tmax. °C/decade	Tmin. °C/decade
Total	Annual	8.01	0.09**(1986)	0.11**(1976)	0.07**
	Summer	10.25	0.10**(1976)	0.12**(1976)	0.09**(1996)
	Autumn	4.64	0.09**	0.1	0.09**
	Winter	-2.3	0.07**	0.09	0.05
	Spring	-4.58	0.08**(1993)	0.12**(1993)	0.04
Andes	Annual	6.06	0.09**(1986)	0.12**(1976)	0.06**
	Summer	7.6	0.11**(1986)	0.15**(1976)	0.08**(1996)
	Autumn	3.76	0.10**	0.11	0.09
	Winter	-2.34	0.06	0.09	0.04
	Spring	-2.96	0.07**(1993)	0.13**(1993)	0.02
Rainforest	Annual	14.74	0.09**(1978)	0.07(1978)	0.11**(1981)
	Summer	19.4	0.08**(1976)	0.02	0.15**(1986)
	Autumn	7.7	0.08**(1979)	0.08	0.09**(1982)
	Winter	-2.16	0.09**(1981)	0.11**(1981)	0.08**(1981)
	Spring	-10.2	0.09**(1981)	0.08(1978)	0.11**(1981)

Table 4 Number of stations with significant trends using Mann-Kendall test (Pos.: positive and Neg.: negative), considering rainfall and temperatures series (1965- 2007) in the three analyzed zones. * Number of stations in each one of the zones. Gray boxes indicate no discernible percentage of stations (0 to 10%).

	Zones	Trend	Annual	Summer	Autumn	Winter	Spring
Rainfall	Regional	Pos.	3	4	3	2	0
	*58	Neg.	4	2	1	3	4
	Andes	Pos.	3	2	3	2	0
	*44	Neg.	2	2	1	2	1
	Rainforest	Pos.	0	1	0	0	0
	*13	Neg.	2	1	0	1	2
Temperature Mean	Regional	Pos.	23	27	20	19	19
	*48	Neg.	1	0	1	4	2
	Andes	Pos.	18	22	15	14	13
	*37	Neg.	1	0	1	3	2
	Rainforest	Pos.	5	5	5	5	6
	*11	Neg.	0	0	0	0	0
Temperature Maximum	Regional	Pos.	17	19	16	15	19
	*48	Neg.	4	3	3	3	3
	Andes	Pos.	13	17	12	9	15
	*37	Neg.	2	1	2	1	2
	Rainforest	Pos.	4	2	4	6	3
	*11	Neg.	2	2	1	2	1
Temperature Minimum	Regional	Pos.	18	21	17	11	15
	*48	Neg.	3	3	2	5	3
	Andes	Pos.	12	14	12	8	8
	*37	Neg.	3	3	2	4	3
	Rainforest	Pos.	4	4	4	2	2
	*11	Neg.	1	1	1	1	1

Table 5. Percentage of stations with significant year of mean-change for periods (α = 0.05) using Pettit test over the three analyzed zones. An: Annual; Su: Summer; Au: Autumn; Wi: Winter; Sp: Spring. Tmax.: Maximum Temperature; Tmin.: Minimum Temperature; Tmean.: Mean Temperature. For the number of stations in each one of the zones see Table 4. Gray boxes indicate no discernible percentage of stations (0 to 10%).

		Regional					Andes					Rainforest				
Variable	Period	An	Su	Au	Wi	Sp	An	Su	Au	Wi	Sp	An	Su	Au	Wi	Sp
Rainfall	1965-1970	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1971-1980	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0
	1981-1990	9	9	9	3	3	11	11	9	4	4	0	0	8	0	0
	1991-2007	14	7	2	10	5	13	7	2	11	7	15	8	0	8	0
Tmean.	1965-1970	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1971-1980	17	21	6	13	19	14	19	3	11	19	27	27	18	18	18
	1981-1990	29	23	31	21	13	30	24	30	19	11	27	18	36	27	18
	1991-2007	13	10	6	13	21	14	11	8	11	22	9	9	0	18	18
Tmax.	1965-1970	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1971-1980	27	27	25	17	10	22	30	19	14	3	45	18	45	27	36
	1981-1990	17	15	10	13	33	16	14	11	5	41	18	18	9	36	9
	1991-2007	10	15	4	10	10	8	11	0	8	5	18	27	18	18	27
Tmin.	1965-1970	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1971-1980	4	2	2	4	6	5	3	3	3	8	0	0	0	9	0
	1981-1990	33	35	27	29	21	30	30	22	32	16	45	55	45	18	36
	1991-2007	17	23	8	8	15	19	30	11	8	11	9	0	0	9	27

