Policy Research Working Paper 5091

# Social Impacts of Climate Change in Peru

## A District Level Analysis of the Effects of Recent and Future Climate Change on Human Development and Inequality

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October 2009

## Abstract

This paper uses district level data to estimate the general relationship between climate, income and life expectancy in Peru. The analysis finds that both incomes and life expectancy show hump-shaped relationships, with optimal average annual temperatures around 18–20°C. These estimated relationships were used to simulate the likely effects of both past (1958-2008) and future (2008–2058) climate change. At the aggregate level, future climate change in Peru is estimated to cause a small reduction in average life expectancy of about 0.2 years. This average, however, hides much larger losses in the already hot areas as well as substantial gains in currently cold areas. Similarly, the average impact on incomes is a modest reduction of 2.3 percent, but with some districts experiencing losses of up to 20 percent and others gains of up to 13 percent. Future climate change is estimated to cause an increase in poverty (all other things equal), but to have no significant effect on the distribution of incomes.

This paper—a product of the Social Development Division, Sustainable Development Department—is part of a larger effort in the department to address climate change. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at dverner@worldbank.org.

Produced by the Research Support Team

# Social Impacts of Climate Change in Peru: A district level analysis of the effects of recent and future climate change on human development and inequality[*]

by

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**Keywords:** Climate change, social impacts, Peru.
**JEL classification:** Q51, Q54, O15, O19, O54.

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[*] This paper forms part of the World Bank research project "Social Impacts of Climate Change and Environmental Degradation in the LAC Region." Financial support from the Danish Development Agency (DANIDA) is gratefully acknowledged. The comments and suggestions of Kirk Hamilton, Jacoby Hanan, and John Nash are greatly appreciated. The findings, interpretations, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the Executive Directors of The World Bank or the governments they represent.

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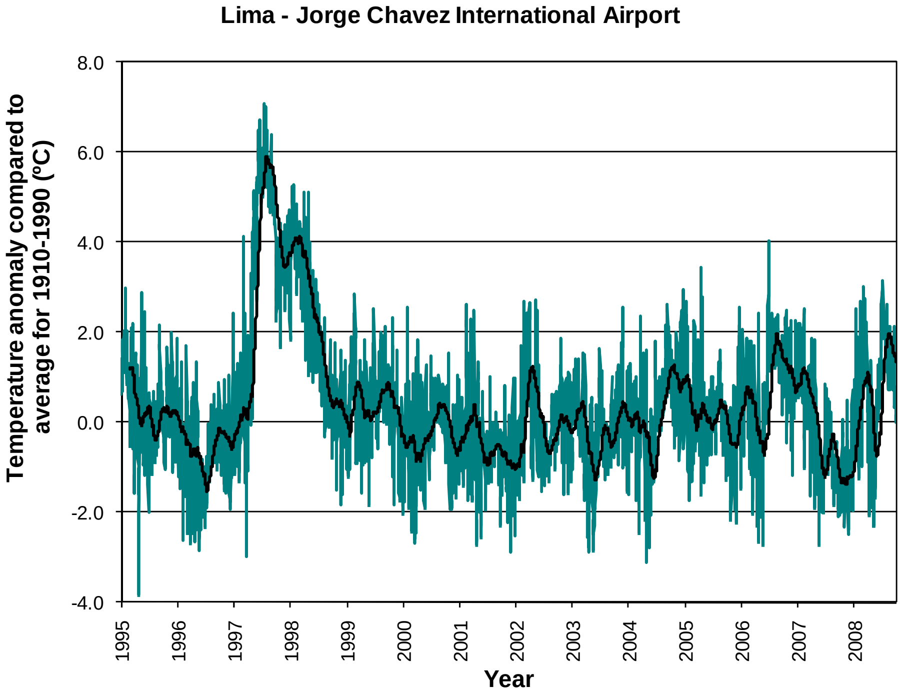
## 1. Introduction and justification

According to research carried out by the Tyndall Centre of Climate Change in the UK, Peru is one of the most vulnerable countries in the world to climate change. When the Mega-Niño of 1997-1998 occurred, cities along the Peruvian coast experienced temperature increases of 6ºC in just a few months (see Figure 1 below), while the impact in most other places in the Americas was limited to a couple of degrees or less.

**Figure 1: Daily temperature anomalies in Lima, Peru, 1995-2008**



*Source:* For daily temperatures: Average Daily Temperature Archive, University of Dayton, GSOD weather station no. 846280, located at 12.00ºS/77.11667ºW, 13 meters above sea level. For 1910-1990 average monthly temperatures: World Climate (www.worldclimate.org) station Lima-Callao/International Airport located at 12.00ºS/77.09ºW, 13 meters above sea level.

El Niño's impact in Peru is not limited to temperature changes, but also causes large precipitation changes. Under normal conditions, the predominant ocean currents keep the water off the Peruvian coasts relatively cold and nutrient rich (Woodman 1998), which contributes to the success of the fishing activities in Peru. When waters are cold there is little evaporation, which explains why it rarely rains along the coast. However, when the El Niño phenomenon occurs, the increase in ocean temperatures causes increased evaporation, which in turn tends to cause excessive rainfall and flooding in the northern part of Peru.

The 1997-98 El Niño, for example, caused extensive damage in Peru. Flooding affected 120,000 homes and destroyed 50 bridges, hundreds of kilometers of paved roads, and 50,000 hectares of crops. The unusually warm water off the coast caused fish to migrate to colder, more nutritious waters, causing sharp reductions (about 74%) in the Peruvian fish harvest, which in turn adversely affected the manufacturing chain dependent on fish as a raw material. An excess number of cases of diarrhea were registered as were outbreaks of malaria, cholera, and dengue fever. Due to the breakdown of infrastructure, prices in some places rose by 20-100% due to lack of supply of basic goods. Exports were also adversely affected. Total losses were estimated at close to a billion dollars (Meerhoff, 2008).

While GDP growth in 1997 was relatively high (6.9%), it turned negative (-0.7%) in 1998 and remained close to zero for three more years before finally recovering in 2002. An even more adverse impact was experienced in the previous Mega-Niño of 1982-83, with negative growth of -12% in 1983 (World Development Indicators)[1].

The El Niño Southern Oscillation (ENSO) is an irregularly occurring phenomenon that has been documented to have taken place at least ten thousand years back in time with varying intensity and frequency (Carré et al., 2005). While the latest IPCC review found no scientific evidence that global warming through carbon emissions would affect the frequency or amplitude of the ENSO cycle (Meehl et al., 2007, p. 751), the strong, adverse effects of recent El Niño events do suggest that climate change in general might have significant economic and social impacts, although the scale would likely be much smaller, as the magnitude of change that can be expected is in the order of a few degrees over 50 years instead of 6 degrees over 2 months.

The objective of this paper is to estimate the effects of the gradual climate change experienced over the previous 50 years and the expected climate change over the next 50 years on incomes and life expectancy in each of the districts in Peru. We will not be concerned about individual extreme events, but rather the equilibrium effects of climate change (including an averaged effect of extreme events, to the extent that changes in average climate cause changes in extreme events).

A simple way to gauge how climate change affects human development is to compare human development across regions with different climates. This has, for example, been done by Horowitz (2006), which uses a cross-section of 156 countries to estimate the relationship between temperature and income level. The overall relationship found is very strongly negative, with a 2°F increase in global temperatures implying a 13% drop in income. This is very dramatic, but the relationship is thought to be mostly historical and thus not very relevant for the prediction of the effects of future climate change. In order to control for historical factors, the paper includes colonial mortality rates as an explanatory variable, and finds a much more limited, but still highly significant, contemporaneous effect of temperature on incomes. The contemporaneous relationship estimated implies that a 2°F increase in global temperatures would cause approximately a 3.5% drop in world GDP.

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[1] However, during the period 1988-1990, Peru experienced the most profound economic crisis in the last 50 years, without any El Niño at all, so overall it is difficult to establish an empirical relation between the ENSO cycle and the economic cycle in Peru.

In order to further control for historical differences, Horowitz (2006) uses more homogeneous sub-samples, such as only OECD countries or only countries from the Former Soviet Union, and the negative relationship still holds. However, as directions for further research, he recommends empirical studies of income and temperature variations within large, heterogeneous countries, which would provide much more thorough control for historical differences.

This is exactly what we will do in the present paper. Using data from 1,829 districts in Peru[2], we will estimate contemporary relationships between temperature and income as well as between temperature and life expectancy. While it is always dangerous to draw inferences about changes in time from cross-section estimates, we will use the estimated relationships to roughly assess the likely direction and magnitude of the effects of climate change in Peru.

Two different types of climate change will be assessed. First, the documented recent climate change in each of the 1,829 districts, as estimated from average monthly temperature series from 1948 to 2008 for all the Peruvian meteorological stations that have contributed systematically to the Monthly Climatic Data for the World (MCDW) publication of the US National Climatic Data Center.

Second, we will use the predictions of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC4) climate models to simulate the possible effects of projected future climate change in Peru.

The rest of the paper is organized as follows. Section 2 describes the data sources and provides descriptions of the key variables. Section 3 estimates the cross-district relationships between climate and human development, controlling for other key variables that also affect development. Section 4 analyzes past climate change for 24 meteorological stations across Peru, and estimates average trends in temperatures and precipitation. Section 5 uses the results from sections 3 and 4 to simulate the effects of past climate change on income and life expectancy in each of the 1829 districts in Peru. Section 6 summarizes the climate changes that are expected for Peru during the next 50 years, and section 7 simulates the likely effects of these changes on incomes and life expectancy. Section 8 concludes.

## 2. The data

The data used for this paper consist of both cross-section data and time series data. The district level cross-section data base, which was used to estimate the relationship between climate and development in Peru, was constructed using data from many different sources. Table 1 lists the variables, their definitions, and the sources of the information.

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[2] There are 1831 districts in Peru, but we don't include the districts of Mazamari and Pangoa of the Satipo province in Junín, because the local authorities didn't accept to participate in the 2005 Census, thus we do not have social and economic data for these two districts.

### Table 1: Variables in the district level data base for Peru

| Variable | Unit | Source |
|---|---|---|
| Total population per district | - | 2005 National Census – INEI Peru |
| Urbanization rate<br>(Percentage of population living in urban areas) | % | 2005 National Census – INEI Peru |
| Literacy rate<br>(Percentage of the adult population that can read and write) | % | Human Development Report – Peru 2006 |
| Life expectancy | Years | Human Development Report – Peru 2006 |
| Per capita income | Nuevos Soles per month | Human Development Report – Peru 2006 |
| Latitude | Decimal degrees | Department of Energy and Mines – Peru<br>Google Earth |
| Longitude | Decimal degrees | Department of Energy and Mines – Peru<br>Google Earth |
| Elevation | Kilometers above sea level | Data Bank of District Information – INEI Peru |
| Normal average annual temperature | Degrees Celsius | World Climate |
| Normal annual rainfall | Milimeters | New et.al (2002): 10' latitude/longitude data set of mean monthly surface climate over global land areas |

As we did not have meteorological data for each and every district in Peru, this information was estimated. Since average annual temperature in any particular location depends principally on distance from the equator and elevation above sea-level, we estimated a simple model (see Table 2) using information on average annual temperature, latitude, and altitude for all the Peruvian stations for which we could obtain "normal" temperature data (from www.worldclimate.org).

### Table 2: Model used to estimate temperature in districts with missing data

| Variable | Coefficient | t-value | P-value |
|---|---|---|---|
| Elevation | -2.1518 | -4.48 | 0.0000 |
| Latitude | -0.3883 | -8.87 | 0.0000 |
| Constant | 27.2469 | 17.25 | 0.0000 |
| **No. of observations** | 27 | | |
| **$R^2$** | 0.7669 | | |

The model indicates that, for every kilometer of elevation, the temperature drops 2.15ºC, and for every latitudinal degree further south, the temperature drops 0.39ºC. This information was used to estimate temperature in all the remaining districts, using the altitude and latitude of the district capital.

Rainfall does not present such simple regularities, so in order to estimate rainfall for the districts where this information was missing, we used the 10-minute latitude/longitude data set of mean monthly surface climate over global land areas, constructed by New et al. (2002). This data set includes precipitation data and was interpolated from a data set of station means for the period centered on 1961 to 1990.[3]

In order to assess the climate change trends in the different parts of Peru, we obtained monthly temperature and rainfall data from 1948 to 2008 from the Monthly Climatic Data for the world (MCDW) publication of the US National Climatic Data Center (NCDC). The constructed data set was complemented with data from the Global Climate Observing System of the NCDC (sent by request) and data obtained from the National Meteorological and Hydrological Service of Peru (SENAMHI). The data are described in more detail in Section 4 below.

## 3. Modeling climate and human development

In this section, we estimate the contemporary relationship between climate and human development in Peru. Two dimensions of human development are analyzed: income and health, because these are the ones that most directly could be affected by climate change. Education, on the other hand, is treated as an explanatory variable instead of a dependent variable.

As several researchers have pointed out, the relationship between temperature and development is likely to be hump-shaped, as both too cold and too hot climates may be detrimental for human development (Mendelsohn, Nordhaus & Shaw, 1994; Quiggin & Horowitz, 1999; Masters & McMillan, 2001, Tol, 2005). In order to allow for this possibility we include both average annual temperature and its square in the regression. The same argument also holds for precipitation and possibly also urbanization rates, which is why we also include precipitation and urbanization rates squared.

