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VARIABILITY AND CLIMATE CHANGE IN THE MANTARO RIVER BASIN, CENTRAL PERUVIAN ANDES

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ABSTRACT

The present work is part of the "Integrated Local Assessment of the Mantaro River Basin" (ILA Mantaro), whose main objective was: to systematize and to extend the knowledge about climate change in the Mantaro river basin, and to evaluate the climatic, physical and social aspects of its vulnerability, as well as to identify viable adaptation options for the agriculture, hydroelectric energy and health sectors, to be incorporated into local and regional development planning.

In this context, the climatic component of the study consisted in the analysis of the climatic characteristics of the river basin: intraseasonal and interannual variability of rainfall over the basin, the relation of regional climate with atmospheric patterns on regional and global scale, the climatic trends in the last 50 or 40 years, and the characteristics of the freezes and the trends in their frequency and intensity. On the other hand, the generation of future climatic scenarios for the river basin, constituted one of the most important objectives. These results were used for the analysis of the present and future vulnerability in the Mantaro river basin to climate variability and change, as well as for the proposal of adaptation measures

1. INTRODUCTION

The Mantaro river basin, located in the central Andes of Peru, has a great socio-economic importance (Martinez et al., in this volume; Instituto Geofìsico del Perú, 2005b and 2005c), and its exceptional climatic and physiographical characteristics has allowed the installation of hydroelectric power stations that supplies approximately 35% of the energy of the country. On the other hand, the valley of the Mantaro River produces most of the food consumed in Lima, by far the largest city of Peru and its capital. These aspects have motivated the proposal and execution of research projects that help the understanding of the climatic characteristics of the region, their relation to global climate and the possible effects of climatic change.

The Geophysical Institute of Peru (IGP), within the framework of the " Program of National Capacities Building for Impact of Climate Change and Air Pollution Management (PROCLIM), developed the ILA Mantaro through an interdisciplinary and interinstitutional work, with the participation of two working groups. Group A, was in charge of the study about the climatic characteristics of the river basin, its variability, tendencies and downscaling of the future climatic scenarios, the result of which results will be presented in the present paper. On the other hand Group B, was in charge of the study of the present and future vulnerability of the different socio-economic sectors in the river basin, as well as of the elaboration of adaptation measures, on the basis of the information provided by Group A (see Martinez et al., this volume; Instituto Geofísico del Perú, 2005c).

In this document, we present the main results obtained by the Group A: the climatology of the precipitation and air temperature of the Mantaro river basin; analysis of the dry and rainy periods and their relation with the atmospheric circulation; the relation between El Niño phenomenon and rainfall in the river basin; the teleconnection mechanisms; the local physical processes and their relation with the variability of rainfall; the variability in the date of beginning of the rainy season; the tenden-

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cies in the precipitation, maximum and minimum air temperature; the frequency and intensity of the frost; and finally the future climate scenarios for the Mantaro river basin.

2. METHODOLOGY AND DATA

The first stage for Group A consisted in the generation of the climatology and the climatic characteristics of the river basin, which were used as a base line for the future study of the variability and climate scenarios. These results were published in the "Climatic Atlas of precipitation and air temperature in the Mantaro river basin" (Instituto Geofìsico del Peru, 2005a). Parallelly, the Group B in collaboration with the Group A, made the diagnosis of the river basin from the socioeconomic point of view including the dangers of climatic origin (Instituto Geofìsico del Peru, 2005b). These documents set the base line of the study.

The third and last stage for Group A, included the study of the variability and climate tendencies, as well as downscaling of the future climate scenarios, results that were used for the analysis of the present and future vulnerability (Martinez et al., this volume; Instituto Geofísico del Perú, 2005c).

The methodology used for the analysis of the climate variability in the basin, the trends and the climate scenarios, will be described in the corresponding sections.

For the calculation of the climatology, we considered time series that had at least 10 years of data during the period 1960-2000.

The data used was provided by the National Weather Service of Peru (SENAMHI), by the electrical companies: Electro Peru and Electro Andes, and by the IGP.

3. CLIMATIC CHARACTERISTICS OF THE MANTARO RIVER BASIN

A strong seasonal variability in precipitations exists, with maximum values between January and March and minima between June and July. 83% of the annual precipitation takes place between October and April, of which 48% are distributed almost equitably between January, February and March.

The spatial distribution of annual precipitation (Figure 1) is not homogenous in the basin. In the highlands (above 4000 masl) the maximum values are presented in the North and South western regions of the basin (1 000 mm/year), whereas in the rain forest, towards the confluence of the Mantaro river with the Ene river, they reach 1 600 mm/year. On the other hand, the zone with smallest precipitation is located in the central part and in the south Eastern of the basin (between 2600 and 3200 masl) with values around 550 mm/year.

