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Social impacts of climate change in Brazil: A municipal level analysis of the effects of recent and future climate change on income, health and inequality

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Institute for Advanced Development Studies



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Social Impacts of Climate Change in Brazil: A municipal level analysis of the effects of recent and future climate change on income, health and inequality*

by

Lykke E. Andersen^{*}
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July, 2010

Summary:

The paper uses data from 5,507 municipalities in Brazil to estimate the relationships between climate and income as well as climate and health, and then uses the estimated relationships to gauge the effects of past and future climate change on income levels and life expectancy in each of these municipalities.

The simulations indicate that climate change over the past 50 years has tended to cause an overall drop in incomes in Brazil of about four percent, with the initially poorer and hotter municipalities in the north and northeast Brazil suffering bigger losses than the initially richer and cooler municipalities in the south. The simulations thus suggest that climate change has contributed to an increase in inequality between Brazilian municipalities, as well as to an increase in poverty.

The climate change projected for the next 50 years is estimated to have similar, but more pronounced effects, causing an overall reduction in incomes of about 12 percent, holding all other things constant. Again, the initially poorer municipalities in the already hot northern regions are likely to suffer more from additional warming than the initially richer and cooler municipalities in the south, indicating that projected future climate change would tend to contribute to increased poverty and income inequality in Brazil.

Keywords: Climate change, social impacts, Brazil.

JEL classification: Q51, Q54, O15, O19, O54.

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1. Introduction and justification

In order to assess how climate change is likely to affect a population, two things are necessary: First we have to understand how climate is currently affecting them, and second we have to understand how climate is changing.

A simple way to gauge how climate affects human development is to compare human development across regions with different climates. This has, for example, been done by Horowitz (2006), who 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 percent 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 effect 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 percent drop in World GDP.

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 5,507 municipalities in Brazil, we will estimate short-run relationships between temperature and income as well as between temperature and life expectancy. While it is always dangerous to make inferences about changes in time from cross-section estimates, these relationships can at least be used to gauge the likely direction and magnitude of effects of climate change in Brazil.

Two different types of climate change will be assessed. First, the documented recent climate change in each of the 5 macro-regions of Brazil, as estimated from average monthly temperature series from 1948 to 2008 for all the Brazilian 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 likely effects of expected future climate change in Brazil.

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-municipality relationships between climate and human development, controlling for other key variables

that also affect development. Section 4 analyzes past climate change using monthly climate data from meteorological stations across Brazil, and estimates average trends for each macro-region. 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 5,507 municipalities in Brazil. Section 6 summarizes the expected climate changes for Brazil during the next 50 years, and section 7 simulates the likely effects of these changes on incomes and life expectancy. Finally, section 8 concludes.

2. The data

The data used for this paper consists of both cross-section data and time series data. The municipal level cross-section data base which was used to estimate the relationship between climate and development in Brazil was constructed using data from the Brazilian Instituto de Pesquisa Económica Aplicada (IPEA), specifically IPEADATA.¹ Table 1 lists the variables, their units and their sources.

Table 1: Variables in the municipal level data base for Brazil

Variable	Unit	Year	Source
Average annual temperature	Degrees Celsius	1961-90	CRU CL 2.0 10 ⁷ from Climate Research Unit – University of East Anglia (CRU-UEA)
Average annual precipitation	Meters	1961-90	CRU CL 2.0 10 ⁷ de Climate Research Unit – University of East Anglia (CRU-UEA)
Income per capita	\$US/months (PPP adjusted)	2000	Atlas do Desenvolvimento Humano no Brasil , PNUD
Average years of schooling for adults older than 25 years	Years	2000	Atlas do Desenvolvimento Humano no Brasil , PNUD
Life expectancy at birth	Years	2000	Atlas do Desenvolvimento Humano no Brasil , PNUD
Population size	Persons	2000	Atlas do Desenvolvimento Humano no Brasil , PNUD
Urban population size	Persons	2000	Atlas do Desenvolvimento Humano no Brasil , PNUD
Urbanization rate	Percent	2000	Calculated as the ratio of urban population over total population
Latitude and longitude	Degrees	1998	Catastro de ciudades y villas del Instituto Brasileiro de Geografía y Estadística (IBGE)
Municipal area	Km ²	1998	Catastro de ciudades y villas del Instituto Brasileiro de Geografía y Estadística (IBGE)
Altitude of Municipal capital	Meters above sea level	1998	Catastro de ciudades y villas del Instituto Brasileiro de Geografía y Estadística (IBGE)

¹ Available online at: <http://www.ipeadata.gov.br>.

The data base originally contained 5,572 municipalities, but 65 recently created municipalities were excluded due to the lack of information for all the above mentioned variables.