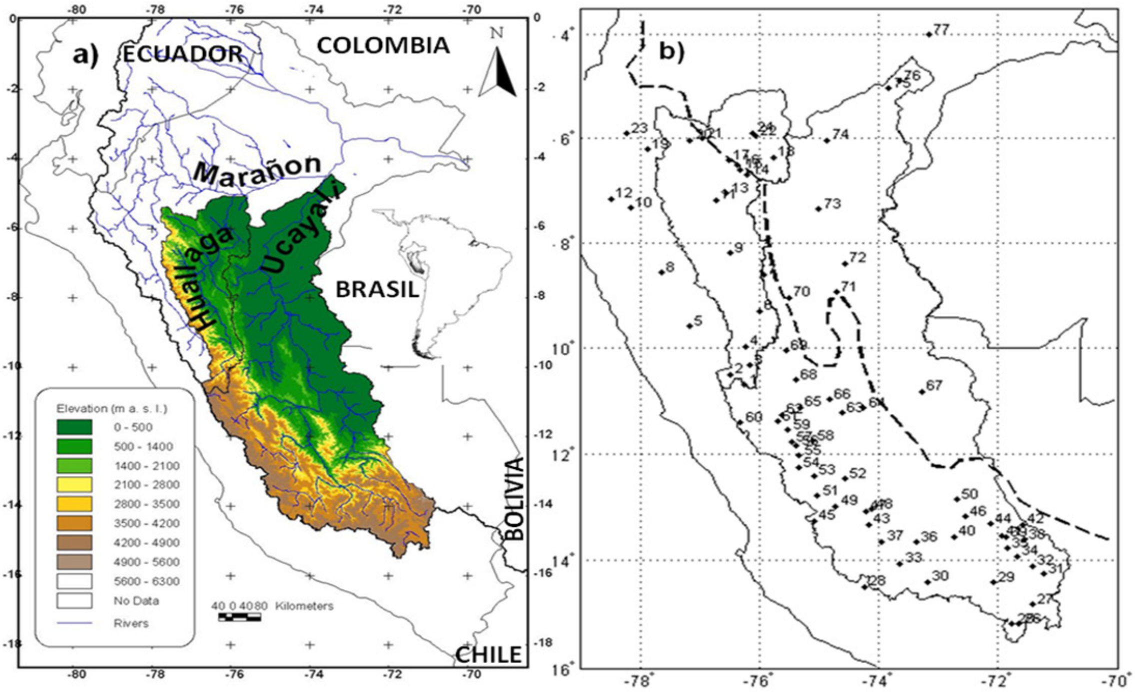

Figure 1. a). Localization and elevation of the region under study, West: Huallaga basin and East: Ucayali basin. b). Localization of the weather stations with number corresponding to codes given in the Table 1. The Ucayali and Huallaga basins are separated by a plain line. The Andes and Rainforest regions are limited by a black dashed line (500 masl).