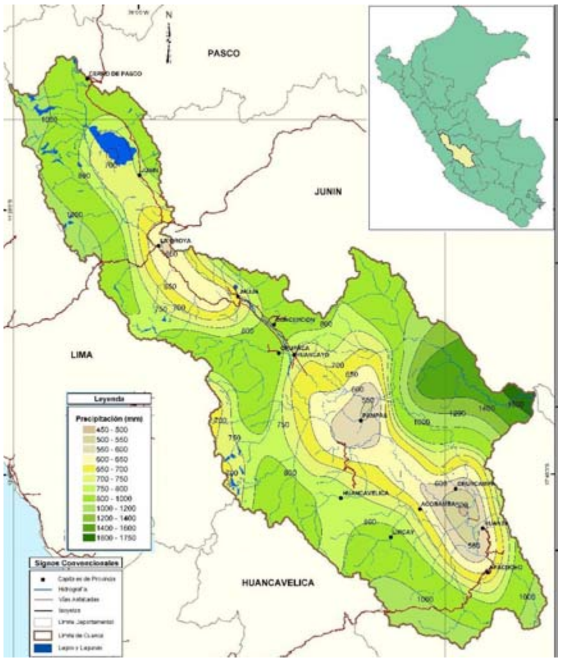

Figure 1: Multiannual average of the annual precipitation in the Mantaro basin (period: 1960-2000). Source: Instituto Geofìsico del Perú, 2005a.

The monthly average of the minimum air temperature, presents a marked annual cycle, with the minimum values between the months of June-July and the maximum between January and March, with an annual range of 4,5ºC (average for whole the basin). On the other hand, the maximum temperature presents weaker seasonality (1,5ºC range) and registers the maximum values in November and the minimums in February, but with a significant semiannual variation.

The annual average of the minimum temperature presents values below -2ºC in the western end of the river basin (4600 masl), reaching -4ºC in the highest parts with data (4900 masl). In the valley of the Mantaro (between 3150 and 3400 masl), the minimum temperatures are around 4ºC, reaching 8ºC in the South Eastern regions of the basin (between 2600 and 3200 masl). In the Eastern end, in the confluence of the Mantaro river with the Ene river (500 masl), the minimum temperatures reach 16ºC.

The annual average of the maximum air temperature presents values of 12ºC in the western and central Eastern part of the river basin. In the valley of the Mantaro the maximum temperature reaches values between 16°C and 18ºC, whereas in the south-Eastern zone of the basin, these reach values up to 22ºC, and 28ºC in the most Eastern end.

The climate, according to the climatic classification of Thornthwaite, varies from Semi Humid to Very Humid conditions in most of the river basin, except in the South part of the basin where dry regimes predominate (Semi Dry and Dry). From the thermal point of view, it varies from a Tundra climate in the high parts of the river basin, to Semi Cold climate in the zone of the valley of the Mantaro river.

4. INTRASEASONAL AND INTERANNUAL RAINFALL VARIABILITY

4.1 Dry and rainy periods

Monthly precipitation data of 38 meteorological stations were used to identify dry and rainy periods between the years 1970 to 2004. The analysis was made for the rainy season (September-April), for the period of September-December and January-April. The rainy or dry periods were identified using the Standardized Precipitation Index (SPI; McKee et al., 1995).

Based on the SPI values we calculated, for each year, the number of stations with positive or negative SPI. A dry (rainy) period was defined as that in which at least 70% of the stations registered negative (positive) values. During the 30 years of analysis data, 8 rainy periods and 6 dry periods were detected. The years with excesses of precipitation occurred at the beginning of the Seventies and during the first half of the Eighties, being 1973 the year with more intense and generalized rains in the Mantaro river basin. On the other hand, the precipitation deficits, happened in the second half of the Seventies and Eighties and in the beginnings of the Nineties, being years 1991 and 1992 when the most significant deficits were registered.

4.2 Atmospheric circulation associated to dry and rainy periods

Using the NCEP[1]/NCAR[2] Reanalysis (Kalnay et. al., 1996), for the period of 1970-2000, the average (climatology) of the behavior of the atmosphere on regional scale for the summer (rainy season, January-March) and winter season (dry season, June-August) were analysed. The analysis were made in the low level (850 mb, approx 1500 masl), in the middle (500 mb, approx 5 000 masl) and in the high level (200 mb approx, 12 000 masl) of the atmosphere. We analyzed the atmospheric variables in the levels mentioned composited for dry and rainy years, centered in the summer months and based on the anomalies.

In the low levels of the atmosphere, during the rainy periods the South Eastern Pacific Anticyclone is more intense and its center is located at 40ºS/100ºW. In the middle-Eastern part of South America an anticyclonic anomaly is observed during the rainy periods, which could favor the entry of humidity from the Atlantic towards the Amazon. In the middle levels of the atmosphere, during the rainy periods the anticyclonic anomaly persists in the middle-Eastern part of the continent extending towards the Atlantic. In addition, a cyclonic anomaly is observed in the North East of the continent. The circulation in the high levels of the atmosphere presents significant differences in the location of the Bolivian High (BH) during the rainy and dry periods. The BH is displaced towards the South West during the rainy periods and towards the North East in the dry periods. The displacement of the center of the BH generates anomalies from the West on the central mountain range of Peru during the dry years and from the East in the rainy years. During the rainy periods the anticyclonic circulation includes greater area, its influence extending to 90ºW on the West and 35ºW on the East.

4.3 The El Niño phenomenon and precipitation

We present a diagnostic of the relationship between El Niño and precipitations in the Mantaro basin, extending the work of Lagos et al. (2005) with a more comprehensive dataset for the basin.