The information about temperature and precipitation in the original IPEA data base was incomplete, so for the 533 municipalities with missing data, we estimated average annual temperature and precipitation. For temperature, a small model was estimated using information from the 4,974 municipalities with complete information. The model was a simple linear regression model that related temperature with the altitude and latitude of each municipality. These variables were both significant at the 1 percent level and the resulting R^2 of the model was 0.82, indicating a good fit. Table 2 presents the regression results. This model was used to predict average annual temperature in the 533 municipalities with missing information.

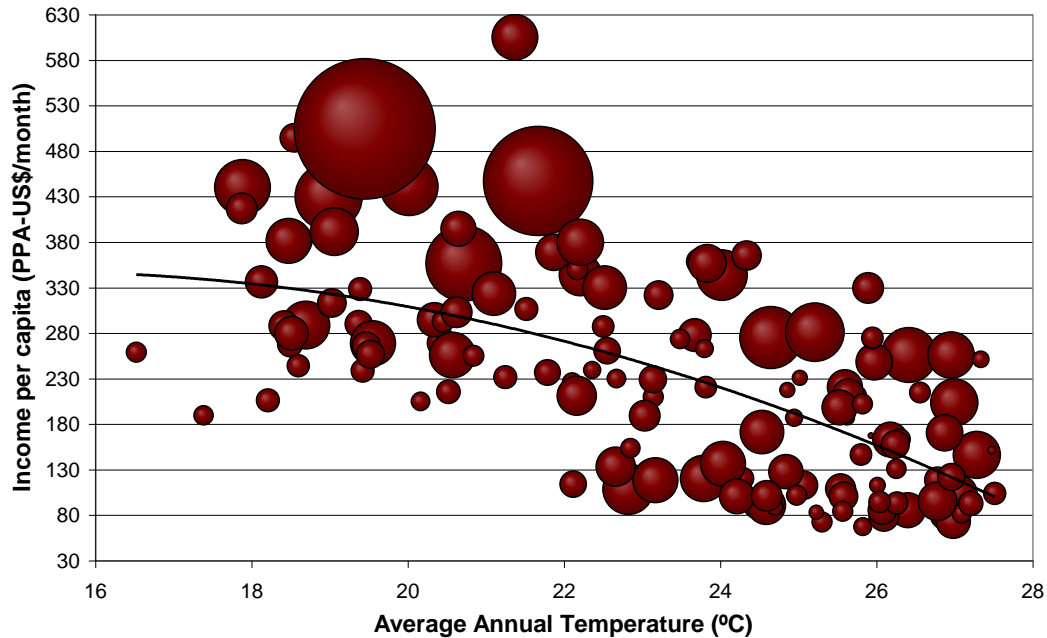
Table 2: Model used to estimate temperature in municipalities with missing data

Variable	Coefficient	Standard Deviation	t-value	P-value
Altitude	-0.0027	0.0001	-38.37	0.0000
Latitude	0.2805	0.0023	121.31	0.0000
Constant	28.5533	0.0373	766.38	0.0000
No. of observations	4973			
R²	0.8207			

Precipitation is not well predicted by altitude and latitude. Instead we used the average amount of precipitation in neighboring municipalities, or specifically, the average annual precipitation of the meso-region to which the municipality belonged. This approach is reasonable since precipitation within each of the 137 meso-regions vary little (between 2 and 10 percent around the average).

Figure 1 shows per capita income plotted against average annual temperature for each of the 137 meso-regions of Brazil. On the horizontal axis is temperature, which varies between 16.5°C in the coldest meso-region and 27.7 °C in the hottest. The vertical axis shows monthly per capita income, which varies between \$68 in the poorest meso-region and \$605 in the Federal District (purchasing power adjusted dollars of the year 2000). The population weighted average temperature of Brazil is 22.6°C, while average monthly per capita income is \$298.

Figure 1: Temperature and per-capita income in Brazil, by meso-region



The figure shows that the meso-regions with the largest and richest populations are located in temperate zones with average annual temperatures between 19°C and 22°C. Warmer regions all have substantially lower levels of income. Although no place in Brazil is so cold that you would expect development to be hindered substantially, unexpected frost can cause considerable problems. For example, the frost events of July 1975 and June 1994 destroyed almost 70 percent of coffee production and 50 percent of orange and grain production in Brazil (Marengo *et al*, 1997; Pezza and Ambrizzi, 2005).

Figure 2 shows the relationship between temperature and life-expectancy, another indicator of human development. Also here is there a negative relationship, although it is not quite as pronounced as in the case of income. Some of the hottest regions do quite well in terms of life-expectancy.