Thus, the regressions in this section will take the following form:

$$\ln y_i = \alpha + \beta_1 \cdot temp_i + \beta_2 \cdot temp_i^2 + \beta_3 \cdot rain_i + \beta_4 \cdot rain_i^2 + \beta_5 \cdot edu_i + \beta_6 \cdot urb_i + urb_i^2 + \varepsilon_i$$

where $y_i$ is a measure of the income level in district $i$, $temp_i$ and $rain_i$ are normal average annual temperature and normal accumulated annual precipitation in district $i$, $edu_i$ is a

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[3] The data are available online at the School of Geography at Oxford (http://www.geog.ox.ac.uk), the International Water Management Institute "World Water and Climate Atlas" (http://www.iwmi.org) and the Climatic Research Unit (http://www.cru.uea.ac.uk).

measure of the education level (percentage of the adult population that can read and write), $urb_i$ is the urbanization rate of the district, and $\varepsilon_i$ is the error term for district $i$.

The life expectancy regression will take the same form as the income regressions, except that we will not apply the natural logarithm to the dependent variable. All regressions are weighted OLS regressions, where the weights consist of the population size in each district.

The regression results for both income and life expectancy are reported in Table 3.

**Table 3: Estimated short-term relations between climate and income/life expectancy in Peru**

| **Explanatory variables** | **(1)** (log per capita income) | **(2)** (life expectancy) |
|---|---|---|
| Constant | 2.5912 | 24.6883 |
| | (14.28) | (19.32) |
| Temperature | 0.1837 | 3.1322 |
| | (11.37) | (27.53) |
| Temperature$^2$ | -0.0051 | -0.0805 |
| | (-11.46) | (-25.64) |
| Precipitation | -0.5562 | -1.8907 |
| | (-17.44) | (-8.42) |
| Precipitation$^2$ | 0.1171 | 0.3730 |
| | (10.77) | (4.87) |
| Education level | 0.0214 | 0.1874 |
| | (15.49) | (19.25) |
| Urbanization rate | -0.0095 | -0.0339 |
| | (-8.17) | (-4.14) |
| Urbanization rate$^2$ | 0.0001 | 0.0006 |
| | (10.67) | (8.30) |
| Number of obs. | 1829 | 1829 |
| $R^2$ | 0.7449 | 0.8147 |

*Source:* Authors' estimation based on assumptions explained in the text.
Note: Numbers in parenthesis are t-values. When t-values are numerically larger than 2, we will consider the coefficient to be statistically significant, corresponding to a confidence level of 95%.

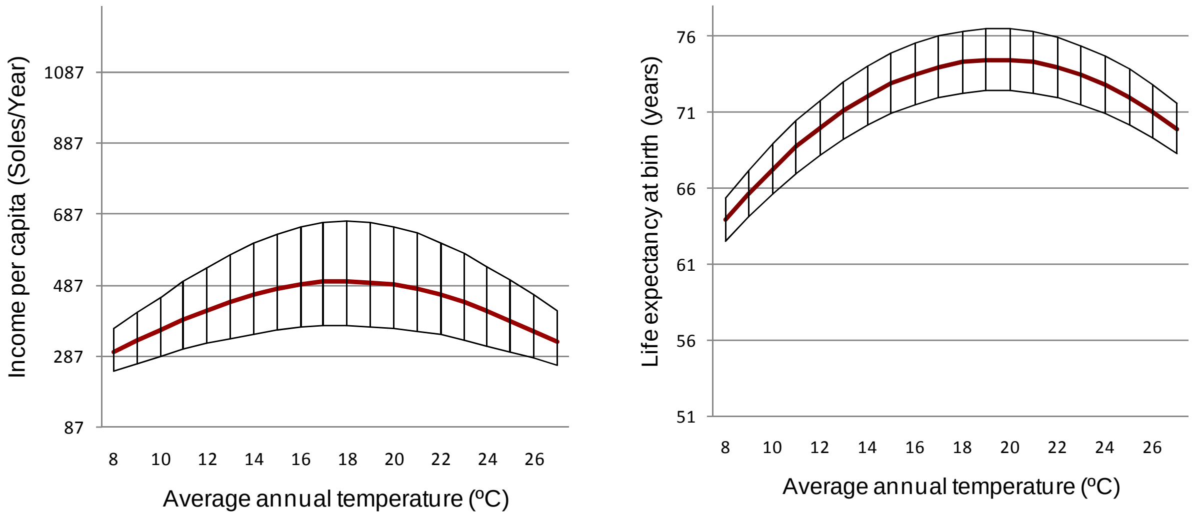
The results at the bottom of the table show that just these four explanatory variables (temperature, rainfall, education, and urbanization rates) explain more than 74% of the variation in incomes between the districts in Peru. This is a very good fit, which suggests that we have included the most important explanatory variables, and that including addition variables would make little difference. The same four variables explain about 81% of the variation in life expectancy, which is even more impressive.

Education level, here measured as the percentage of the adult population that can read and write, is the most important variable, explaining about 48% of the variation in incomes and about 58% of the variation in life expectancy. The remaining variables are also all statistically significant, but in a non-linear way. As it is difficult to judge the effects directly by looking at the estimated coefficients, we have plotted the estimated relationships in Figure 2. The axes are scaled to represent the actual range of temperatures, rainfall, incomes, and life expectancies experienced in different Peruvian districts, so that the magnitude of climate impacts can be seen in the appropriate perspective. 95% confidence intervals on the estimated relationships have also been included in the figure.

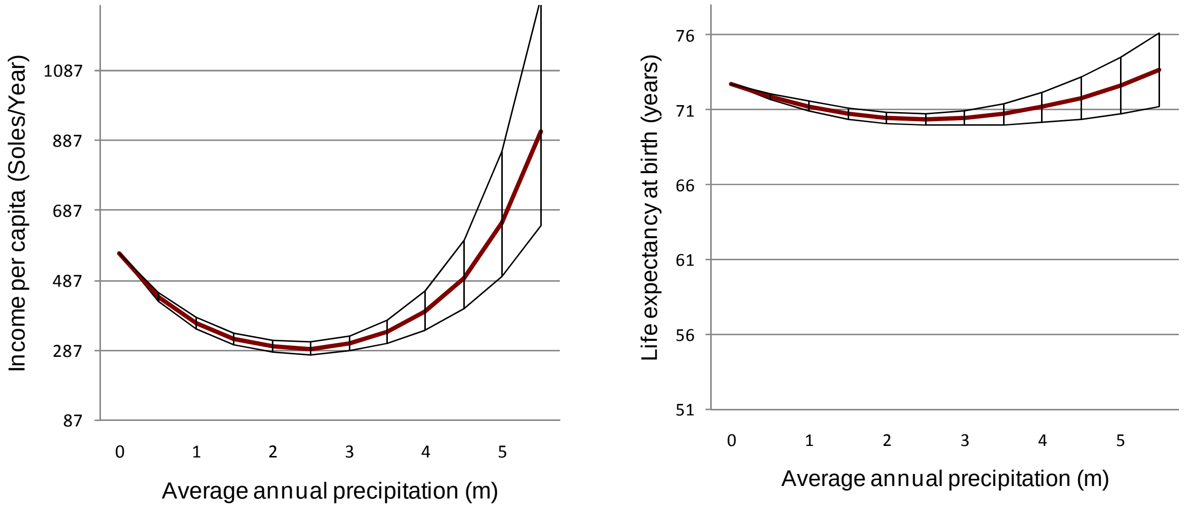
Panel (a) shows a hump-shaped relationship between average annual temperature and per capita income, with inhabitants in the regions located in the optimal temperature range earning at least 50% more than inhabitants living in either the coldest or the hottest regions.

Panel (b) also shows a hump-shaped relationship between temperatures and life expectancy, with a difference of more than 10 years between the optimal temperature and the coldest temperature.

**Figure 2: Estimated contemporary relations between temperature/rainfall and income/life expectancy in Peru**


**(a) Temperature and Income** **(b) Temperature and life expectancy**

**(c) Rainfall and Income** **(d) Rainfall and life expectancy**



*Source:* Graphical representation of the estimation results from Table 3.
*Notes:* The thick red line represents the point estimate from the regressions in Table 3 while the thin black lines

outline the 95% confidence interval on the relationship as estimated by Stata's lincom command.

Panel (c) and (d) suggest that people in Peru do better with either very little rain or with a lot of rain. For intermediate amounts of rain, incomes and life expectancies are considerably lower. This is somewhat counter-intuitive, but the results are very robust.

## 4. Recent climate change in Peru

In this section we will analyze climate data from Peru from May 1948 to May 2008 to test whether there are any significant trends, and whether these trends differ between regions.

Most of the data come from the Monthly Climatic Data for the world database collected by the National Climatic Data Center (NCDC) in the US. This project started in May 1948 with 100 selected stations spread across the world. Peru started contributing with data from four stations (Piura, Chiclayo, Lima, and Cuzco) in August 1948. Since then, many more stations have been included in the data base, and 20 Peruvian stations have contributed more or less regularly. The original data were organized in 61 printed volumes with 12 issues in each (one for each month of the year), totaling 723 months. All data were quality-checked and published by the NCDC about 3 months after the raw data had been collected. Data for 5 stations (Arequipa, Chachapoyas, Iquitos, San Juan and Tarapoto) were very incomplete in the original publications, but NCDC had the data in their database, and made it available to us.[4]

Monthly data from 4 other stations (Augusto Weberbauer, Campo de Marte, Granja Kcayra, and La Pampilla) were obtained directly from the National Meteorological and Hydrological Service of Peru (SENAMHI).

In total we have obtained temperature and precipitation series for 24 stations in Peru. These are listed in Table 4.

**Table 4: Meteorological stations in Peru with reasonably complete monthly data from 1948 to 2008**

| Station | Latitude (ºS) | Longitude (ºW) | Elevation (m) | Complete-ness |
|---|---|---|---|---|
| AREQUIPA | -16.33 | -71.57 | 2539 | 85% |
| AUGUSTO WEBERBAUER | -7.15 | -78.48 | 2660 | 71% |
| CAJAMARCA | -7.13 | -78.47 | 2622 | 55% |
| CAMPO DE MARTE | -12.07 | -77.03 | 159 | 53% |
| CHACHAPOYAS | -6.20 | -77.85 | 2540 | 49% |
| CHICLAYO | -6.78 | -79.82 | 30 | 87% |
| CUZCO | -13.53 | -71.93 | 3249 | 85% |

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[4] The data request was made in the website of the NCDC, through the Global Climate Observing System's portal (GSNMON).

| | | | | |
|---|---|---|---|---|
| GRANJA KCAYRA | -13.55 | -71.52 | 3219 | 72% |
| IQUITOS | -3.78 | -73.30 | 126 | 97% |
| JUANJUI | -7.17 | -76.72 | 363 | 56% |
| JULIACA | -15.48 | -70.15 | 3827 | 57% |
| LA PAMPILLA | -16.40 | -71.52 | 2400 | 74% |
| LIMA-CALLAO/AEROP. | -12.00 | -77.12 | 13 | 75% |
| PISCO | -13.73 | -76.22 | 7 | 90% |
| PIURA | -5.20 | -80.60 | 55 | 77% |
| PUCALLPA | -8.37 | -74.57 | 149 | 83% |
| SAN JUAN | -15.38 | -75.17 | 60 | 74% |
| TACNA | -18.05 | -70.27 | 458 | 80% |
| TALARA | -4.57 | -81.23 | 85 | 75% |
| TARAPOTO | -6.50 | -76.37 | 282 | 77% |
| TINGO MARIA | -9.28 | -76.00 | 665 | 60% |
| TRUJILLO | -8.08 | -79.10 | 30 | 80% |
| TUMBES | -3.55 | -80.40 | 27 | 59% |
| YURIMAGUAS | -5.88 | -76.12 | 184 | 63% |

*Sources:* NCDC's Monthly Climatic Data for the world, SENAMHI.

Once the temperature and precipitation series had been constructed and checked for unrealistic values (there were 21 unrealistic temperatures and 11 unrealistic precipitation observations, which were eliminated), we proceeded to calculate "normal" temperatures and "normal" rainfall for each station-month for the reference period 1960-1990.

### *4.1. Temperature trends*

Using the "normal" values for each station and each month, we calculated monthly anomalies for each station for the whole period (actual temperature minus normal temperature for that month). Anomalies are easier to analyze than the raw temperature and rainfall data, since the seasonal variation is eliminated through the subtraction of normal monthly temperatures. All 24 temperature anomaly series are plotted in Appendix A.

Once we have the series of temperature anomalies, it is straightforward to test whether there is a significant trend. This is done by regressing the anomaly on a trend-variable which has been scaled so that the coefficient can be directly interpreted as temperature change per decade in degrees Celsius. We use a confidence level of 95% to decide whether the trend is statistically significant, which means that the P-value should be less than 0.05 for the trend to be significant.

Table 5 shows the estimated trends for each of the 24 stations in Peru. Of these, 15 show a significant warming trend, typically of 0.2-0.3ºC/decade, 4 show a significant negative trend of -0.1 to -0.2ºC/decade, and 5 show no significant trend. La Pampilla shows exceptional warming compared to all other stations, but an inspection of the anomaly series (see Appendix A) shows that no warming has taken place during the last 25 years, and that a strange, abrupt drop in temperatures take place in the beginning of the series.