Precipitation data from 50 stations located in the basin in the period 1960-2004 were used, although in some stations the time series are shorter. The following indices of sea surface temperature (SST) anomalies in the equatorial Pacific ocean were also used: Niño 1+2, Niño 3, Niño 3.4 and Niño 4. These data were obtained from NOAA .

The methodology used is the same one as described by Lagos et al. (2005). The coeffi-

[1] National Center for Environmental Prediction
[2] National Center for Atmospheric Research

cients of linear correlation between the standardized precipitation data and SST were calculated. The analysis was done first considering every year and later considering the years identified with El Niño events according to the definitions of SCOR (1983) and the NOAA (2002). The monthly analysis was made, as well as seasonal for the rainy period (September-April).

The correlations obtained individually for the months between September to December are insignificant but they are significant for the months of January to March.

There is no significant relation between precipitation in the Mantaro river basin and the SST anomalies off the northern coast of Peru, Niño 1+2 region (Figure 2). As we consider the SST in regions more distant from the coast of Peru, the correlation increases. The relations are stronger with the SST in El Niño 4 region. This is inverse relation, that is, a warm anomaly in the central or western equatorial Pacific inhibits precipitations in the Central and South part of the river basin, whereas a cooling in that region would favor precipitations in the river basin. Nevertheless, these relations are not perfect. For example, the very strong1997-1998 El Niño event was not a dry period in the river basin, but El Niño 1982-1983 was.

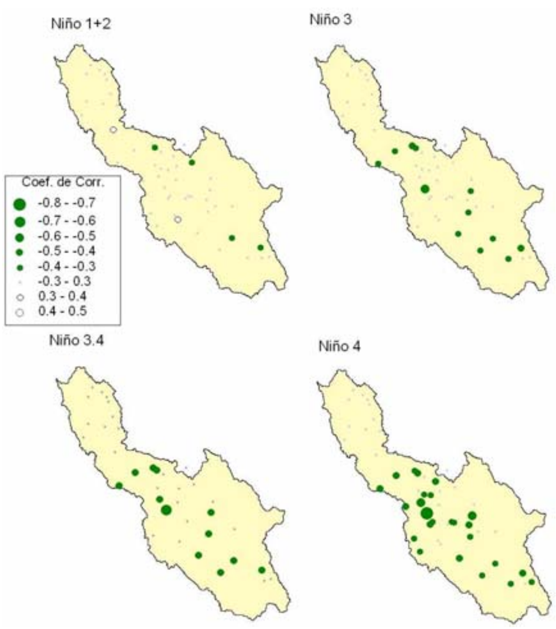

Figure 2: Correlation between precipitation in the Mantaro basin and SST in el Niño regions. Source: Instituto Geofìsico del Perú, 2005c.

4.4 Teleconnections Mechanisms

In order to analyze the space and temporal behavior of the ocean-atmospheric patterns on global scale, that could be associated with the climate in the Mantaro river basin, maps of the correlation coefficients between the global fields of SST anomalies, pressure at sea level and geopotencial height (500mb) with monthly data of precipitation and air temperature anomalies in the Mantaro river basin were calculated for the period 1964-1999. In the same way the correlations between diverse teleconnection indices (Wallace and Gutzler, 1981): North Atlantic Oscillation (NAO), Pacific-North America (PNA), West Pacific (WP), East Pacific (EP) and East Atlantic (EA) and the anomalies of precipitation and air temperature in the river basin were calculated.

Monthly precipitation data of 22 stations and air temperature at the Huayao station were used; Reynolds (1994) global SST data and global data of pressure at sea level and 500mb geopotencial height from the NCEP/NCAR Reanalysis and the climatic indices were used.

Previously to calculate the correlations, sub-regions with similar precipitation characteristics were identified and an analysis of space coherence was made. For this, the technique of Principal Components Analysis (PCA), applied to the matrix of correlation between precipitations (period January-March) of all the stations, identified four sub-regions: North subregion (the high part of the river basin), central subregion (in the middle of the river basin), South sub-region (in the lower part of the river basin) and western high sub-region. As the North sub-region is the one that presents minor space coherence, a representative index of the sub-region was applied to the PCA technique precipitation. For the case of the other sub-regions a representative station was chosen: for the central subregion - Huayao (3308 masl); Kichuas (2650 masl) for the South sub-region and Yauricocha (4375 masl) for the western high sub-region.

Correlating the seasonal precipitation (January-March and October-December) in Huayao with the global SST, we found that the period of January-March is the one that shows the greater correlation with the tropical Pacific and with the North and South Atlantic, and that the precipitation for the period January-March has an inverse and moderate relation (-0,3 to -0,5) with the tropical Pacific and the North Atlantic, and direct and moderate (0,3 to 0,5) with the South Atlantic. On the other hand, it was observed that during the month of February the correlation is stronger with the tropical Pacific, whereas for March, the correlation with the

North and South Atlantic increases. This pattern is stronger in the western high sub-region.

Considering only warm years (El Niño events), the correlation between the SST and precipitations in the river basin increases. The correlation in the western high sub-region for the month of March becomes more positive and stronger (0,5 to 0,7) with the South Atlantic, and an inverse and strong relation (-0,5 to -0,7) with the North Atlantic. On the other hand, when correlating the representative precipitation of each sub-region with each of the teleconexión indices, there is a moderate and positive correlation for the month of January, with NAO and EP indices.