Figure 2: Temperature and life expectancy in Brazil, by meso-region

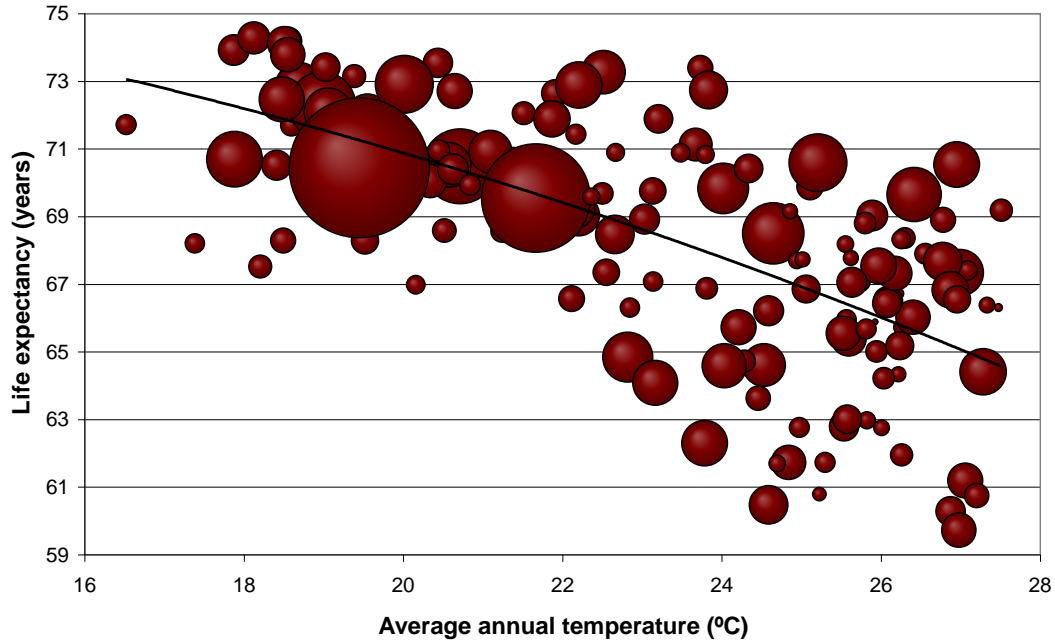


Figure 3 and 4 show the other main climatic variable, namely precipitation, and its relations to incomes and life expectancy at the meso-region level. In both cases there is a hump-shaped relationship suggesting that moderate amounts of precipitation is more beneficial for human development than either very little or too much precipitation. The optimal amount of rain seems to be about half a meter per year.