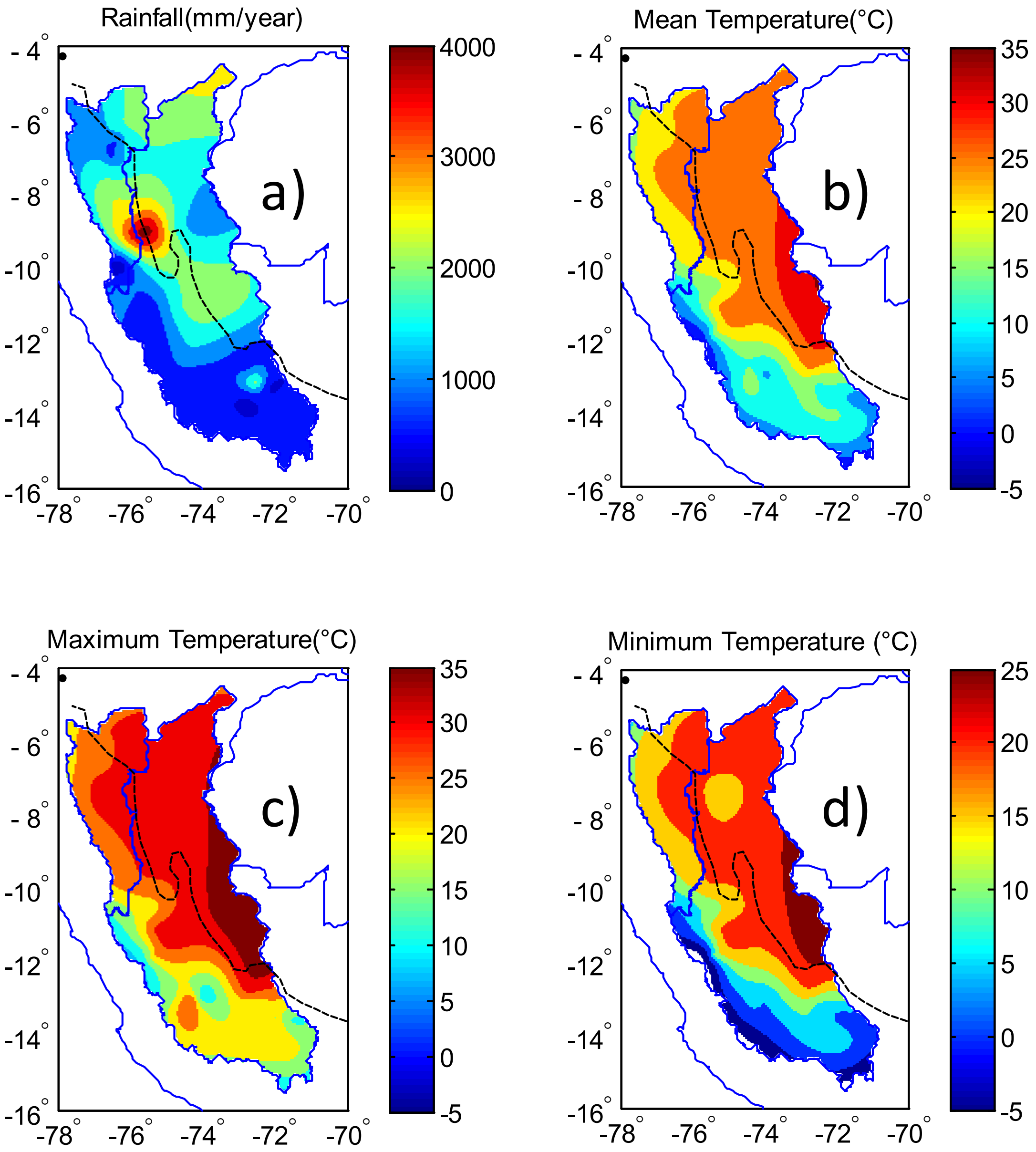

Figure 2. Mean (1965-2007) annual values for a) rainfall (mm/year), b)mean temperature (°C), c)maximum temperature (°C) and b)minimum temperature (°C) in Huallaga and Ucayali basins. The Andes and Rainforest region are limited by blue dashed line. The Huallaga and the Ucayali basins are separated by a blue plain line. Kriging method was used in the interpolation.