Also was found, that the anomalies of the maximum air temperature in Huayao is highly correlated with the anomalies of SST in the Tropical Pacific (Figure 3). This pattern is stronger in the month of February (0,5 to > 0,7).

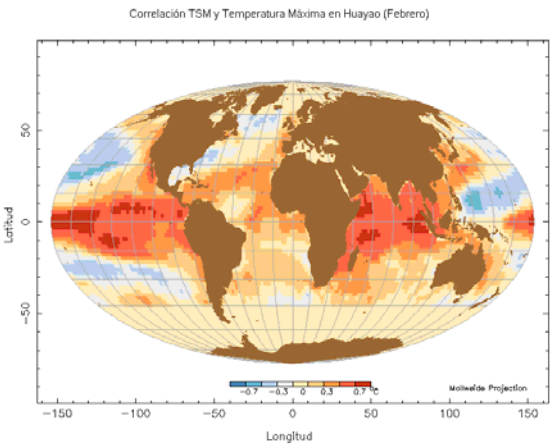

Figure 3: Correlation between SST and maximum air temperature in Huayao. Source: Instituto Geofisico del Perú, 2005c.

4.5 Local physical processes and their relation with the interannual precipitation variability

Statistical relations between large-scale climatic variables with precipitations in the Mantaro river basin were obtained. These relations allowed to understand the interannual variability in precipitations and were used as basis for the statistical downscaling. In the statistical model, indices of precipitation, zonal wind, humidity and temperature were used.

The precipitation indices were calculated as December to February means, averaged over the three regions (North Zone or Chinchaycocha sub-basin, Center Zone and South Zone) determined by Group B (Martinez, et al., 2006, in this volume).

The specific (q) and relative (HR) humidity and temperature (T) indices were constructed based on temperature, pressure and relative humidity daily data registered in the Huayao climatologic station at 7 a.m., 1 p.m. and 6 p.m. for the period 1958-89. Although these data are point measurements, it is expected that their interannual variability, associated with large-scale processes, also represents the variability of the river basin.

For the zonal wind index (u200), zonal wind data in 200mb were used from daily radiosoundings on Lima in the period 1957-2001, this data were available from the data base GCOS Upper Air Network (GUAM) of NOAA. Later, monthly averages were calculated and finally averages for the summer season were calculated (December to February). These data are considered representative of the atmospheric circulation on great scale that includes the central mountain part of Peru. In particular, they are representative of the high system circulation known as Bolivian High.

Statistical model of the precipitation variations

The correlations between the different indices with those from precipitation are shown in Table 1. The low correlation between specific humidity and precipitations suggests that the variations in moisture transport from the Amazon by the zonal wind do not modulate the interannual precipitation variations in the Mantaro, as it happens in the Altiplano (Garreaud et al., 2003). The greater positive correlations are with the relative humidity, suggesting that this is the critical parameter that modulates the condensation of the water vapor and, therefore, the convection. The correlations with the temperature also are significant but negative. This suggests a mechanism different from that one proposed by Garreaud, in which the precipitation variations are due to the variations in the relative humidity, which is smaller when the temperature is greater and vice versa. The significant and negative correlations with the zonal wind are probably a consequence the geostrophic relation, since the increase of temperature in the tropical band implies greater meridional pressure gradient in this region and, therefore, an increase in the eastward component in this level.

Table 1: Coefficients of correlation between accumulated precipitation in the period December to February in different zones of the river basin and averaged climatic indices on the same period.

Zone	u200	q 6pm	HR 6pm	T 6pm
Subbasin: Chichay-cocha	-0,51	0,12	0,50	-0,48
Central Zone	-0,47	0,19	0,67	-0,54
Southern Zone	-0,57	0,24	0,68	-0,58

In agreement with the previous considerations, a statistical model was constructed based exclusively on linear regressions between relative humidity and precipitations. The inter-annual precipitation variations for a unitary relative humidity change are given by the coefficients of linear regression. These coefficients also were used to consider the precipitation change associated to the relative humidity change projected by global climatic models under different scenarios of gas discharge from Greenhouse Effect.

Because the availability of relative humidity data from the global models is limited, it was necessary to develop a method to determine the change in this variable on the base of other variables. For this purpose, changes in relative humidity were diagnosed from changes in temperature and specific humidity using a lin-earized version of the definition of relative humidity and Clasius-Clapeyron equation. Although the temperature dominates the interannual variability, specific humidity might play a more significant role in climate change.

4.6 Variability in the date of beginning of the rainy season in the western South of the Mantaro river basin

The agricultural activities in the Andean zones of Peru depend to a large extent on the beginning of the rainy season. Therefore, we analyzed the variability that exists in the dates of beginning of the rainy season.

An standard definition of the "beginning of the rainy season" does not exist. In the present analysis 6 objective measures of the date of beginning of the rainy season were defined, those that will allow to study their interannual variability. The used measures are the dates in which the accumulated precipitation from the be-ginning of the agricultural year reaches the values of 100, 200, 300, 400, 500 and 600 mm. Daily precipitation data registered in 2 stations: Huancalpi (3800 masl) and Lircay (3150 masl) were used. The stations are located in the south-western part of the Mantaro river basin and were chosen because they have the longest and most continuous series, during the period 1965-2001.