Figure 3: Precipitation and per capita income in Brazil, by meso-region

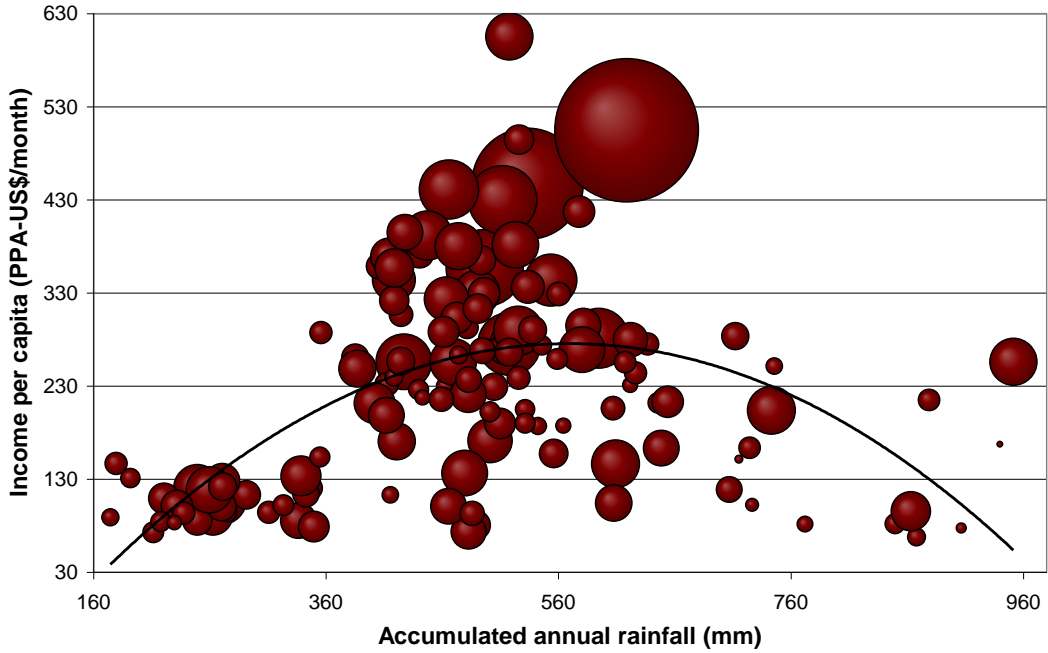
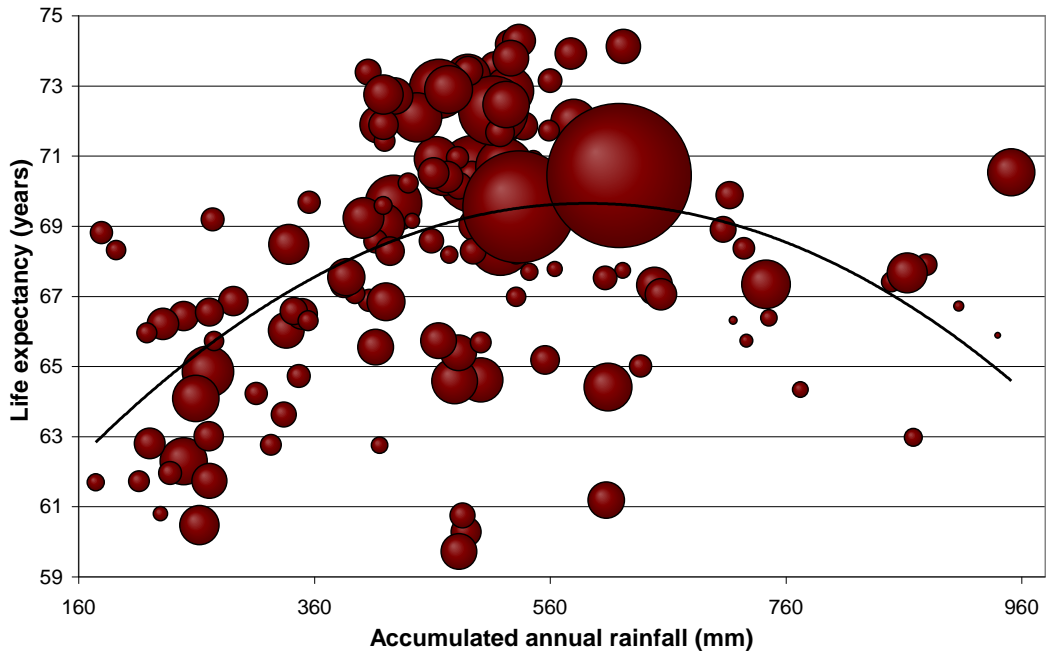


Figure 4: Precipitation and life expectancy in Brazil, by meso-region



In order to assess the climate change trends in the different parts of Brazil, we obtained monthly temperature and precipitation data from 1948 to 2008 from the Monthly Climatic

Data for the World (MCDW) publication of the US National Climatic Data Center.² Section 4 below contains an analysis of this data.

3. Modeling climate and human development

The figures in the previous section show the long-run relationships between climate and development in Brazil after centuries of direct and indirect climate impacts. In this section, we will try to estimate a more short-run relationship (a few decades) by controlling for factors that are insensitive to climate change in the short run. For example, while climate in the very long run may have a substantial effect on education levels (through accumulated indirect effects working through health, productivity, investment, etc.), climate change during the next few decades is not expected to be able to reverse education levels. Likewise, cities tend to be more prosperous and attract more people if they are located in places with a pleasant climate, which means that very hot regions typically end up with much lower urbanization rates than temperate regions. In the short run, however, climate change is not expected to be able to reverse the urbanization process.

When estimating the short-run relationship between temperature and income, we will therefore control for education levels and urbanization rates. We will also control for the level of precipitation, since the limiting climatic variable in some regions may be precipitation rather than temperature. Temperature and precipitation are related, as indicated by Global Circulation Models, but in an extremely complex way, so we want to be able to control the two variables independently in our simple model.

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 and Shaw, 1994; Quiggin and Horowitz, 1999; Masters and 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 for urbanization rates, which is why we also include precipitation and urbanization rates squared.

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

$$\ln y_i = \alpha + \beta_1 \cdot temp_i + \beta_2 \cdot temp_i^2 + \beta_3 \cdot rain_i + \beta_4 \cdot rain_i^2 + \beta_5 \cdot edu_i + \beta_6 \cdot urb_i + \beta_7 \cdot urb_i^2 + \varepsilon_i$$

where y_i is a measure of the income level in municipality i , $temp_i$ and $rain_i$ are normal average annual temperature and normal accumulated annual precipitation in municipality i , edu_i is a measure of the education level (average years of schooling of the population aged 25 or older), urb_i is the urbanization rate of the municipality, and ε_i is the error term for municipality i .

Apart from using income level as a measure of development, we will also use life expectancy. 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.

² This data is available for free at <http://www7.ncdc.noaa.gov/IPS/mcdw/mcdw.html>.