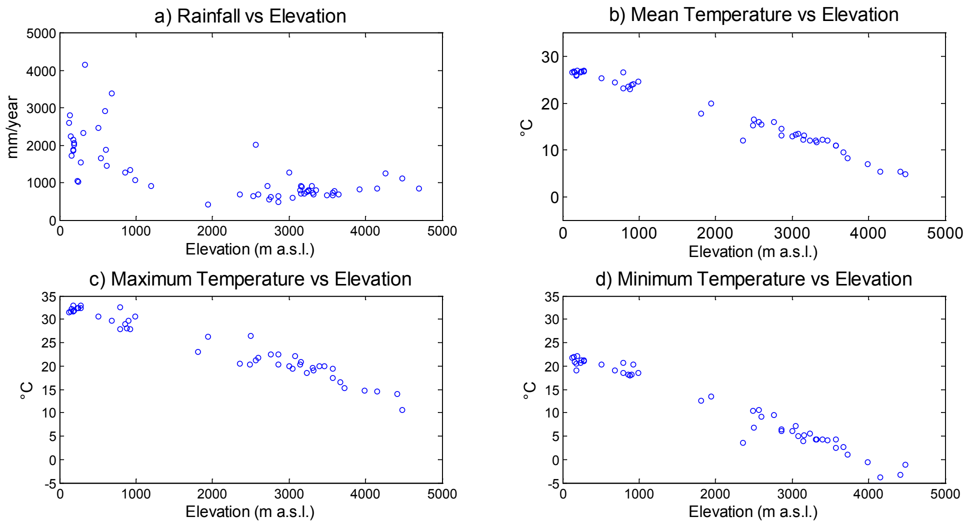

Figure 3. Mean (1965-2007) annual values versus elevation for a) rainfall (mm/day), b) mean temperature (°C), c) maximum temperature (°C) and d) minimum temperature (°C) using the whole station data in the Huallaga and Ucayali basins.

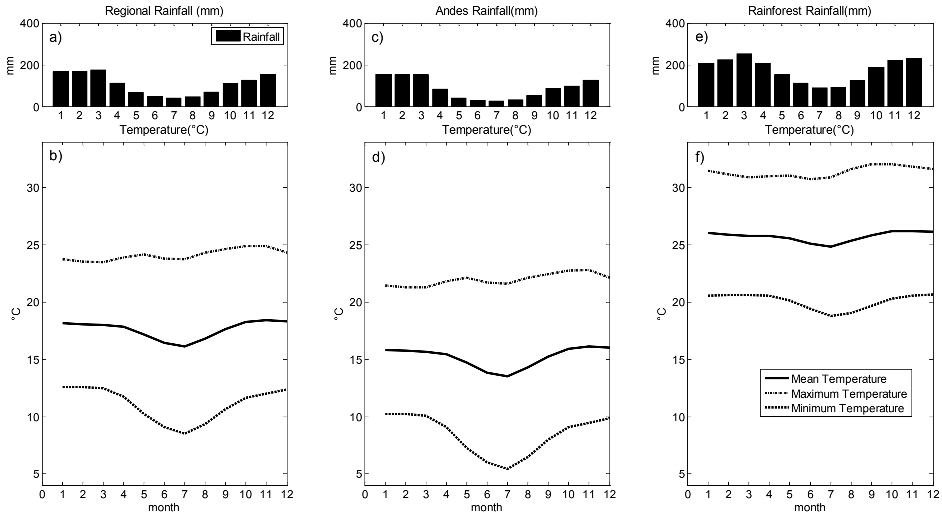

Figure 4. Monthly regimes of rainfall mean temperatures, maximum temperatures and minimum temperatures at Regional (4a and 4b), Andes(4c and 4d) and Rainforest region (4e and 4f). X axis are the month of the year (1 : January, 2 : February,…).