The data of the two stations were averaged and a running mean of 21 days was applied in order to eliminate all type of variation that is within this period. Considering that the agricultural year begins at 01 of July and finishes at 30 of June of the following year, the day in which the precipitation reached the amounts of 100, 200, 300, 400, 500 and 600 mm was obtained. Six time series (for each amount of precipitation) were generated that indicate, for each year, the day in which the different amounts of precipitation were accumulated. The average and standard deviation of these six series were calculated (Table 2). A year in which the ob-served date was earlier (later) than the average minus (plus) one standard deviation, was considered to have experienced an advance (delay) of the beginning of the rainy season.

The dates in which the amounts of accumulated precipitation must be reached and their standard deviation are shown in Table 2.

Table 2: Date of precipitation accumulation and standard deviation for different amounts of precipitation.

Amount of accumu-lated (mm)	Date of accumu-lation	Standard deviation (days)
100	10 of October	45
200	24 of November	52
300	25 of December	52
400	22 of January	59
500	14 of February	75
600	01 of March	78

A comparison with the dry or rainy periods found in Section 4.1, indicates a relation between the rainy years (period September - December) with and advances of the rainy season. This was evident for the years 1981, 1990 and 1993. On the other hand, there is not a good agreement between dry years and the delay of the beginning of rains, neither during the months of September to December, nor during January-April.

5. CLIMATE TRENDS

Although inhabitants of the Mantaro river basin indicate that they have perceived a climatic change in the region, these perceptions tend to be dominated by what has happened in the most recent years (Instituto Geofísico del Peru, 2005b). Therefore, it is difficult to discriminate on the base of this if the observed changes are associated with a sustained trend or climate variability. The most direct form to establish objectively the existence of a trend in the climate is using observations of meteorological variables and the technique of the linear regression to obtain the linear rate of change in these variables, which is the quantitative measurement of this trend.

5.1 Precipitation

The trends of the annual precipitation average are analyzed, during the rainy season (September-April), during the months of maximum precipitations (January-March) and during the beginning of the rainy season (September-December). The data series considered, in their majority, are for the period 1964-2003, although some stations have data only for the period 1970-2003.

The trend of the annual precipitation (Figure 4) shows a generalized diminution of rains in the north and central parts of the river basin, including the Mantaro valley, whereas in the western and central South part, the trend is slightly positive. The trends during the rainy season (September-April) and during the January-March follow the pattern of the annual tendency, but the values are greater in the latter. Averaging all the stations, the tendencies indicate a diminution of around 3% of present precipitations by every 10 years, which, projected to 50 years towards the future, would give a diminution of the order of 15%.

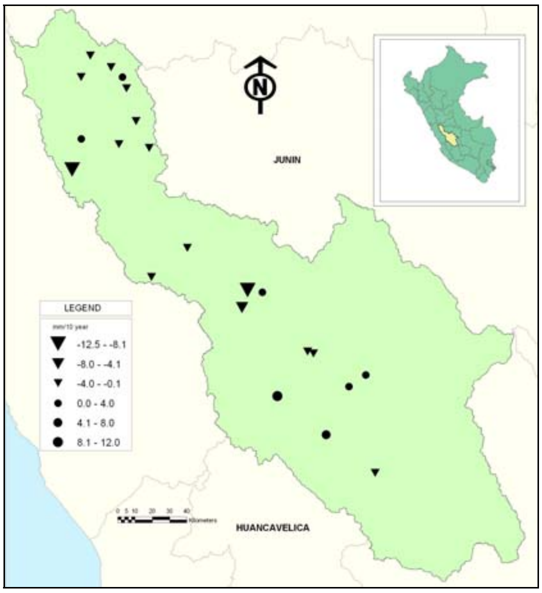

Figure 4: Trends in the annual precipitation (period: 1964-2003). Source: Instituto Geofìsico del Perú, 2005c.

5.2 Extreme air temperatures

The maximum air temperature in the Mantaro valley, analyzed in Huayao (Figure 5), shows a noticeable positive tendency (+0,24ºC /decade), which is consistent with Vuille and Bradley (2000), which indicate a tendency of +0,2ºC/decade in the central Andes.

The annual minimum temperature shows a large interannual variability (Figure 6) and does not present any trend, although in the winter months there is a positive (+0,16ºC/decade) trend and negative trend in the other months of the year, most markedly in October-December (Table 3). These results indicate that the diurnal thermal amplitude is increasing.

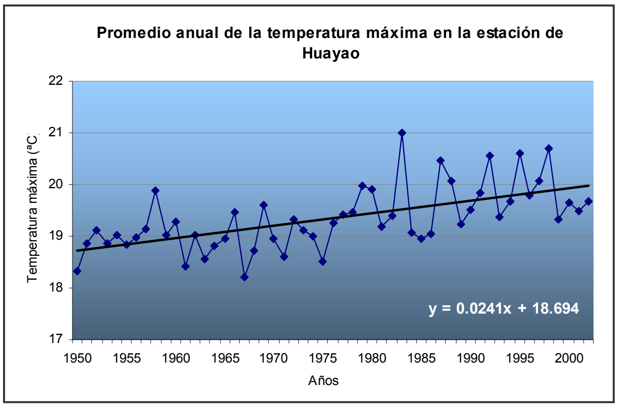

Figure 5: Trends in the maximum air temperature in Huayao (period: 1950-2002). Sour-ce: Instituto Geofìsico del Perú, 2005c.