**Table 5: Estimated temperature trend (ºC/decade) for 24 stations in Peru**

| Station | Trend | t-value | P-value | # of obs. |
|---|---|---|---|---|
| AREQUIPA | -0.1865 | -7.26 | 0.000 | 614 |
| AUGUSTO WEBERBAUER | 0.3128 | 14.83 | 0.000 | 510 |
| CAJAMARCA | 0.2751 | 8.38 | 0.000 | 395 |
| CAMPO DE MARTE | -0.1169 | -1.74 | 0.082 | 386 |
| CHACHAPOYAS | 0.0292 | 0.76 | 0.448 | 352 |
| CHICLAYO | 0.2894 | 8.34 | 0.000 | 623 |
| CUZCO | -0.1340 | -5.38 | 0.000 | 617 |
| GRANJA KCAYRA | 0.2812 | 15.81 | 0.000 | 523 |
| IQUITOS | -0.1145 | -8.75 | 0.000 | 703 |
| JUANJUI | 0.2478 | 8.42 | 0.000 | 397 |
| JULIACA | 0.3257 | 8.71 | 0.000 | 406 |
| LA PAMPILLA | 0.7237 | 22.25 | 0.000 | 534 |
| LIMA-CALLAO/AEROP. | 0.1684 | 4.07 | 0.000 | 543 |
| PISCO | 0.2788 | 10.93 | 0.000 | 652 |
| PIURA | -0.2066 | -6.87 | 0.000 | 557 |
| PUCALLPA | -0.0205 | -0.74 | 0.462 | 598 |
| SAN JUAN | 0.3359 | 12.20 | 0.000 | 538 |
| TACNA | 0.0476 | 1.70 | 0.090 | 578 |
| TALARA | 0.3765 | 8.99 | 0.000 | 540 |
| TARAPOTO | 0.2946 | 10.48 | 0.000 | 559 |
| TINGO MARIA | 0.1988 | 7.54 | 0.000 | 432 |
| TRUJILLO | 0.2237 | 5.66 | 0.000 | 575 |
| TUMBES | 0.0096 | 0.24 | 0.810 | 430 |
| YURIMAGUAS | 0.2564 | 8.92 | 0.000 | 455 |

*Source:* Authors' estimation based on data from the NCDC's Monthly Climatic Data for the world and SENAMHI.

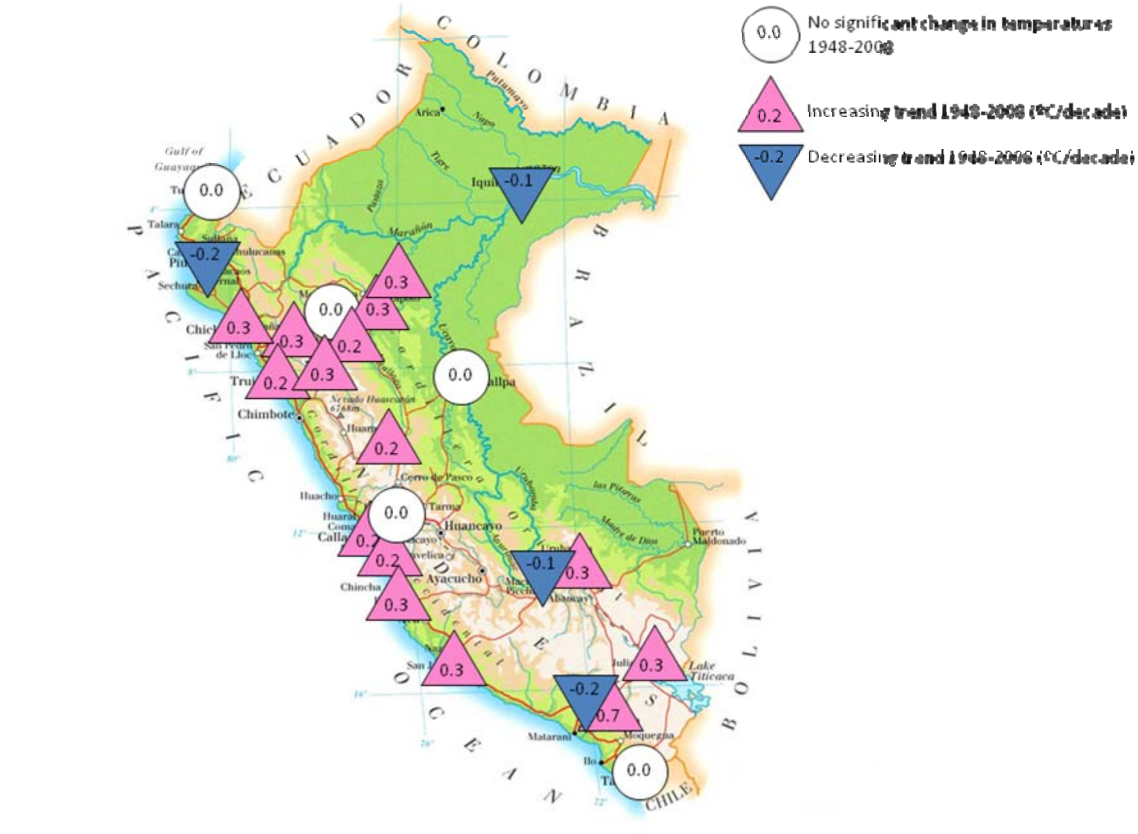
Map 1 shows that warming trends and cooling trends seem to be spread randomly across the Peruvian territory. The coast is dominated by warming trends, but interspersed with a cooling trend and a couple of insignificant trends. The mountains have a couple of cooling trends, but also several warming trends. Iquitos, in the rainforest, has the most complete temperature series of all the Peruvian stations, and show cooling, but other rainforest stations show warming. Based on these estimated trends, it is not possible to establish any systematic differences between regions, and our simulations in the next section will therefore be based on an average trend for the whole country.

The average trend over all 24 stations is +0.16ºC per decade. If we limit ourselves to the stations that have at least 500 observations (out of 723 possible), the average trend is +0.17ºC/decade. If we rely only on the most complete series with over 600 observations the trend is reduced to +0.02ºC/decade, which is indistinguishable from no trend. This suggests that the estimated trend is sensitive to the starting and end points of the series. This is because temperature data show strong cyclical patterns, and if a series happens to start at the bottom of a cycle and end at the top of a cycle, it will show a stronger average trend than if it happens to start at the top of a cycle and end at the bottom. No century-long series exist for Peru, so the trend we have estimated for 1948-2008 is strictly for that period, and cannot be expected to continue neither backwards nor forwards.

It should also be pointed out that these are the raw temperature data without any adjustments due to urbanization and land use changes. This is appropriate for an analysis on the impacts of experienced climate change, but not appropriate for an analysis about the causes of such climate change. This paper does not distinguish between the different causes of climate change (natural variation, increased $CO_2$, land use changes, etc), but simply simulates the likely effect of actual measured climate change.

An average warming of 0.15ºC per decade seems to be a reasonable value to choose for the simulations in the following chapter. That is, an average increase of 0.75ºC over the last 50 years.

**Map 1: Temperature trends 1948-2008 at 24 meteorological stations in Peru**



*Source:* Plot of the location of the temperature trends estimated in Table 5.

### *4.2. Precipitation trends*

Using the same methodology as above, the precipitation data for 24 stations are analyzed to detect systematic trends. All the 24 precipitation anomaly series are plotted in Appendix B. Table 6 shows that 4 stations had a significant negative trend in precipitation, 3 stations had a significant positive trend, but the majority of stations (17) had no significant trend at all.

**Table 6: Estimated precipitation trend (mm/decade) for 24 stations in Peru**

| Station | Trend | t-value | P-value | # of obs. |
|---|---|---|---|---|
| AREQUIPA | -0.8564 | -1.27 | 0.206 | 608 |
| AUGUSTO WEBERBAUER | 1.8484 | 1.62 | 0.107 | 511 |
| CAJAMARCA | 0.0183 | 0.01 | 0.992 | 379 |
| CAMPO DE MARTE | -0.2280 | -4.02 | 0.000 | 374 |
| CHACHAPOYAS | 0.0819 | 0.04 | 0.972 | 398 |
| CHICLAYO | -1.0942 | -1.49 | 0.136 | 609 |
| CUZCO | -0.8844 | -0.76 | 0.446 | 578 |
| GRANJA KCAYRA | 0.7333 | 0.66 | 0.512 | 438 |
| IQUITOS | 12.8737 | 5.06 | 0.000 | 679 |
| JUANJUI | 0.3905 | 0.13 | 0.897 | 390 |
| JULIACA | -2.4703 | -1.44 | 0.151 | 392 |
| LA PAMPILLA | -0.4479 | -0.78 | 0.437 | 423 |
| LIMA-CALLAO/AEROP. | -1.3658 | -1.55 | 0.122 | 502 |
| PISCO | -1.2435 | -3.13 | 0.002 | 624 |
| PIURA | 2.2242 | 1.25 | 0.212 | 537 |
| PUCALLPA | -3.0125 | -1.34 | 0.180 | 575 |
| SAN JUAN | -0.6679 | -1.20 | 0.233 | 430 |
| TACNA | -1.0533 | -5.64 | 0.000 | 556 |
| TALARA | 3.7294 | 2.66 | 0.008 | 513 |
| TARAPOTO | -3.1772 | -2.46 | 0.014 | 611 |
| TINGO MARIA | -0.6414 | -0.13 | 0.893 | 424 |
| TRUJILLO | 0.1481 | 0.37 | 0.709 | 541 |
| TUMBES | 7.3707 | 2.46 | 0.014 | 387 |
| YURIMAGUAS | -0.1102 | -0.04 | 0.966 | 446 |

*Source:* Authors’ estimation based on data from the NCDC’s Monthly Climatic Data for the world.

There seem to be no systematic differences between regions. Among the coastal stations, three showed a reduction, two showed an increase and five no change. Among the mountain stations, all stations showed no significant change. Among the rainforest stations, one showed increase, one showed decrease and four showed no change.

In no region is there convincing evidence of a systematic change in precipitation, so for the purpose of simulation in the following section, we will assume no change in precipitation patterns over the last 50 years.

## 5. Simulating the impact of recent climate change

In this section, we will use the two models estimated in Table 3 above to simulate the impacts of the climate change experienced during the last 50 years on per capita income and life expectancy in each of the 1,829 districts in Peru.

To gauge the impacts of climate change we will compare the following two scenarios: 1) Climate Change, which is the factual scenario, and 2) No Climate Change, which is the counterfactual scenario. The Climate Change temperatures are the actual temperatures in each district, whereas the No Climate Change temperatures are the actual temperatures minus the temperature changes experienced over the last 50 years, according to the analysis in the previous section, i.e. 0.75ºC lower. Precipitation is the same in both scenarios. Education levels and urbanization rates are also held constant in order to isolate the effect of changes in climate.

### *5.1 Impacts of recent climate change on life expectancy*

The Climate Change level of life expectancy can be written as:

$$LE_{i,CC} = \hat{\beta}_1 \cdot t_{i,CC} + \hat{\beta}_2 \cdot t_{i,CC}^2 + \hat{\beta}_3 \cdot r_i + \hat{\beta}_4 \cdot r_i^2 + \sum_{j=1}^{k} \hat{\alpha}_j X_{j,i} + \hat{\varepsilon}_i \,,$$

where the index *i* refers to district *i*; *t* and *r* are the temperature and rainfall variables; the $\hat{\beta}$ s are the estimated coefficients on the temperature and rainfall variables; the $X_j$s are the remaining *j* explanatory variables including the constant term; the $\hat{\alpha}_j$ s are the coefficient to these variables; and $\hat{\varepsilon}_i$ are the estimated error terms for each district.

Equivalently, the counterfactual level of life expectancy under the assumption of No Climate Change can be written as:

$$LE_{i,NCC} = \hat{\beta}_1 \cdot t_{i,NCC} + \hat{\beta}_2 \cdot t_{i,NCC}^2 + \hat{\beta}_3 \cdot r_i + \hat{\beta}_4 \cdot r_i^2 + \sum_{j=1}^{k} \hat{\alpha}_j X_{j,i} + \hat{\varepsilon}_i \,,$$

where the only thing that differ is the temperature variable.

The difference between the two scenarios is the difference in life expectancy that can be directly attributed to climate change:

$$\Delta_{CC} LE_i = LE_{i,CC} - LE_{i,NCC} = \hat{\beta}_1 \cdot (t_{i,CC} - t_{i,NCC}) + \hat{\beta}_2 \cdot (t_{i,CC}^2 - t_{i,NCC}^2)$$
$$+ \hat{\beta}_3 \cdot (r_{i,CC} - r_{i,NCC}) + \hat{\beta}_4 \cdot (r_{i,CC}^2 - r_{i,NCC}^2)$$

Since rainfall is assumed to be the same in the two scenarios, the third and fourth term of this expression drops out.

*Simulation results*

Table 7 shows the simulation results aggregated at the regional level and at the country level. Overall, the warming experienced over the last 50 years is estimated to have no effect on life expectancy, but this is a net effect resulting from the initially cool regions having gained from warming and the initially warm regions having lost.