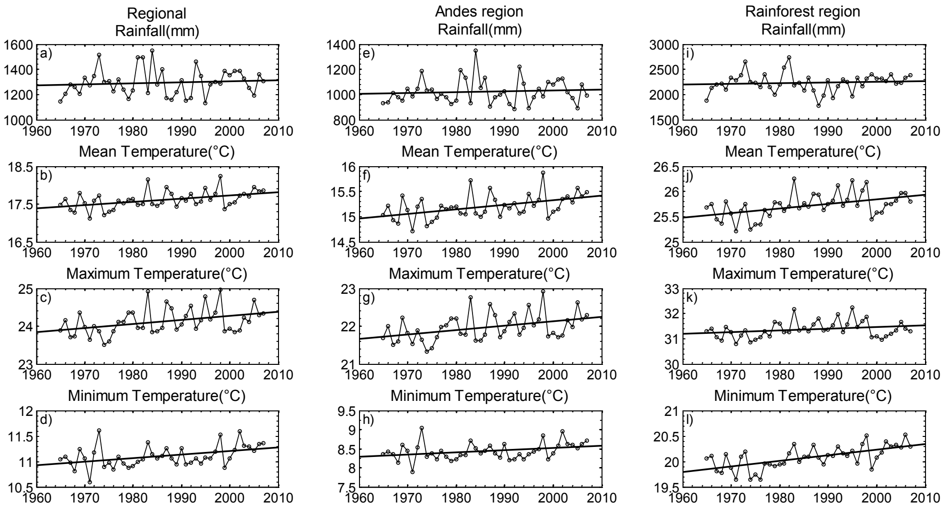

Figure 5. Plot of annual values means over the Regional region, Andes region y Rainforest region in the 1965-2007 period. Black line represents the trend using linear regression.

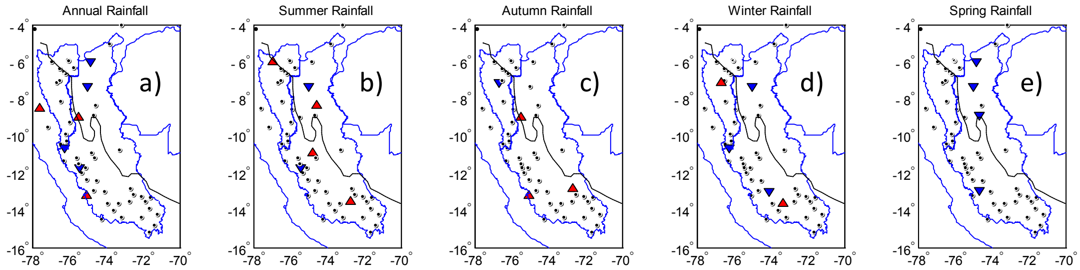

Figure 6. Presence of a local trend (Mann-Kendall test) in Rainfall for the five period analyzed (annual, summer, autumn, winter and spring) over the 1965-2007 period. Stations with positive significant trend (α equal 0.05) are with an upward red triangle and stations with negative significant trend (α equal 0.05) with a downward blue triangle. The Huallaga and the Ucayali basins are separated by a dark plain line. The Andes and Rainforest region are limited by a blue dashed line.