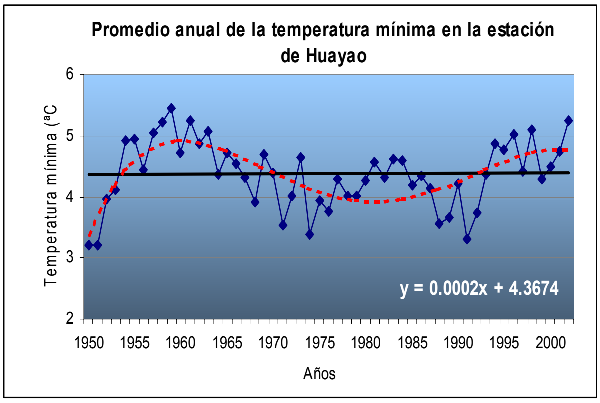

Figure 6: Trends in minimum air temperature in Huayao (period: 1950-2002). Source: Instituto Geofisico del Perú, 2005c.

Table 3: Tendencies in the maximum and minimum air temperature in Huayao (ºC/10 years)

Temperature	Annual	Sep-Apr	Jan-Mar	Jun-Aug	Oct-Dec
Maximum	0,24	0,26	0,28	0,17	0,22
Minimum	0,00	-0,07	-0,01	0,16	-0,13

5.3 Frequency and intensity of freezes

The analysis was made for last the forty years (1960 to the 2002), centered in the period of September-April, which is when freezes affect the crops the most. Time series of daily minimum temperature (Tmin) in 6 stations were used, with consideration that the series contain a minimum of 30 years of data. Freezes were considered to occur when Tmin was lower or equal than the threshold value of 5ºC, determined in the work-shops of the Group B. The number of days with freezes (frequency) was calculated for each 8-month period, and on the other hand the intensity of the freezes (the value of the lowest Tmin for each period) was also calculated. The linear trend was also calculated.

Table 4 presents the trends in the frequency as well as in the intensity of the frosts for the 6 stations. According to the table, generally positive tendencies in the frequency of frosts is observed, so the number of days with presence of frosts is increasing in average by 8 day/decade, this tendency was only statistically significant in the stations of Huayao and Jauja, with values of 2,8 day/decade and 14,87 days/decade respectively.

On the other hand, the intensity has a variable behavior, not defined in space, almost without tendencies in Huayao and Pilchaca (towards the center of the river basin). Positive tendencies in the stations located to greater altitude (Cerro de Pasco and Marcapomacocha). Negative trends in Jauja and Lircay (to the center and the south of the river basin) were obtained.

In summary, during the rainy season (September - April), a positive trend in the frequency of frosts at the rate of 8 days/decade was found, whereas the intensity of the freezes does not present a defined trend (more detail analysis can be found in Trasmonte et. al. 2006, in this volume).

Table 4: Trends in the frequency (days/10 years) and intensity (ºC/10 years) of freezes in the Mantaro river basin. Period: September-April between 1960 and 2002

Station	Altitude (masl)	Frequency of freezes	Intensity of freezes
Cerro de Pasco	4260	+2,9	+0,51
Marcapomacocha	4413	+6,0	+0,35
Jauja	3322	+14,8	-0,95
Huayao	3313	+2,8	+0,054
Pilchaca	3570	-12,7	+0,08
Lircay	3150	+12,4	-0,37

6. Future climate scenarios in the Mantaro river basin

The future climate scenarios produced by the different international centers for the Intergubernamental Panel on Climate Change (IPCC) were made using global climate models. These models allow to consider the response of the climate to changes in the Greenhouse Effect Gases (GEG) and aerosols concentrations, which have been estimated by the IPCC for different emission scenarios (Boer, et al., 2000).

The process of obtaining information on how the geographic conditions affect the climatic scenarios on a regional scale is known as downscaling. Currently, downscaling is made mainly using the following complementary methodologies: dynamical and statistical. In the present work both methodologies were applied to obtain climatic scenarios in Mantaro basin.

6.1 Dynamical downscaling

Dynamical downscaling was applied to the climate scenarios produced by the NCAR using global climate model CCSM2 (Climatic Community System Model 2; Buja and Craig, 2002). These climate scenarios are based on the emission scenarios denominated GEG A1, A2 and B2.

The regional climate scenarios were made for two periods: first for the years 1990-1999, that would be the base line; and the projection for years 2046-2055. It was decided not to consider intermediate periods, on one hand, because the expected climatic signal would be small compared to the interannual variability and, on the other hand, because of computational limitations. The results of the scenarios A1 and B2 were considered. The frequency of the global atmospheric information used was 6-hourly for the base line and daily for the period 2046-2055, whereas the oceanic information was quarterly.