**Table 7: Simulated effects of recent climate change on life expectancy (in years), by state**

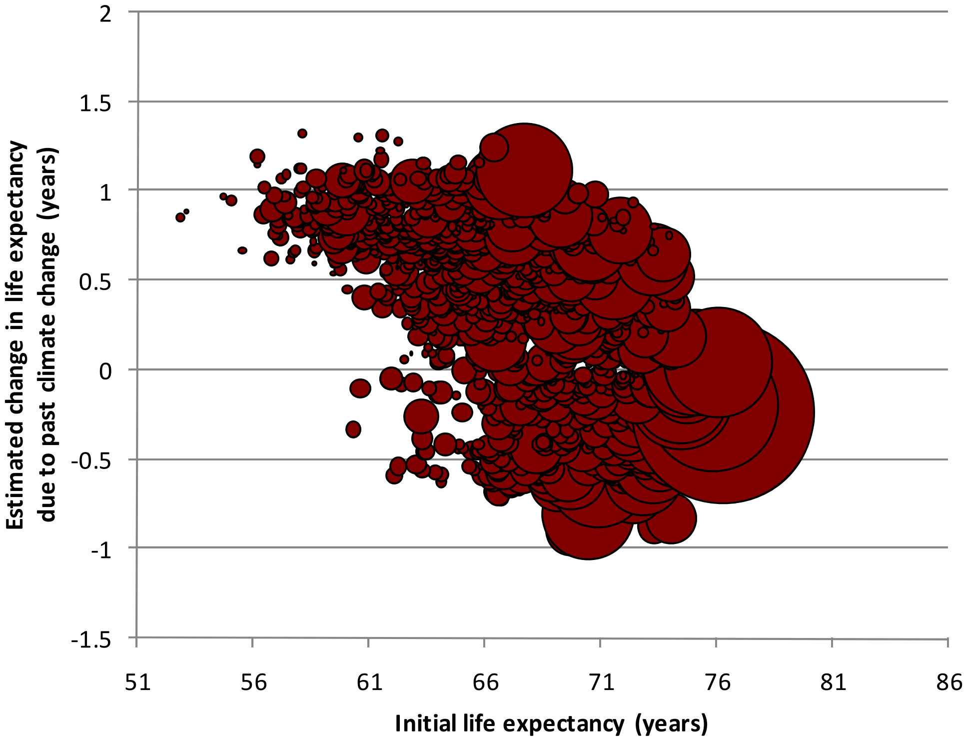
| Region | Population 2005 (thousands) | Total effect of recent climate change |
|---|---:|---:|
| Amazonas | 389 | -0.2 |
| Ancash | 1,039 | 0.1 |
| Apurimac | 419 | 0.7 |
| Arequipa | 1,141 | 0.5 |
| Ayacucho | 619 | 0.6 |
| Cajamarca | 1,359 | 0.2 |
| Callao | 811 | -0.3 |
| Cusco | 1,172 | 0.7 |
| Huancavelica | 447 | 0.8 |
| Huanuco | 731 | 0.2 |
| Ica | 666 | -0.1 |
| Junin | 1,092 | 0.5 |
| La Libertad | 1,540 | -0.1 |
| Lambayeque | 1,092 | -0.4 |
| Lima | 7,819 | -0.2 |
| Loreto | 884 | -0.7 |
| Madre de Dios | 92 | -0.3 |
| Moquegua | 159 | 0.3 |
| Pasco | 267 | 0.6 |
| Piura | 1,631 | -0.4 |
| Puno | 1,246 | 1.0 |
| San Martin | 670 | -0.4 |
| Tacna | 274 | 0.2 |
| Tumbes | 192 | -0.7 |
| Ucayali | 402 | -0.6 |
| **Total** | **26,152** | **0.0** |

*Source:* Authors' estimations.

According to the simulations, the most adversely affected district in all of Peru is Yurimaguas in the province of Alto Amazonas in Loreto. This was an already hot district which got even warmer, thus having an adverse effect on life expectancy of about 0.9 years. More than 100 highland districts were estimated to gain at least 1 year of life expectancy due to climate change during the last 50 years, as temperatures warmed towards more optimal levels.

Figure 3 plots the changes in life expectancy due to past climate change against the initial level of life expectancy (the level they would have had in the absence of climate change). There is a significant negative relationship, implying that districts that initially had relatively low levels of life expectancy generally have gained from past climate change, while the districts that initially had higher levels of life expectancy have experienced and adverse impact from past climate change. Thus, the simulations suggest that climate change during the last 50 years has contributed to reducing inequalities in life expectancy between Peruvian districts.

**Figure 3: Estimated change in life expectancy due to past climate change versus initial life expectancy, district level**



## *5.2 Impact of recent climate change on income levels*

The ratio of Climate Change Income to No Climate Change Income can be written as:

$$\Delta_{CC}Y_i = \frac{Y_{i,CC}}{Y_{i,NCC}} = \frac{\exp\left\{\hat{\beta}_1 \cdot t_{i,CC} + \hat{\beta}_2 \cdot t_{i,CC}^2 + \hat{\beta}_3 \cdot r_{i,CC} + \hat{\beta}_4 \cdot r_{i,CC}^2\right\}}{\exp\left\{\hat{\beta}_1 \cdot t_{i,NCC} + \hat{\beta}_2 \cdot t_{i,NCC}^2 + \hat{\beta}_3 \cdot r_{i,NCC} + \hat{\beta}_4 \cdot r_{i,NCC}^2\right\}}$$

After estimating this ratio for each district, it is straightforward to calculate the percentage change in income levels that can be attributed to climate change.

At the national level, the simulation indicates that past climate change has had a negative effect on overall income levels of about 1%. This modest effect at the aggregate level, however, hides much larger variations at the state and district levels. The jungle state of Loreto, for example, is estimated to have experienced a reduction in incomes of about 5.1%, while the mountain state of Puno is estimated to have benefitted in the order of 5.5%.

**Table 8: Simulated effects of recent climate change on income (% change), by region**

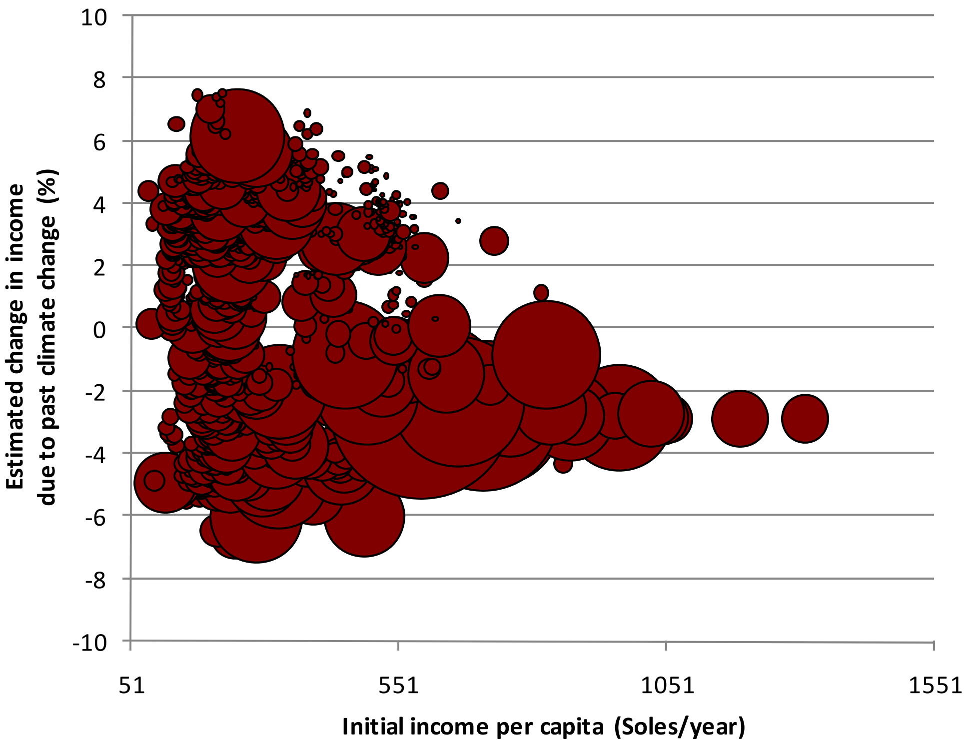
| Region | Population 2005 (thousands | **Total effect of recent climate change** |
|---|---:|---:|
| Amazonas | 389 | -2.4 |
| Ancash | 1,039 | -0.1 |
| Apurimac | 419 | 3.4 |
| Arequipa | 1,141 | 2.2 |
| Ayacucho | 619 | 2.6 |
| Cajamarca | 1,359 | -0.1 |
| Callao | 811 | -3.0 |
| Cusco | 1,172 | 3.5 |
| Huancavelica | 447 | 3.8 |
| Huanuco | 731 | 0.2 |
| Ica | 666 | -1.8 |
| Junin | 1,092 | 2.3 |
| La Libertad | 1,540 | -1.9 |
| Lambayeque | 1,092 | -3.6 |
| Lima | 7,819 | -2.5 |
| Loreto | 884 | -5.1 |
| Madre de Dios | 92 | -2.8 |
| Moquegua | 159 | 0.7 |
| Pasco | 267 | 2.6 |
| Piura | 1,631 | -3.8 |
| Puno | 1,246 | 5.5 |
| San Martin | 670 | -3.8 |
| Tacna | 274 | 0.2 |
| Tumbes | 192 | -5.2 |
| Ucayali | 402 | -4.8 |
| **Total** | **26,152** | **-1.0** |

*Source:* Authors' estimations.

Figure 4 plots the estimated change in income at the district level against the income level each district would have had in the absence of recent climate change. The figure indicates that many initially poor districts have experienced substantial drops in income, which suggest that past climate change may have contributed to an increase in poverty in Peru.

There is a statistically significant negative relationship between initial level of income and estimated impact from past climate change, indicating that while recent climate change has had an adverse effect on overall income levels and poverty levels, it may have contributed slightly to an improvement in the income distribution. According to the simulations, many cold, poor districts have benefitted from a little warming, while all the initially richer, warm areas (including Lima) have been adversely affected by further warming.

**Figure 4: Estimated change in incomes due to past climate change versus initial income level, district level**



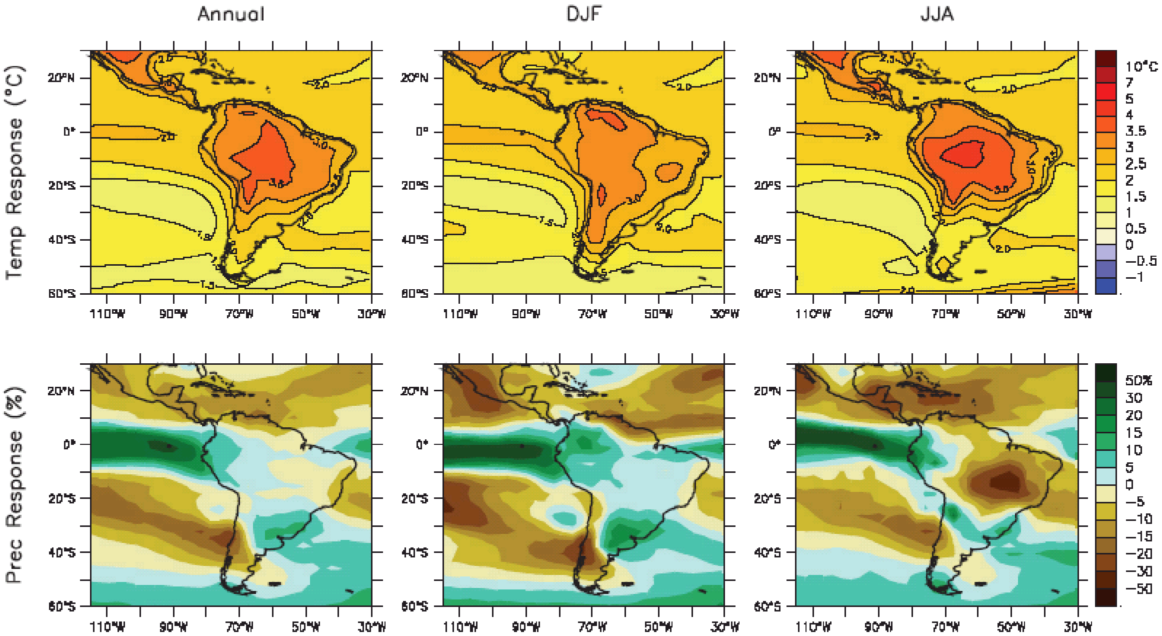
## 6. Expected future climate change in Peru

Having quantified the impacts of climate change during the last 50 years, we now turn to an assessment of the likely impacts of possible climate change during the next 50 years.

For that purpose we will use the regional climate projections made by Working Group 1 for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, which provides a comprehensive analysis based on a coordinated set of 21 Atmosphere-Ocean General Circulation Models (Christensen *et al*, 2007). The use of several different models allows an assessment of the level of confidence with which predictions can be made.

According to the model simulations reported in Christensen *et al* (2007), temperatures are going to increase fastest in the rainforest region and slowest along the coast (see Figure 5). This does not really correspond to what has been observed in the past (see Map 1), but the past includes all effects, both natural and manmade, while the simulations for the future only includes the expected effect of increased concentrations of $CO_2$ in the atmosphere.

**Figure 5: Temperature and precipitation changes predicted by the climate models used by IPCC 4, 1990-2090**



*Source:* Christensen *et al* (2007, Figure 11.15).

Since temperatures are projected to increase approximately linearly over this century, the IPCC projections lead us to assume that temperature increases over the next 50 years will be about 1°C in the coastal region, 1.5°C in the mountain region, and 2°C in the rainforest region.

The 21 IPCC models show little agreement about expected precipitation changes in Peru. About half the models predict a slight increase, especially in the northern part of Peru, but the evidence is very weak (Christensen et al (2007), p. 895). For the purposes of the simulations in the following section, we will assume no systematic changes in precipitation over the next 50 years.

## 7. Simulating the impact of expected future change

Table 9 shows how the expected climate changes described in the previous section would likely affect life expectancy in Peru over the next 50 years (holding all other factors constant).