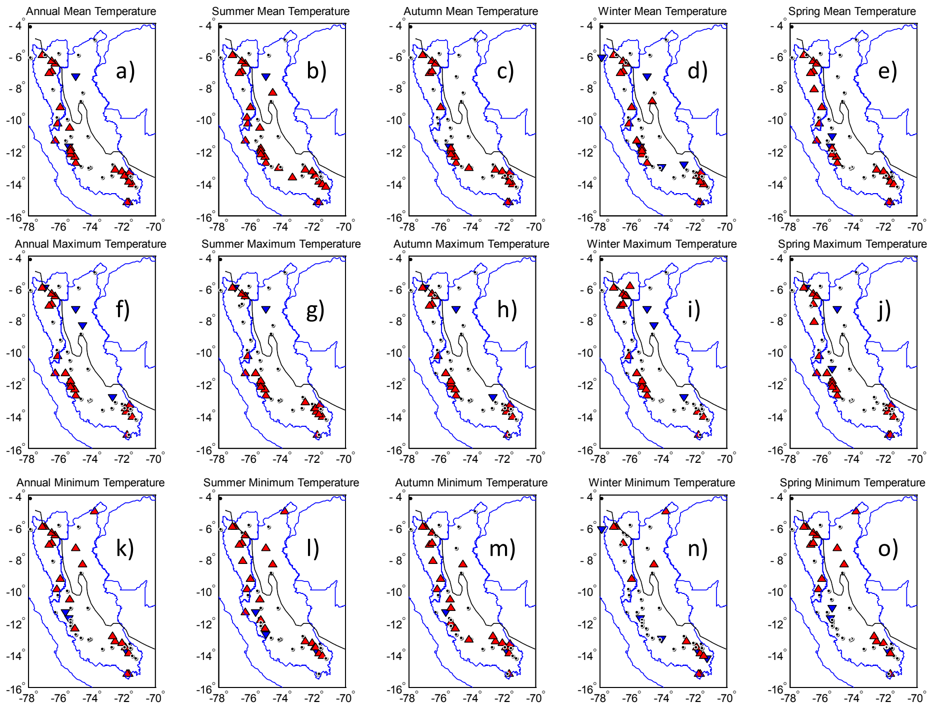

Figure 7. Top: As in Figure 3, but for trends in Mean Temperature. Center: As in Figure 3, but for trends in Maximum Temperature. Bottom: As in Figure 3, but for trends in Minimum Temperature.

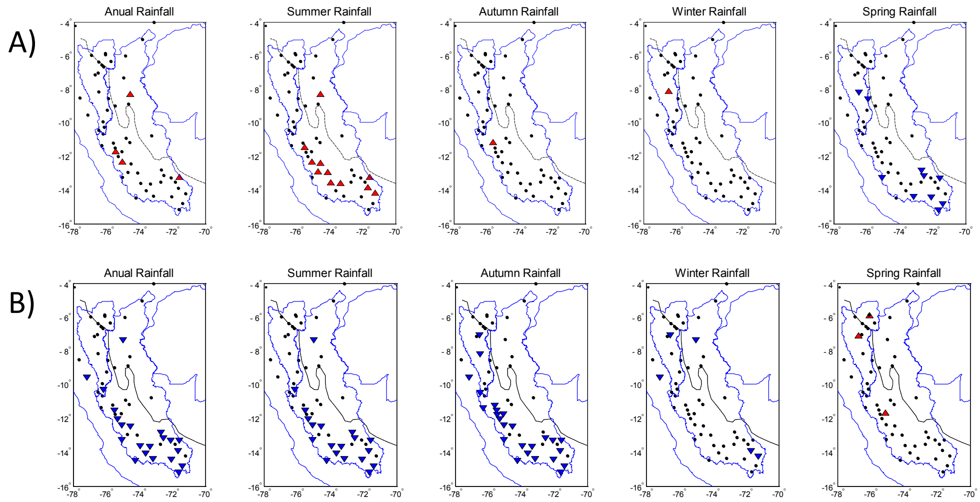

Figure 8. Correlation between annual and seasonal rainfall in the Huallaga and Ucayali basins A) the Southern Oscillation Index (SOI), B) SST difference between NATL-SATL. Stations with positive and negative significant correlation (p > 95%) are represented. Positives correlations are represented by upward red triangles and negative ones by downward blue triangles. The Huallaga and the Ucayali basins are separated by a dark plain line. The Andes and Rainforest region are limited by a blue dashed line.