All regressions are weighted OLS regressions, where the weights consist of the population size in each municipality. 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 Brazil

Explanatory variables	(1) (log per capita income)	(2) (life expectancy)
Constant	1.4138 (8.40)	62.3107 (24.95)
Temperature	0.2093 (14.25)	0.0798 (0.37)
Temperature ²	-0.0056 (-17.30)	-0.0114 (-2.35)
Precipitation	0.7086 (9.24)	9.8058 (8.62)
Precipitation ²	-0.6324 (-9.43)	-7.0129 (-7.05)
Education level	0.3312 (119.73)	0.9282 (22.61)
Urbanization rate	1.0284 (14.36)	8.1852 (7.70)
Urbanization rate ²	-0.8880 (-15.57)	-5.8241 (-6.88)
Number of obs.	5507	5507
R ²	0.9275	0.5029

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%.

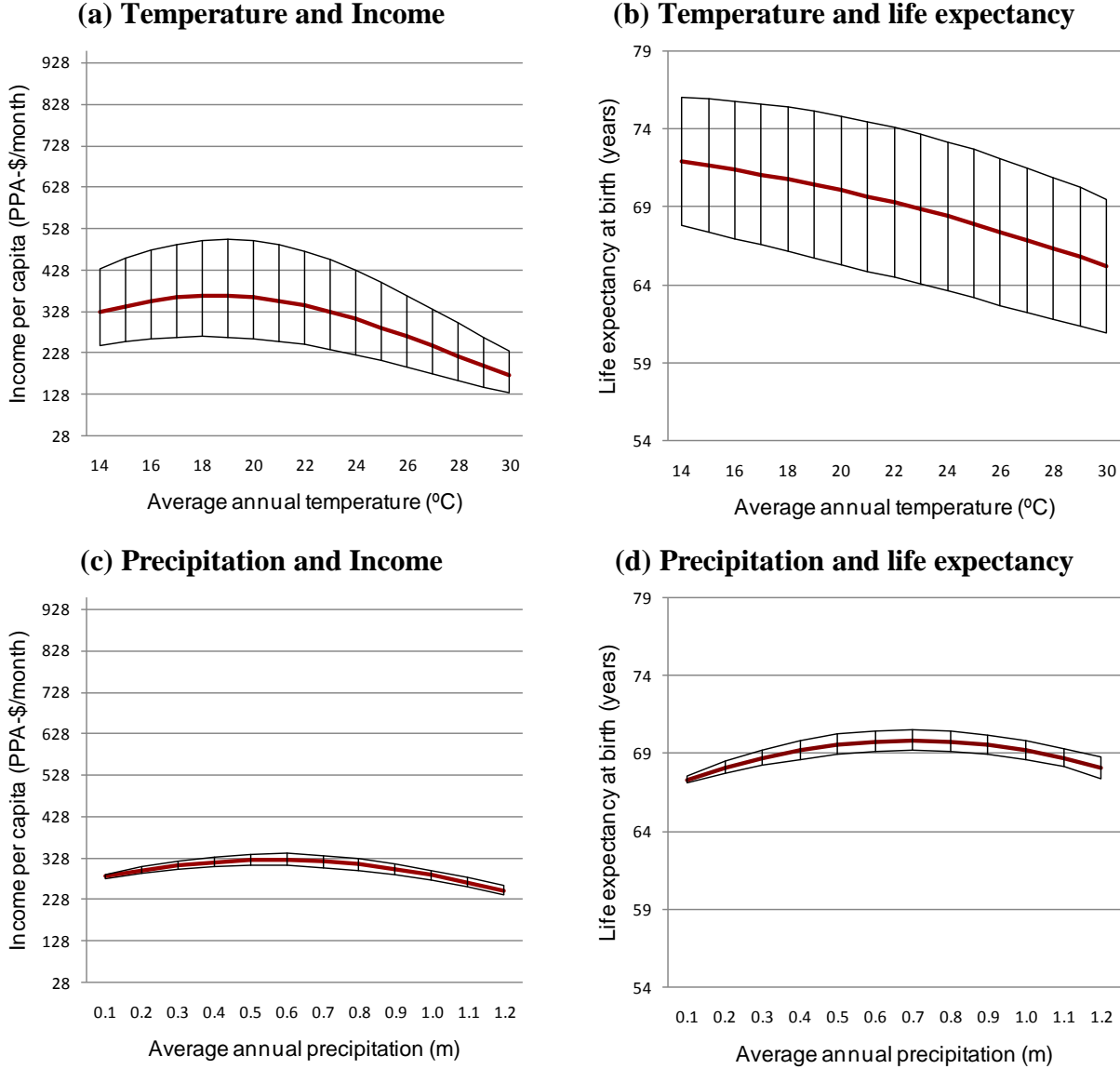
The results at the bottom of the table show that just these four explanatory variables (temperature, precipitation, education, and urbanization rates) explain almost 93 percent of the variation in incomes between the 5507 municipalities in Brazil. This is an extremely good fit, which suggests that we have included the most important explanatory variables, and that including addition variables would make little difference. The same four variables only explain about 50 percent of the variation in life expectancy, which is less impressive but still a good model.