At the aggregate level, future climate change in Peru is estimated to cause a small reduction in average life expectancy of about 0.2 years. This average, however, hides much bigger losses in the already hot areas as well as substantial gains in currently cold areas. The state that is estimated to benefit most from expected future warming is Puno located high up in the Andes Mountains. In contrast, the simulations suggest that Loreto in the jungle would suffer a 2 year reduction in life expectancy due to future warming of 2ºC.

**Table 9: Simulated effects of future climate change on life expectancy (in years), by region**

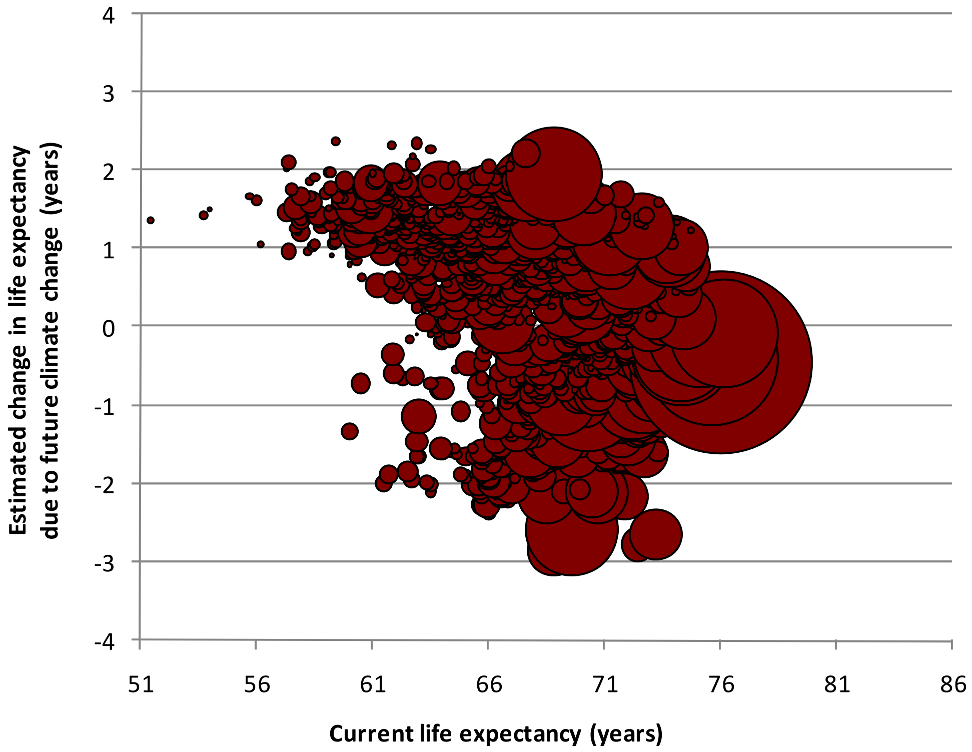
| **Region** | **Estimated effect of future climate change** |
|---|---|
| Amazonas | -1.0 |
| Ancash | 0.2 |
| Apurimac | 1.1 |
| Arequipa | 0.8 |
| Ayacucho | 0.9 |
| Cajamarca | -0.0 |
| Callao | -0.5 |
| Cusco | 1.1 |
| Huancavelica | 1.2 |
| Huanuco | 0.0 |
| Ica | -0.3 |
| Junin | 0.7 |
| La Libertad | -0.3 |
| Lambayeque | -0.8 |
| Lima | -0.5 |
| Loreto | -2.2 |
| Madre de Dios | -1.2 |
| Moquegua | 0.4 |
| Pasco | 0.8 |
| Piura | -0.8 |
| Puno | 1.8 |
| San Martin | -1.6 |
| Tacna | 0.2 |
| Tumbes | -1.0 |
| Ucayali | -2.0 |
| **Total** | **-0.2** |

*Source:* Authors' estimations.

Figure 6 plots the estimated change in life expectancy in each district against current life expectancy. There is a significantly negative correlation ($\rho$ = -0.45) between the two, implying that currently rich districts are likely to lose from future climate change, whereas the majority of the currently poorest districts are projected to experience an increase in life expectancy due to currently temperatures getting closer to optimal.

Thus, while future climate change is estimated to reduce overall life expectancy in Peru, it is estimated to reduce differences in life expectancy between districts, and to have a beneficial effect on the majority of currently disadvantaged districts.

**Figure 6: Estimated change in life expectancy due to future climate change versus current life expectancy, district level**



The simulated effects of future climate change on incomes are presented in Table 10. The overall reduction in incomes due to the climate change we can expect over the next 50 years is around 2.3%, but this average hides much larger impacts at the state and district levels. The incomes in the jungle state of Loreto are estimated to be more than 15% smaller in 50 years if the region experiences a 2ºC increase in temperatures, compared to a situation of no climate change. In contrast, the mountain state of Puno is estimated to experience increases in incomes in the order of 9% if temperatures in the region is going to be 1.5ºC higher.

**Table 10: Simulated effects of future climate change on income (% change), by region**

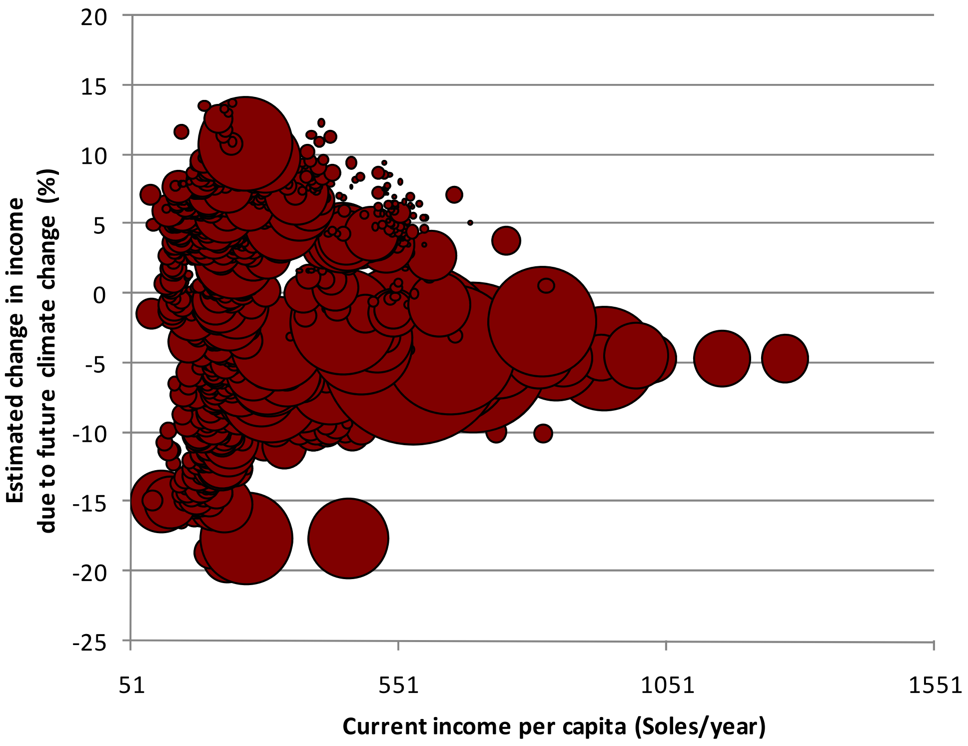
| Region | Estimated effect of future climate change |
|---|---|
| Amazonas | -8.4 |
| Ancash | -0.8 |
| Apurimac | 5.0 |
| Arequipa | 3.0 |
| Ayacucho | 3.3 |
| Cajamarca | -2.5 |
| Callao | -4.8 |
| Cusco | 5.2 |
| Huancavelica | 5.8 |
| Huanuco | -1.9 |
| Ica | -3.3 |
| Junin | 2.3 |
| La Libertad | -3.3 |
| Lambayeque | -6.7 |
| Lima | -4.3 |
| Loreto | -15.5 |
| Madre de Dios | -10.0 |
| Moquegua | 0.5 |
| Pasco | 3.0 |
| Piura | -6.5 |
| Puno | 9.4 |
| San Martin | -12.4 |
| Tacna | -0.5 |
| Tumbes | -7.7 |
| Ucayali | -14.6 |
| **Total** | **-2.3** |

*Source:* Authors' estimations.

Figure 7 plots the estimated change in incomes for each district against the current level of incomes. It is seen that among the currently poor districts, there will both be winners and losers from projected future climate change, with losers being in majority. This means that future climate change is estimated to contribute to increasing poverty in Peru.

There is a very weak negative correlation ($\rho = -0.06$) between current income levels and estimated changes due to future climate change, suggesting that climate change will likely have no significant effect on the income distribution in Peru.

**Figure 7: Estimated change in incomes due to future climate change versus current income, district level**



## 8. Conclusions

In this paper we first used a district level cross-section database to estimate the general relationship between climate and income in Peru. We found that the inhabitants of regions with average annual temperatures around 18-20ºC are considerably better off than inhabitants in both colder and warmer regions, both in terms of income and life expectancy.

These estimated relationships were then used to simulate the effects of both past (1958-2008) and future (2008-2058) climate change. Past changes in climates were analyzed using historical data from 24 meteorological stations spread across the territory, and estimating average trends for each station. It was found that average annual temperatures have increased by about 0.15ºC per decade over the last 6 decades. Although there were local variations, no systematical differences were found between the main three eco-regions. No systematic changes in precipitation were found, either.

The consequences of past warming were then simulated using the estimated cross-section models. The results indicate that initially cold regions have likely benefitted from past warming, while initially hot regions have been adversely affected by further warming. The net effect at the national level was a 1% decrease in incomes attributed to the 0.75ºC warming that has taken place over the last 50 years, but zero net effect on life expectancy, as the positive and negative effects exactly cancel each other out.

Whereas temperatures over the past 50 years have shown moderate warming of about 0.75ºC across the territory, future warming is projected by the IPCC to be considerably stronger, especially in the rainforest region for which IPCC models indicate a 2ºC increase in average annual temperatures over the next 50 years. No systematic changes in rainfall are indicated by IPCC models for Peru.

The paper simulated the likely effects of these projected climate changes, and found again that there are both winners and losers from expected climate change in Peru, but that the negative effects tend to dominate. In terms of life expectancy, the currently most disadvantaged regions are projected to benefit from warming, whereas currently better off regions are projected to experience losses in life expectancy, implying that future climate change may contribute to a reduction in health inequalities between Peruvian districts.

In terms of income, future climate change is estimated to cause substantial changes in the income distribution, as more than 500 presently poor districts are projected to gain at least 5% more income due to warming, whereas another 400 poor districts are projected to lose at least 5% of income. Lima, one of the richest regions, is projected to lose about 4% if temperatures along the coast increase by another 1ºC.

Some qualifications to these results are in order. First of all, it is always dangerous to make inferences about changes in time based on cross-section estimates. The results should not be interpreted as forecasts, merely simulations indicative of the likely direction and magnitude of effects.

Second, the simulations have been carried out by varying temperature, but holding all other factors constant. Holding everything else constant is of course not realistic. Education levels are likely to increase and the structure of the economy is likely to keep changing towards activities that are less sensitive to the climate. If the high growth rates experienced since 2000 (4.5% per year) continue, incomes in 2058 would be 9 times higher than now if there were no climate change, and 8.8 times higher if climate changes as projected by the IPCC models. In either case, people are considerably richer than they are now, and their ways of living may be so different, that the climate-income relationships of today are no longer relevant.

Third, people do not necessarily have to stick around as temperatures increase, as the simulations in the present paper have assumed. Internal migration could potentially reduce the costs of climate change, if people can move towards regions with more suitable climates.

Fourth, this paper compares equilibrium situations before and after climate change, but ignores transition costs. Since climate changes are expected to happen in slow motion, especially compared to the natural variation from month to month and from place to place, such transition costs are likely small, but they may include additional investments in new reservoirs and irrigation systems, as hydroelectric facilities and water supplies are affected by changes in the water flow from melting glaciers.

Finally, it should be warned that the impacts found for Peru cannot be generalized to other countries. The impacts of climate change differ from country to country depending on the spatial distribution of the population, the types of activities they are engaged in, and the particular patterns of climate change.