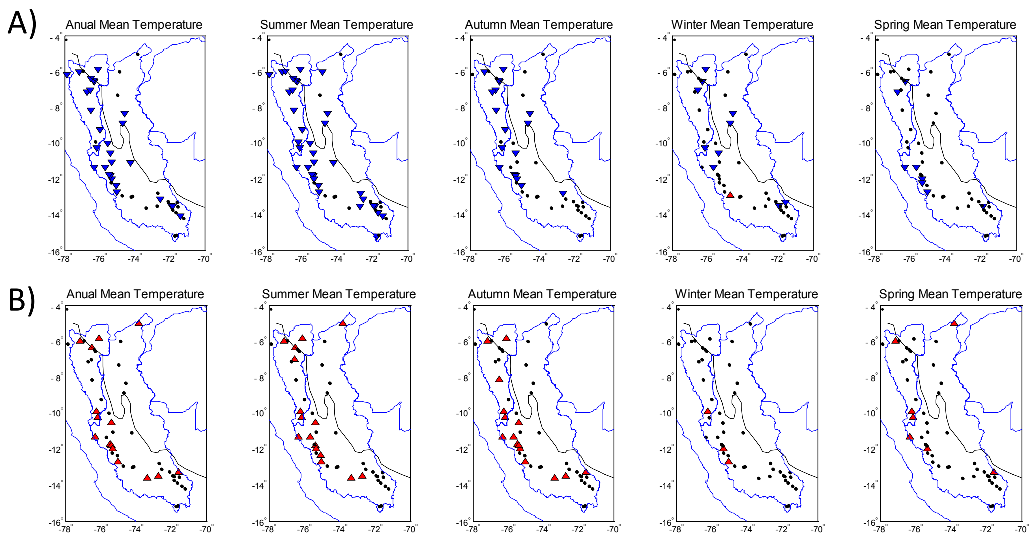

Figure 9. Correlation between annual and seasonal mean temperature in the Huallaga and Ucayali basins A) the Southern Oscillation Index (SOI), B) SST difference between NATL-SATL. Stations with positive and negative significant correlation (p > 95%) are represented. Positives correlations are represented by upward red triangles and negative ones by downward blue triangles. The Huallaga and the Ucayali basins are separated by a dark plain line. The Andes and Rainforest region are limited by a blue dashed line.

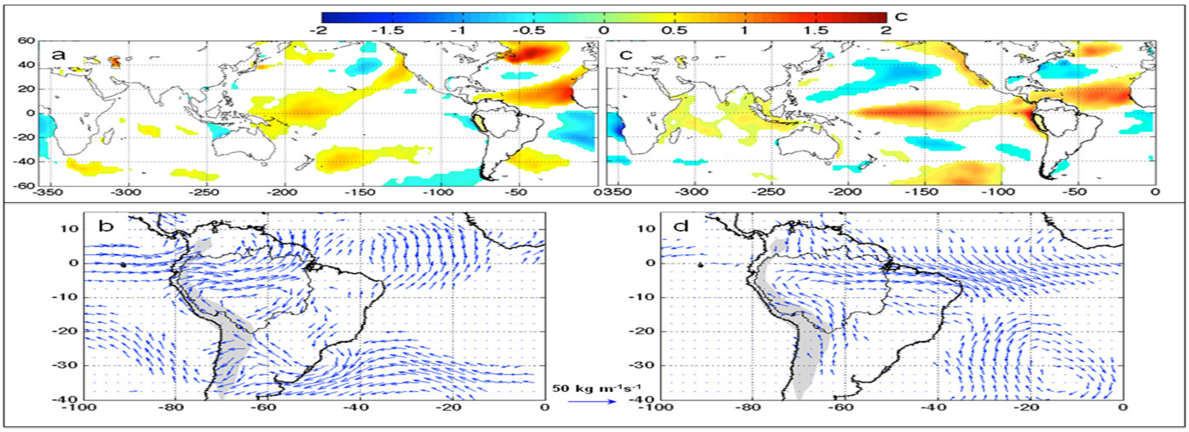

Figure 10. a) and b) Differences between DJF seasons for 1969-1970, 1995-1996, 1996-1997, 2001-2002 minus 1972-1973, 1984-1985, 1988-1989, 1993-94, for a) SST (˚C) and b) Vertically integrated (from the ground until 300 hPa) water vapor flux differences (kg m^{-1} day^{-1}). c) and d) differences between MAM seasons for 1974, 1981, 1984, 1989, 1994, 2008, 2009 minus 1970, 1978, 1983, 1997, 2005, 2010 for c) SST (˚C) and d) Vertically integrated (from the ground until 300 hPa) water vapor flux differences (kg m^{-1} day^{-1}). Only values higher than 2 × standard deviation are plotted.