Education is by far the most important variable, explaining 88 percent of the variation in incomes and about 39 percent of the variation in life expectancy. The remaining variables are also all statistically highly significant. Since the effects are non-linear, however, it is difficult to judge the effects by looking at the estimated coefficients. Therefore we plot the estimated relationships in Figure 5 together with the 95% confidence intervals as estimated by Stata's `lincom` command. All axes are scaled to span the actually observed range of average temperatures, average precipitation, average income, and average life expectancy at the municipal level.

Panel (a) shows a hump-shaped short run relationship between temperature and per-capita income, with the optimal average annual temperature being around 19°C. Income levels in the hottest regions fall to about half the income level in the optimal region, so even in the short run (a few of decades) there is a substantial effect of temperature on income levels.

Panel (b) indicates that life expectancy in the short run (when holding other factors constant) is almost 7 years shorter in the warmest regions compared to the coldest regions, but the relationship is not very tight, and the 95% confidence interval actually includes a flat line, suggesting that temperature and life expectancy are not significantly related.

Figure 5: Estimated short-term relations between temperature/precipitation and income/life expectancy in Brazil



Source: Graphical representation of the estimation findings from Table 3.
 Notes: The red line graphs the point estimates as calculated by the coefficients estimated in Table 3, whereas the thin black lines mark the 95% confidence interval as calculated using Stata's lincom command.

Panel (c) shows a hump-shaped relationship between precipitation and incomes, with the optimal amount of precipitation being about 60 centimeters per year. The optimal amount of precipitation for life expectancy is slightly higher at 70 centimeters per year. The difference in life expectancy between the optimal and the least favorable is only about 2.5 years, however; see panel (d).

The urbanization rate has a positive effect on incomes to a rate of about 60 percent. When municipalities urbanize in excess of this level, incomes start to suffer. The same is true for life expectancy which is maximized for urbanization rates about 70 percent.

4. Recent climate change in Brazil

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

We use 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, including 9 in Brazil. Since then, many more stations have been included in the data base, with 143 Brazilian stations having been included for shorter or longer periods.

The original data was organized in 61 printed volumes with 12 issues in each (one for each month of the year), totaling 719 months. All data is quality-checked and published by the NCDC about 3 months after the raw data has been collected.

From each of these monthly issues, we extracted average monthly temperature and total monthly precipitation for all Brazilian stations, in order to create time series for each station. None of the stations had complete information for the whole period, and although the data is supposed to have been quality-checked by the NCDC, there were unrealistic observations, which had to be deleted.

Once the temperature and precipitation series had been constructed and checked, we proceeded to calculate “normal” temperatures and “normal” precipitation for each station-month for the reference period 1960-90. We discarded all stations which did not have at least eight observations with which to calculate each station-month average.³ This procedure left us with only 53 out of the original 143 stations. The 53 stations used are distributed across the territory with 14 in the North region, 16 in the Northeast, six in the Centerwest, seven in the South, nine in the Southeast and one on Trindade, an island, east of continental Brazil.

Table 4 shows the average “normal” values for temperature and precipitation for each month for each of these macro-regions. In the North and Northeast, there is very little inter-

³ We thus needed at least eight January observations, at least eight February observations, etc, for each station during the period 1960-90.

annual variation in temperatures, due to the location close to the Equator. Instead there is a clear rainy season (January-June) and a relatively dry season (July-December). In the South, there is almost a 10 degree difference between the warmest and the coldest month, whereas precipitation is spread more equally over the year.

Table 4: Average temperature (°C) and precipitation (mm) for 1960-90, by macro-region in Brazil