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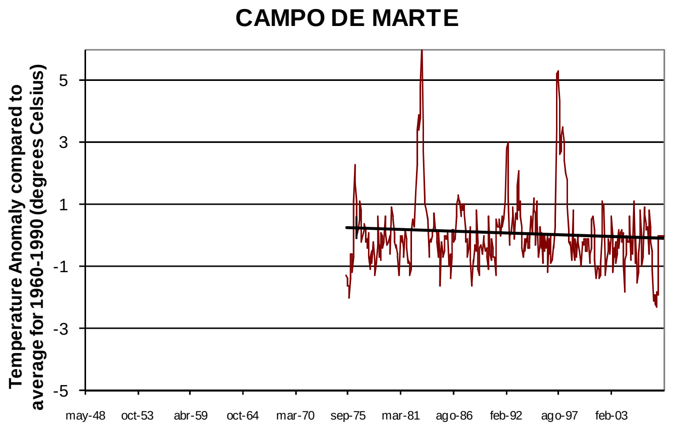
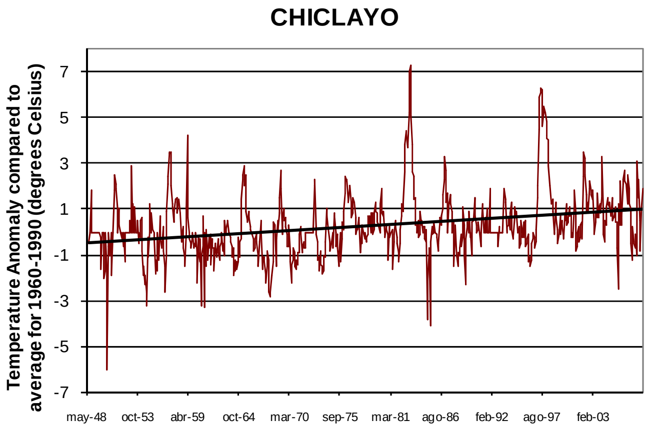
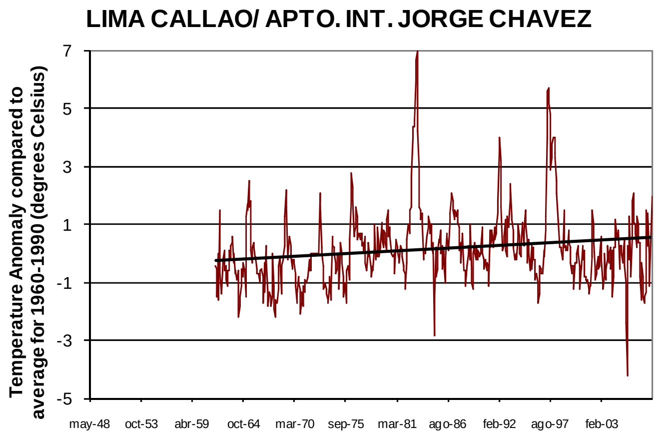
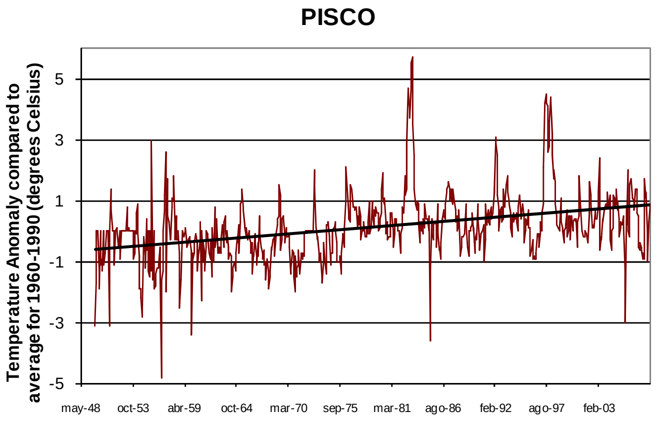
# Appendix A: Plots of temperature anomalies