The regional climate model RegCM2 (Giorgi et al, 1993a,b) was used. The RegCM2 model has been evaluated in the IGP and diverse tests of sensitivity of the model have been done, in particular to the parameterization schemes, as well as to the domain size. The domain for which the regional model for the future scenarios was run, was centered in 14ºS and 60ºW, including a large part of the South American continent, from 10ºN to 42ºS and 87ºW to 30ºW, with a space resolution of 80x80 km. It is important to mention that the version of RegCM we had (version 2), did not allow to implement the changes in GEG concentrations corresponding to the considered emission scenarios, which could limit the ability of the model to reproduce the expected climate changes.
Data of SST from Reynolds (1994) were used for the base line, and for the future runs, in addition to these data, the CSM2 model monthly anomaly for years 2050 to 2055 was used. With this a more approximate model forced of the SST reality was obtained hoping that the model reflects improvements in its result. The topography and land uses were obtained from the United States Geological Survey and Global Cover Characterization (Loveland, et al. , 2000), with 10 minutes resolution. 12 types of land use were considered.

The global model presents a warming of around 2ºC for the zone of the Mantaro, while that the regional model reproduces warming in the east but with a smaller magnitude, varying from 0,2ºC in the eastern part of the river basin to 1,0ºC in the Western part, this warming is accentuated during the summer (January-March)and with the B2 scenarios.

According to the results of the regional model, the precipitation would present a diminution from 5% in the Western part of the river basin to 20% in the South Eastern part of the river basin (Figure 7).

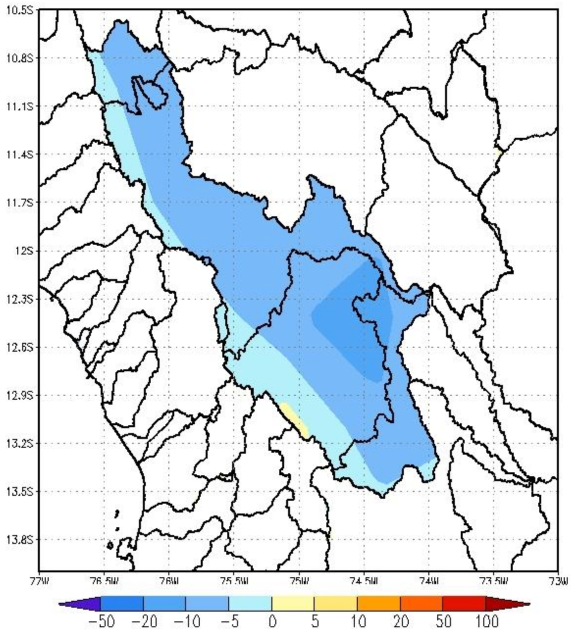

Figure 7: Changes in annual precipitation (%) from the regional model with B2 scenarios. Average temperature in 2045-2055 minus average in 1990-1999.

During the summer months the precipitation deficit of up to 10% is accentuated only in the central part of the river basin, in the North, South and south-Eastern part of the river basin the model produces an increase in precipitations of up to 20%(Figure 8).

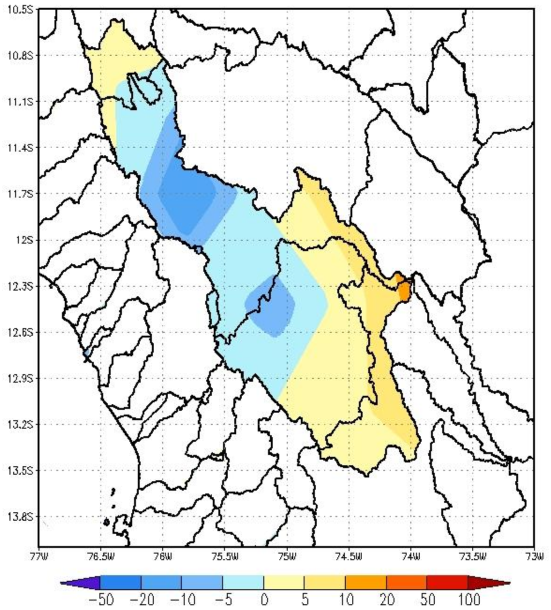

Figure 8: Changes in summer precipitation (%) from the regional model with B2 scenarios. Average precipitation in 2045-2055 minus average in 1990-1999.

6.2 Statistical downscaling

This method consists of looking for statistical relations between the climatic variables in the region of interest and parameters representing the climatic conditions of great scale that can be suitably represented by the global climate models. Then, the relations found can be applied to the data of the global climate scenarios to determine the regional scenarios. The advantage of this method is that it is simple to apply and implicitly incorporates the regional geographic effects. One of its fundamental limitations is the empirical nature of the method that does not include explicitly the knowledge of the physical laws, while the dynamical method does. In addition, it is assumed that those relations found with historical data will continue being valid in the future, is not possible to know a priori.

The objective of this study was to determine the changes in the temperature, precipitation, and relative and specific humidity during the rainy months of December to February between the periods of 1990-99 and 2045-54. The changes in temperature and specific humidity were directly considered of the results of 12 combinations of global climate models of the IPCC and emission scenarios. The results were then used for the estimation of the changes in relative humidity and the precipitation in the three sub-river basins, according to that described in section 4.5.