Month	Macro regions										Trindade Island	
	North		Northeast		Centerwest		South		Southeast			
	TEMP	PREC	TEMP	PREC	TEMP	PREC	TEMP	PREC	TEMP	PREC	TEMP	PREC
JANUARY	25.7	254	26.2	130	24.5	226	23.9	154	24.1	226	27.1	69
FEBRUARY	25.7	258	26.1	152	24.3	190	23.7	143	24.1	176	27.8	43
MARCH	25.9	286	26.1	203	24.3	169	22.5	139	23.7	167	27.6	71
APRIL	25.9	253	25.8	193	23.1	114	19.7	114	22.0	94	26.9	80
JUNE	25.6	175	25.3	142	21.1	77	16.7	113	20.1	73	25.6	85
JULY	25.1	107	24.7	109	19.9	32	14.6	113	18.5	52	24.3	58
AUGUST	25.1	93	24.3	96	19.8	25	14.3	98	18.3	43	23.1	68
SEPTEMBER	25.9	83	24.9	51	21.7	28	15.5	95	19.5	45	22.9	58
OCTOBER	26.3	111	25.9	44	23.0	69	16.8	128	20.4	75	23.1	77
NOVEMBER	26.3	160	26.3	63	24.1	146	19.2	135	21.9	118	23.7	61
DECEMBER	26.2	175	26.5	81	24.2	189	21.2	122	22.6	162	25.0	77

Source: Authors' estimation based on data from the NCDC's Monthly Climatic Data for the World.

4.1. Temperature trends

Using the “normal” values for each station and each month, we calculate monthly anomalies for each station for the whole period. Anomalies are easier to analyze than the raw temperature and precipitation data, since the seasonal variation is eliminated through the subtraction of normal monthly temperatures.

Once we have the series of temperature anomalies, we 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 percent 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. For the trend estimation we use only stations that have at least 360 observations (corresponding to 30 years, but not necessarily consecutive).

Table 5 shows the estimated trends for each of the 34 stations for which we have sufficient data to estimate a trend with confidence. Of these, 31 stations show significant warming since the middle of the previous century, while three show no significant change. No stations show significant cooling.

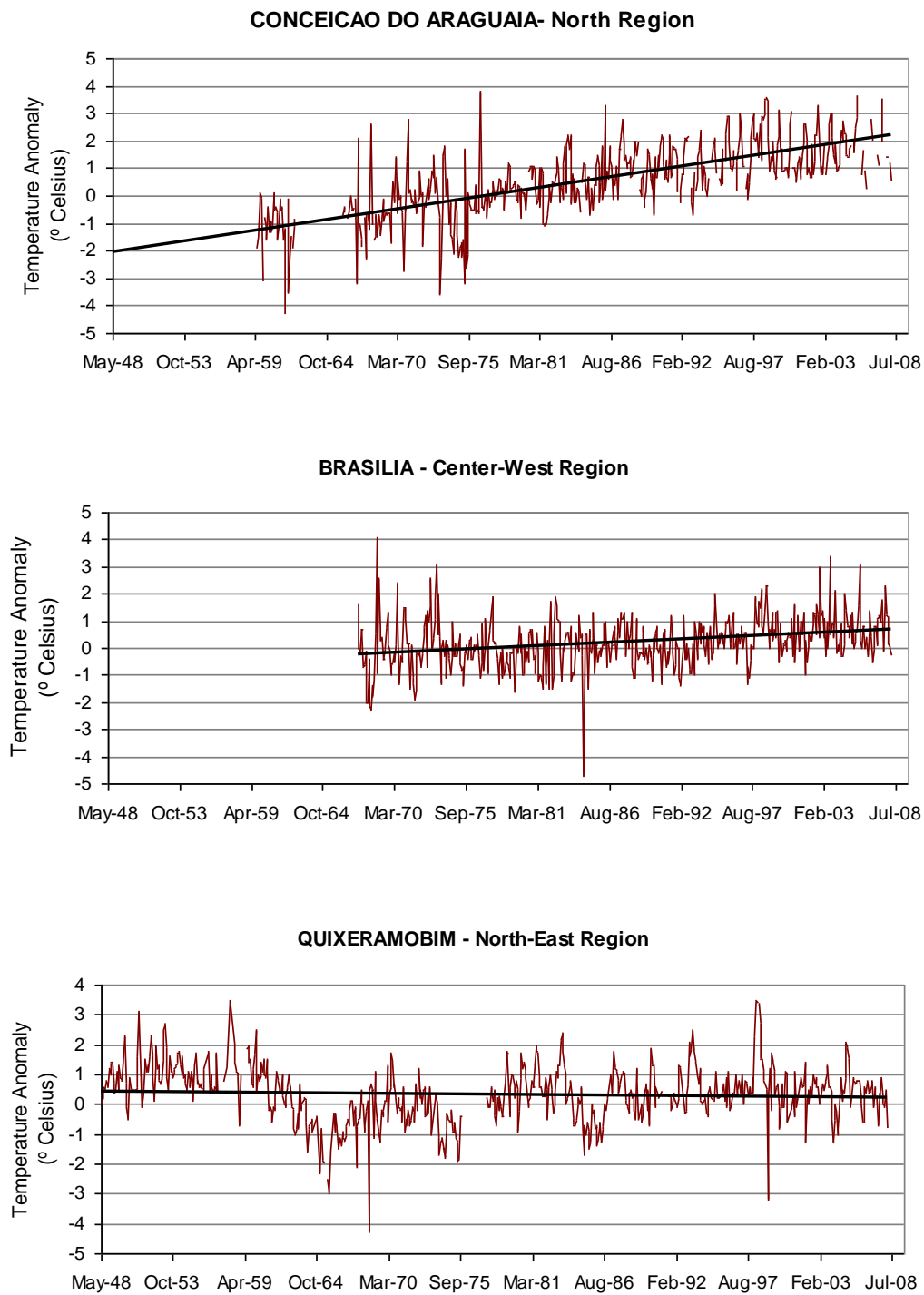
Table 5: Estimated trends in temperatures (°C/decade) during 1948-2008 for 34 high-quality stations in Brazil