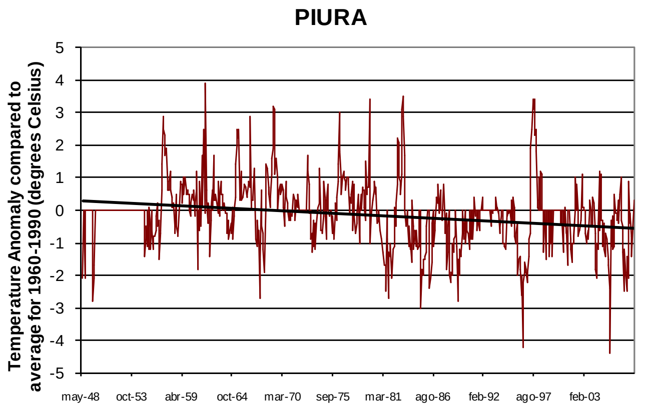
## *Coastal stations*

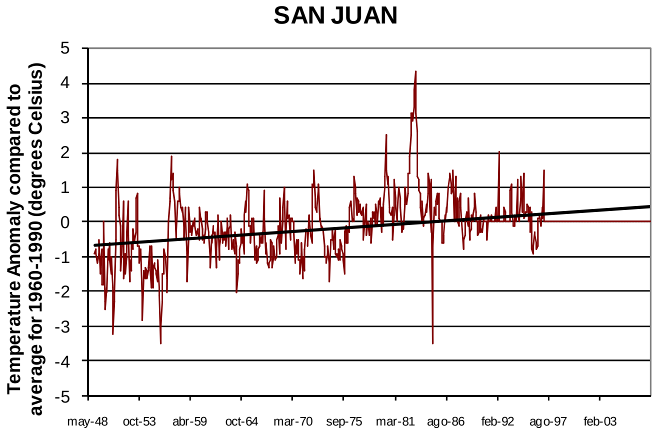


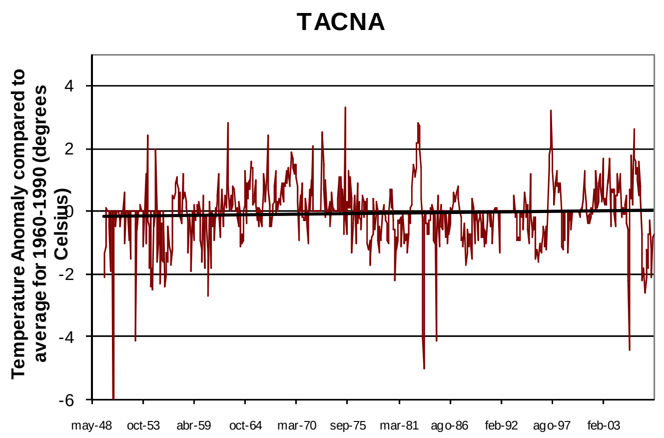


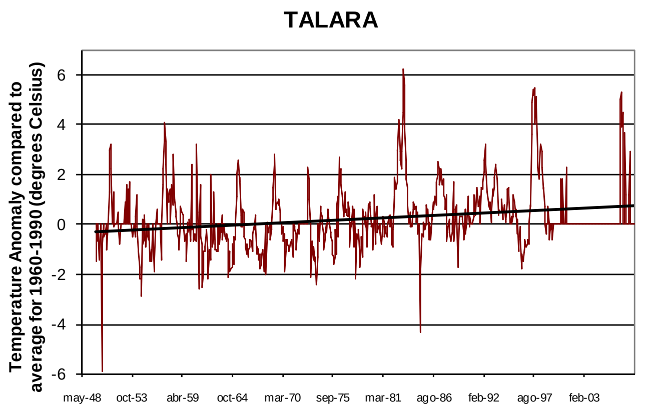


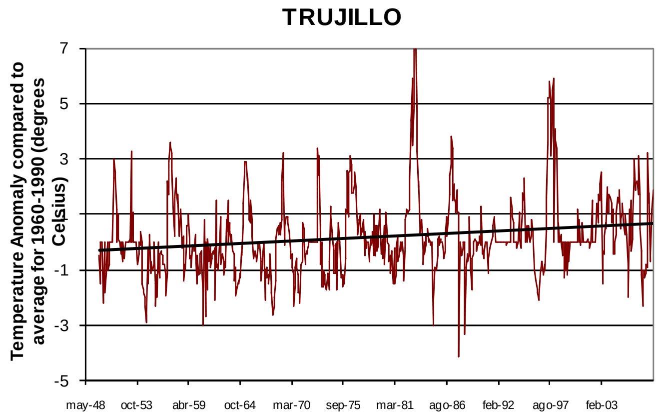


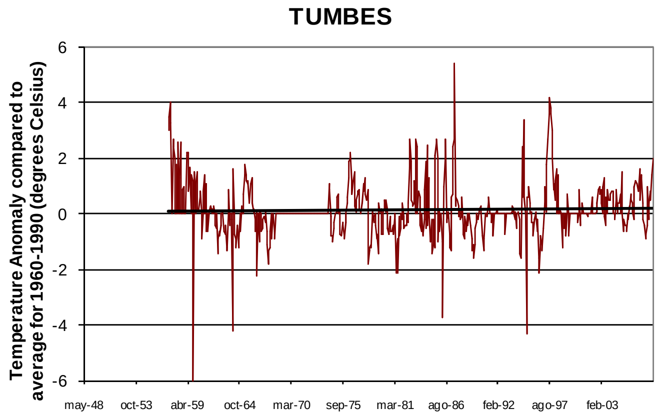




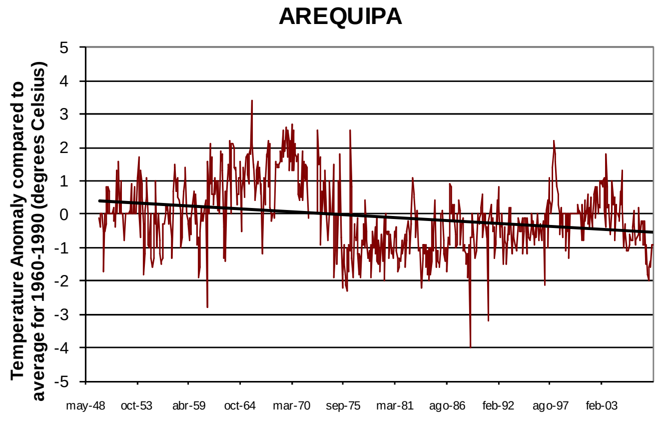


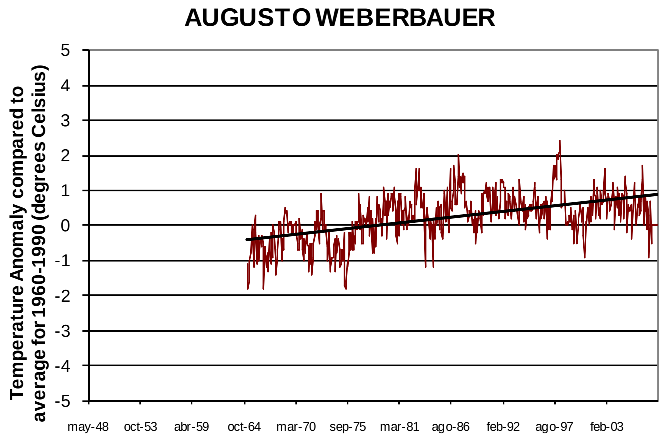


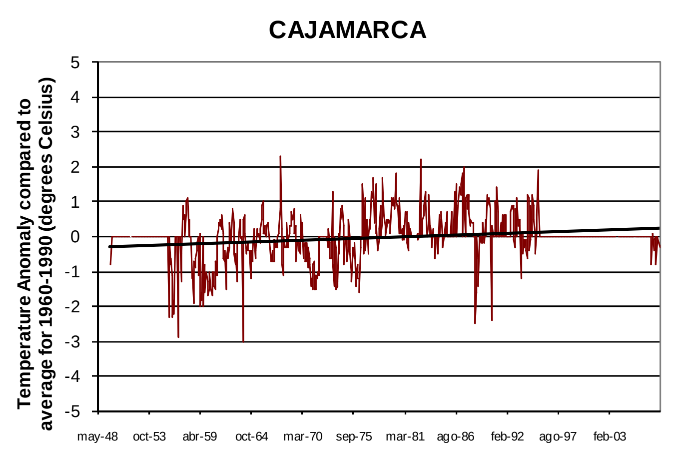


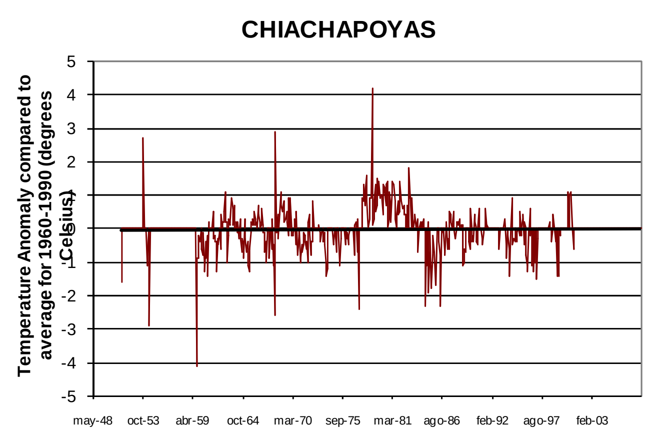


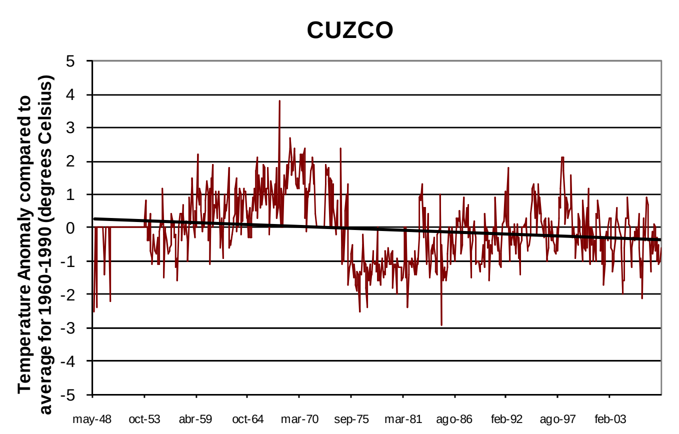
*Mountain stations*

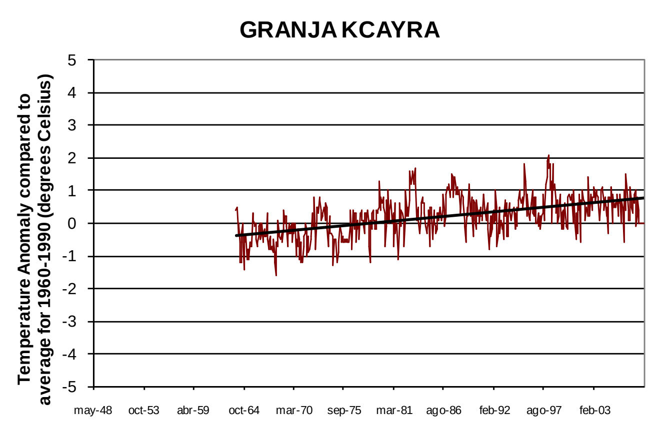


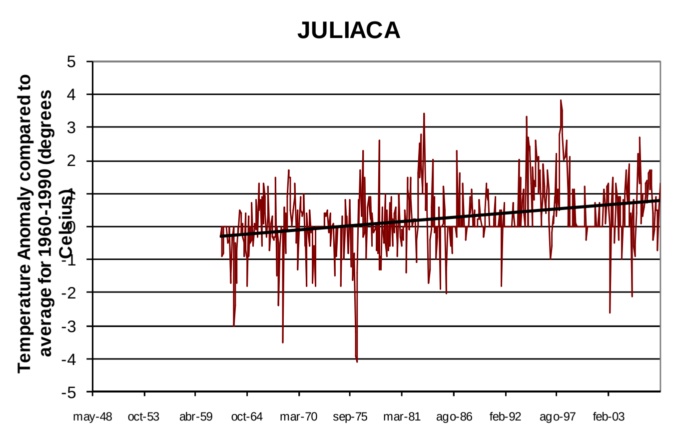


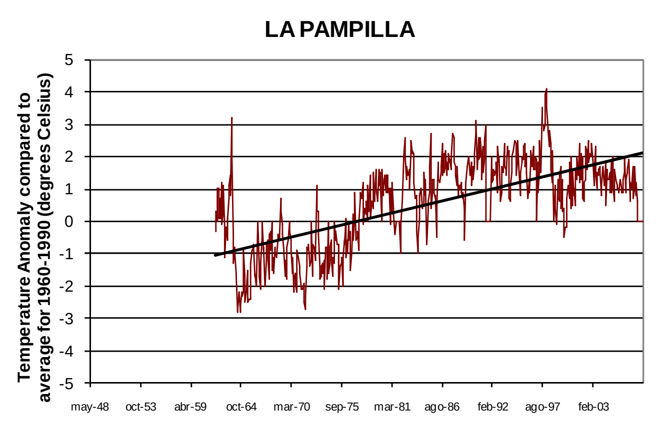

CAJAMARCA
Temperature Anomaly compared to average for 1960-1990 (degrees Celsius)
5
4
3
2
1
0
-1
-2
-3
-4
-5
may-48
oct-53
abr-59
oct-64
mar-70
sep-75
mar-81
ago-86
feb-92
ago-97
feb-03


CHIACHAPOYAS
Temperature Anomaly compared to average for 1960-1990 (degrees Celsius)
5
4
3
2
1
0
-1
-2
-3
-4
-5
may-48
oct-53
abr-59
oct-64
mar-70
sep-75
mar-81
ago-86
feb-92
ago-97
feb-03

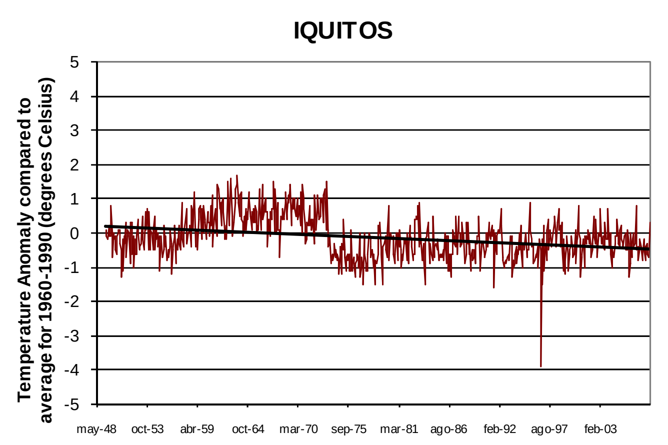

CUZCO
Temperature Anomaly compared to average for 1960-1990 (degrees Celsius)
5
4
3
2
1
0
-1
-2
-3
-4
-5
may-48
oct-53
abr-59
oct-64
mar-70
sep-75
mar-81
ago-86
feb-92
ago-97
feb-03

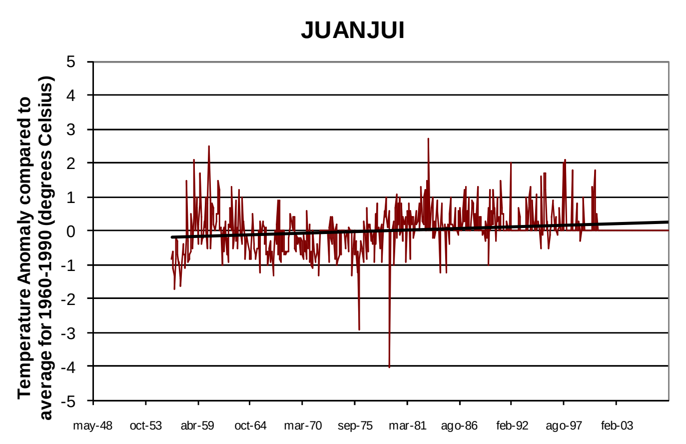

GRANJA KCAYRA
Temperature Anomaly compared to average for 1960-1990 (degrees Celsius)
5
4
3
2
1
0
-1
-2
-3
-4
-5
may-48
oct-53
abr-59
oct-64
mar-70
sep-75
mar-81
ago-86
feb-92
ago-97
feb-03

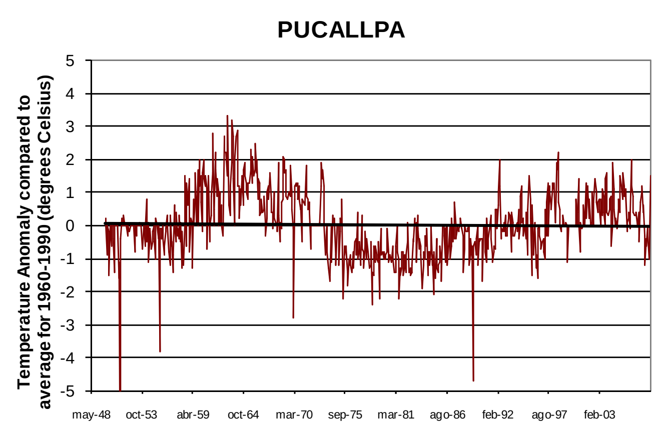

JULIACA
Temperature Anomaly compared to average for 1960-1990 (degrees Celsius)
5
4
3
2
1
0
-1
-2
-3
-4
-5
may-48
oct-53
abr-59
oct-64
mar-70
sep-75
mar-81
ago-86
feb-92
ago-97
feb-03

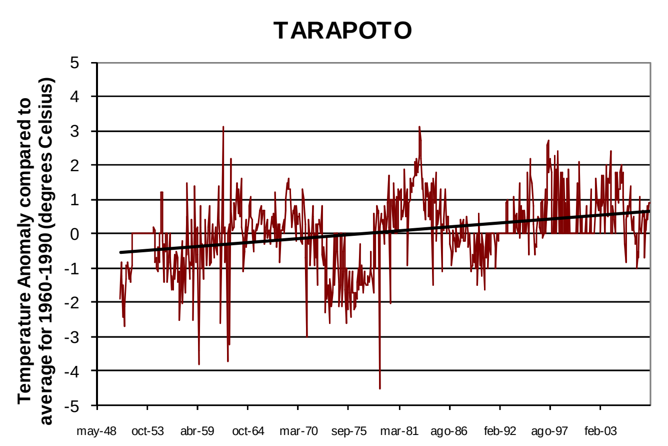

LA PAMPILLA
Temperature Anomaly compared to average for 1960-1990 (degrees Celsius)
5
4
3
2
1
0
-1
-2
-3
-4
-5
may-48
oct-53
abr-59
oct-64
mar-70
sep-75
mar-81
ago-86
feb-92
ago-97
feb-03

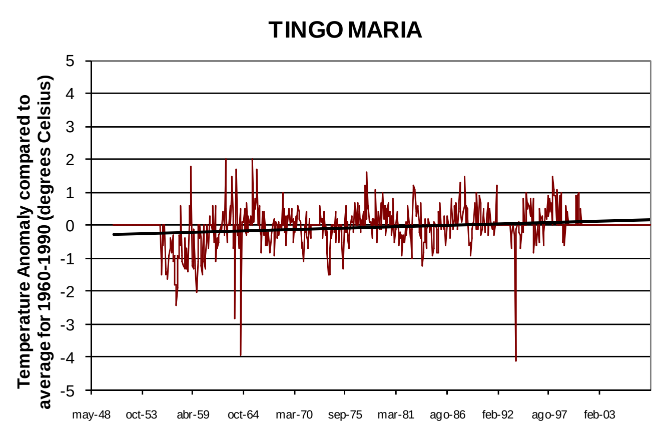
*Rainforest stations*

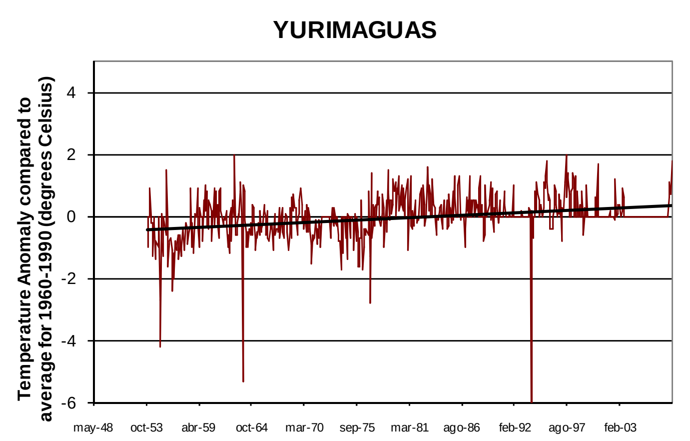






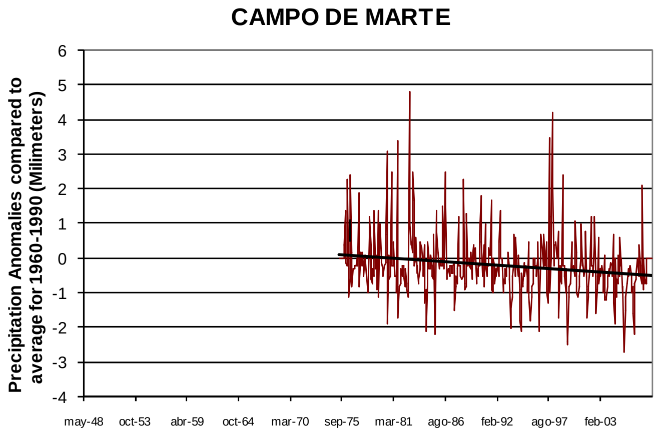


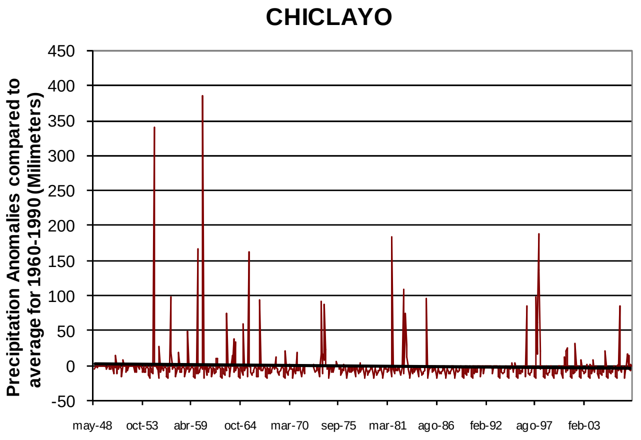


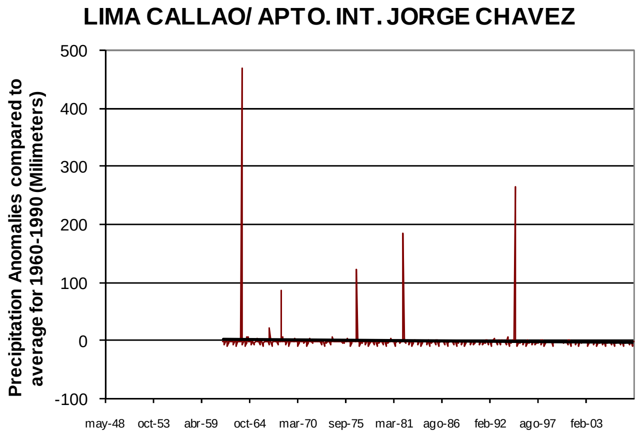


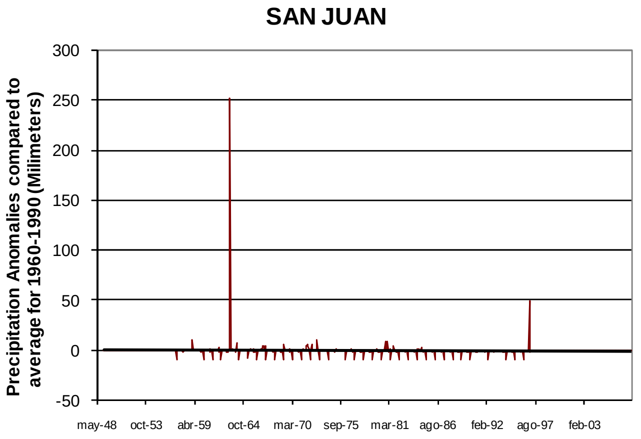
## Appendix B: Plots of precipitation anomalies