The estimations of the change in temperature and specific humidity for the Mantaro river basin show greater dispersion between models than between scenarios, although in general it is relatively small. The average changes for all models and scenarios were +1,3ºC in temperature and +1 g/kg in the specific humidity, whereas the in relative humidity is of -6 %. The sign of the changes is consistent between all the 15 models and the dispersion is small compared with the magnitude of the changes. In addition an average diminution in the precipitation during the summer period of 19% in the Central Region, 14% in the South Region and 10% in the Sub-river basin of Chinchaycocha (North Region) were estimated. The dispersion (standard deviation) of these is relatively small. These results are similar to what would be obtained assuming the persistence of the observed trends in precipitation (section 5.1).

6.3 Consolidated results

The results of dynamic downscaling present a generalized heating on the Mantaro river basin, which is more accentuated in the Western region and with the B2 scenarios, similar, the model presents a diminution of the annual precipitation in all the river basin. The pattern of smaller heating in the Eastern region of the Andes is consistent with observations (Vuille, et al., 2003) and other models. The results of the B2 scenarios are warmer and dry than those of the A1 scenarios, which is consistent with the results of the statistical model, which indicates reduced precipitation associated with greater temperature.

The results obtained had, in addition, the support of other sources. This is particularly important for the changes considered in precipitation, that depend on which the relation between temperature and precipitation stays under the climate change conditions. In the first place, as it was noticed previously, the estimated precipitation reductions are consistent with which it would be obtained by extrapolation of the precipitation trends observed in station data (section 5.1). Secondly, if we considered the negative relation observed between precipitations in the Mantaro and the sea surface temperature in the central equatorial Pacific (El Niño 3.4 and Niño 4, sections 4.3 and 4.4), an additional contribution to the reduction in precipitations in the Mantaro associated to the tendency projected by climatic models towards the more similar El Niño conditions in the future (Cubasch, et al., 2001). Finally, the results of dynamic downscaling for the B2 scenario are warmer and dry than those of the A1 scenario (section 6.1), which is consistent with the results of the statistical model, which they relates reduced precipitation to greater temperature.

The increase of air temperature projected, is also consistent with observations. In particular, Vuille and Bradley (2000) indicated a trend of around +0,2°C per decade (1°C/50 years) for period 1959-1998, whereas the trends observed in the basin are +0,24ºC/decade average (+1,24ºC/50 years).

7. CONCLUSIONS

The main conclusions of the climate variability study, tendencies and future climate scenarios in the Mantaro river basin are:

7.1 Interannual and intraseasonal climate variability

In the period between 1970 and 2004, the occurrence of 8 rainy periods and 6 dry periods were determined, being year 1973 the rainiest and years 1991 and 1992 the driest ones.

During the rainy years, an anticyclonic anomaly in the atmospheric circulation in low and middle levels in the center-Eastern part of South America is observed, it could favor the humid air entrance from the Atlantic to the Amazonian.

The anticyclonic system in the high atmosphere known as the Bolivian High, is displaced towards the south-west during the rainy periods and towards the northeast in the dry periods.

A significant negative relation exists between the variations of the sea surface temperature (SST) in the central equatorial Pacific (Niño 3.4 and Niño 4 regions) and precipitations in the Mantaro river basin. That is, El Niño phenomena tends to be associate with smaller precipitations in the Mantaro river basin.

The correlations between precipitations and the SST in the tropical Pacific are greater during the period of January to March that during October to December.

The variability of the maximum and minimum air temperatures in the river basin is strong and positively correlated with the variability of the SST in the tropical Pacific.

Locally, no significant relation between the variability of the precipitation with the variability of the specific humidity was found, but a significant negative relation between precipitation and relative humidity and temperature exist. The interpretation of this result is that the relative humidity variations forced by those of temperature have greater control on rains that the humidity transport from the Amazon.

The date of beginning of the rainy season presents great variability, with a standard deviation of around of 50 days, in average.

The variability of the date of beginning of the rainy season does not present a significant relation with the variability of accumulated precipitations during the season.

7.2 Climate trends

During last the 50 years, an increase in the maximum temperature has been observed of around +1,3°C (+0,24°C/decade).

The trend in the annual minimum temperature is weak and more difficult to separate of the interannual variability. However, in the winter months, the trend is positive, whereas in the other months it is negative.

The increase in the maximum temperature is greater during the summer months (+0,28C/decade or +1,40°C in 50 years) that in the winter months (+0,17ºC/decade or +0,87ºC in 50 years).

The precipitation trend is generally negative, with exception of some stations in the western and central South zone, where it is slightly positive. In average, the trend is for a diminution of 3% per decade (15% in 50 years).

The frequency of freezes has presented a general trend of increase during the last 40 years. The number of days with frosts in the period of September to April, in average has been increasing at a rate of 8 days/decade (40 days in 50 years).

The intensity of the freezes, on the other hand, has not presented a well defined trend.

7.3 Future climate scenarios

The future climate scenarios for year 2050, consolidated from the results of dynamical and statistical down-scaling, including the observed tendencies, are the following:

Increase in the average temperatures in summer of 1,3°C.

Increase in the specific humidity during the summer in 1 g/kg.

Diminution in the relative humidity in summer of 6%.

Diminution in precipitations in the North zones, center and the south in 10%, 19% and 14% with respect to the present ones, respectively.

Increase in the diurnal amplitude of temperature of approximately 1°C.

Increase in the number of days with frosts in the months of summer of 40 days.

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