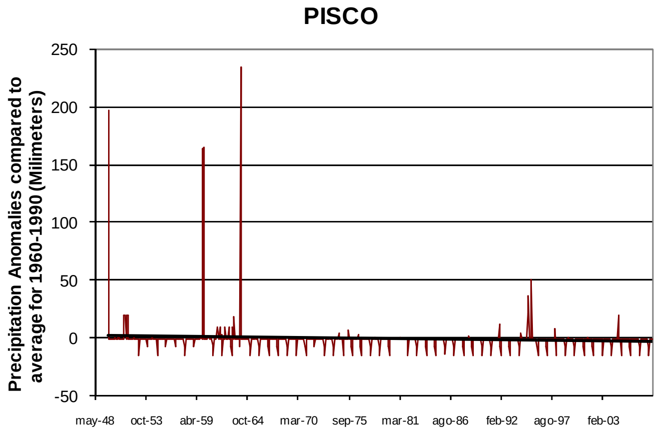
*Coastal stations*

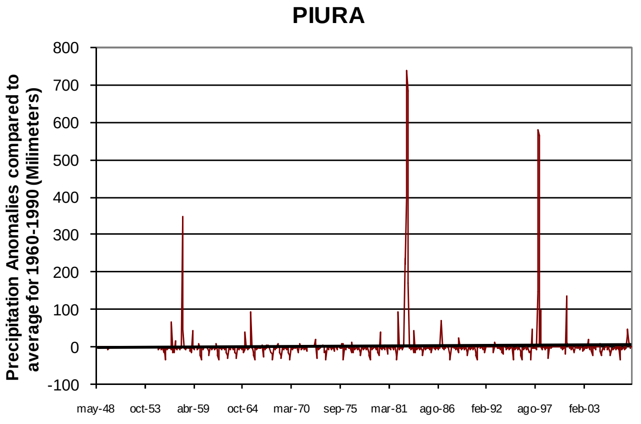


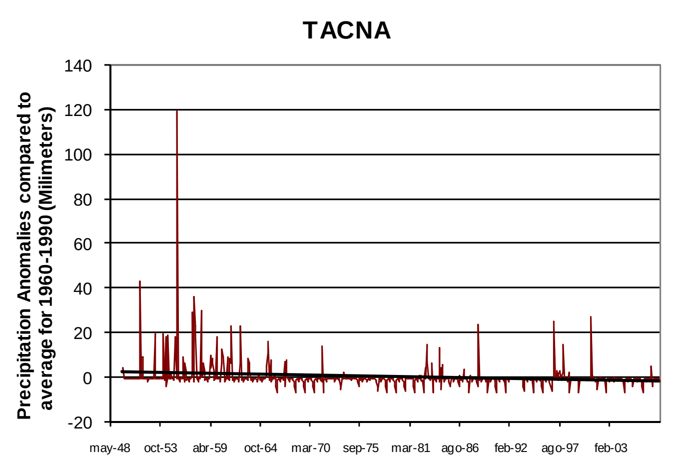


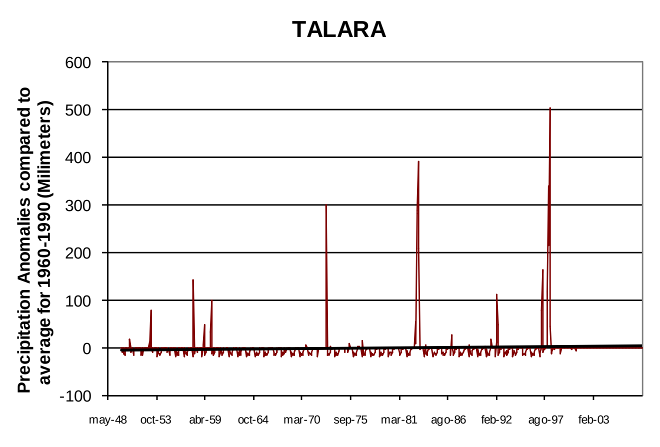


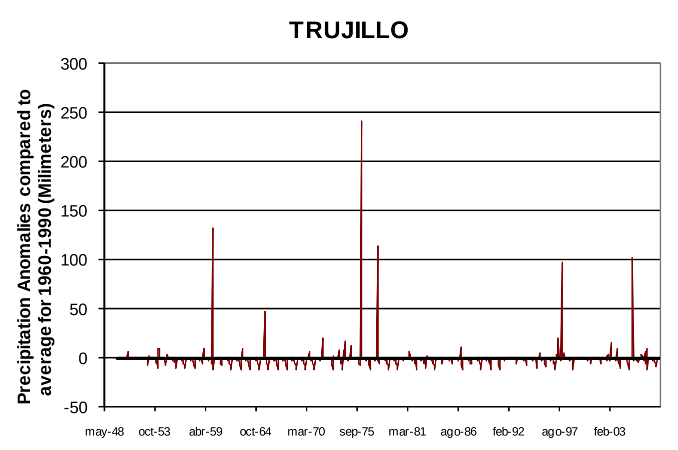


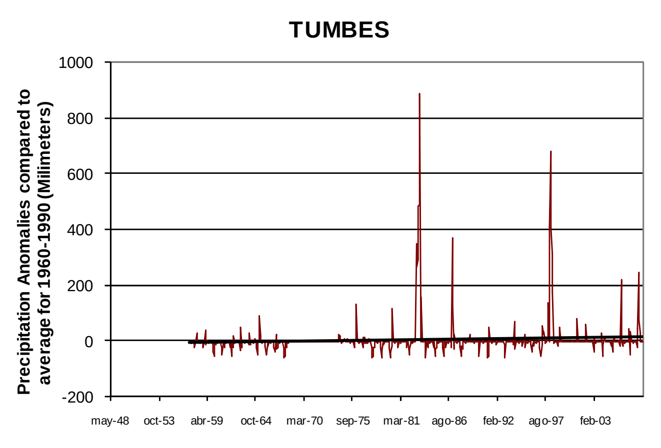




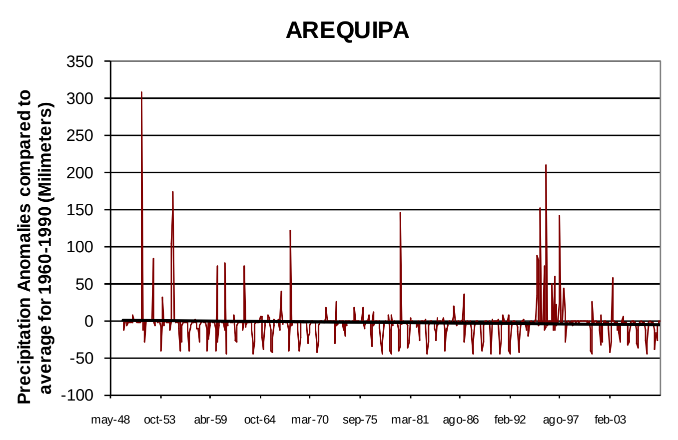


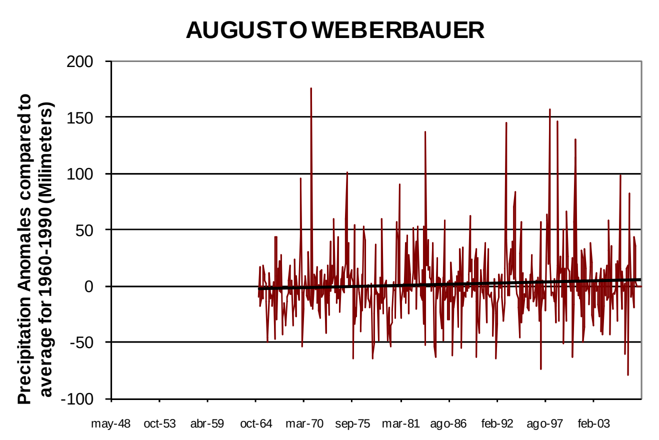


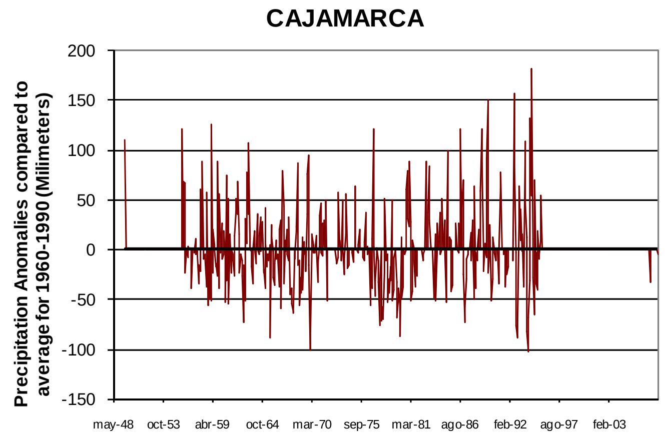


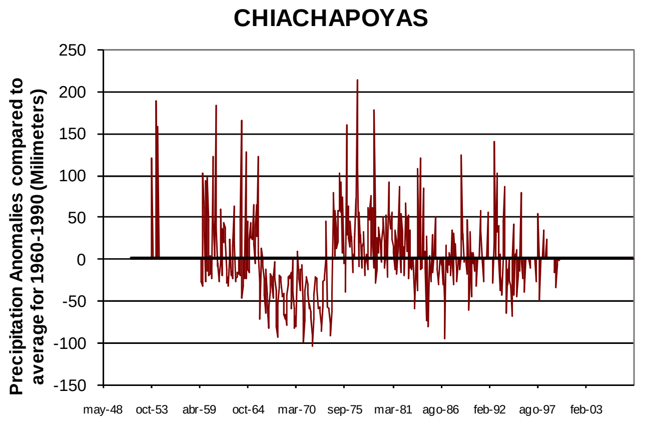


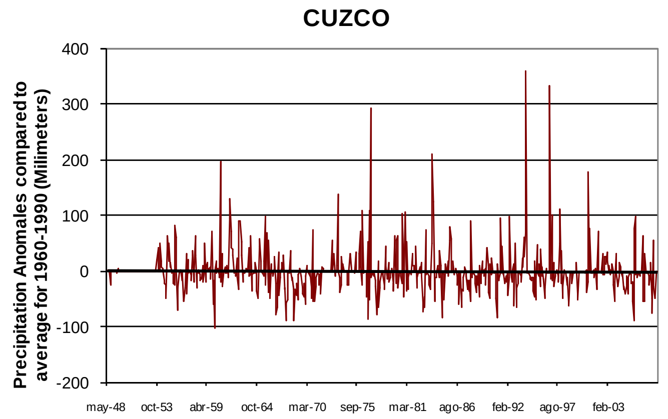
*Mountain stations*

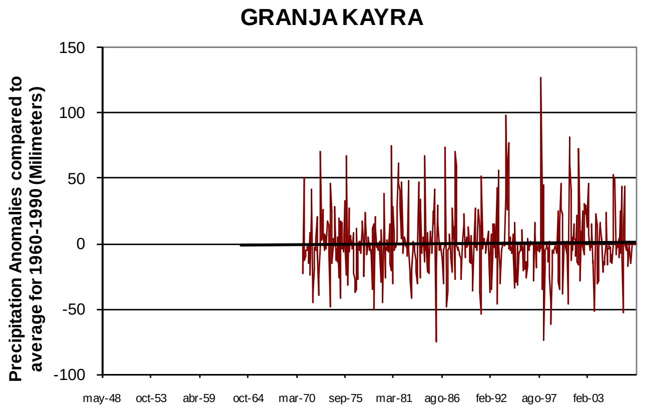


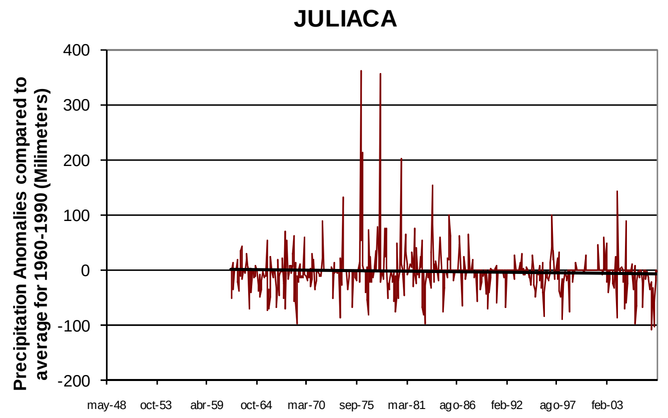


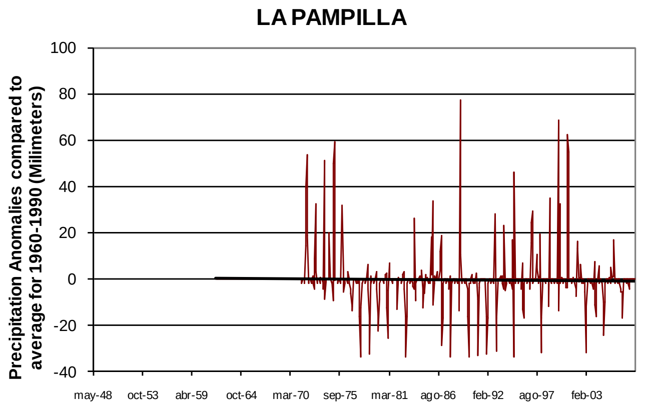

CAJAMARCA


CHIACHAPOYAS


CUZCO


GRANJA KAYRA


JULIACA


LA PAMPILLA

## *Rainforest stations*