Region	Trend	St.Dev.	t-value	P-value	# obs
North					
Sao Gabriel Da Cachoeira	0.30	0.02	17.98	0.000	496
Belem	0.19	0.01	13.96	0.000	636
Manaus	0.15	0.02	6.08	0.000	502
Coari	0.30	0.06	5.31	0.000	386
Cruzeiro Do Sul	0.38	0.03	14.07	0.000	417
Porto Velho	0.06	0.02	2.57	0.010	535
Conceicao Do Araguaia	0.71	0.03	23.07	0.000	510
Porto Nacional	0.38	0.02	15.64	0.000	536
Northeast					
Sao Luiz	0.04	0.02	2.56	0.011	481
Fortaleza	0.06	0.02	4.06	0.000	481
Barra Do Corda	0.31	0.03	11.00	0.000	481
Quixeramobim	-0.03	0.02	-1.60	0.110	610
Natal	0.17	0.02	8.31	0.000	366
Carolina	0.54	0.03	18.69	0.000	370
Recife	0.14	0.02	8.64	0.000	493
Petrolina	0.33	0.05	6.76	0.000	379
Aracaju	0.23	0.02	9.76	0.000	582
Salvador	0.18	0.01	13.14	0.000	638
Bom Jesus Da Lapa	0.12	0.06	1.91	0.057	394
Caravelas	0.25	0.02	13.19	0.000	627
Centerwest					
Cuiaba	0.10	0.03	3.93	0.000	643
Brasilia	0.23	0.03	6.72	0.000	475
Goiania	0.46	0.03	14.06	0.000	395
Campo Grande	0.04	0.06	0.64	0.522	359
Tres Lagoas	0.26	0.04	6.62	0.000	500
Ponta Pora	0.27	0.04	6.99	0.000	489
South					
Curitiba	0.29	0.03	8.41	0.000	549
Porto Alegre	0.06	0.03	2.10	0.036	636
St.Vitoria Do Palmar	0.09	0.03	3.19	0.001	640
Southeast					
Corumba	0.17	0.03	5.06	0.000	496
Araxa	0.39	0.05	7.31	0.000	389
Belo Horizonte	0.29	0.03	10.10	0.000	635
Rio De Janeiro	0.19	0.03	5.70	0.000	492
Sao Paulo	0.39	0.03	15.43	0.000	667

Source: Authors' estimation based on data from the NCDC's Monthly Climatic Data for the World.

In order to provide a visual interpretation of some of the data, we have plotted below the temperature anomalies for three stations representing highest warming (Conceicao do Araguaia with +0.71 degrees per decade), average warming (Brasilia with +0.23 degrees per decade), and lowest warming (Quixeramobim with -0.03 degrees per decade). See Figure 6.

Figure 6: Temperature anomalies for three selected stations in Brazil, 1948-2008.



Source: Author's elaboration based on data from NCDC's Monthly Climatic Data for the World.
Note: The "normal" period, which is used to calculate the anomalies, is 1960-90.

The average level of warming across Brazil is 0.24 degrees Celsius per decade, with no signs of acceleration. While some stations show higher levels of warming than others, this can be due to local idiosyncrasies. It is necessary to average over several different stations within a region, in order to get robust results. Table 6 shows the average trend for each macro-region. According to these results, the North region is warming about twice as fast as the South region, and the Northeast and Centerwest regions are warming at intermediate rates. This general pattern is confirmed by other studies, such as Timmins (2007). The Southeast with the mega-cities of São Paulo and Rio de Janeiro show warming that is almost as fast as the North.⁴ We will use these average macro-regional trends for the 1948-2008 period to simulate the effects of past climate changes in Section 5.

Table 6: Average temperature trend (°C/decade), by macro-region

Trends	mean	Max	min
North	0.31	0.71	0.06
Northeast	0.20	0.54	-0.03
Centerwest	0.23	0.46	0.04
Southeast	0.29	0.39	0.17
South	0.15	0.29	0.06
Brazil	0.24	0.71	-0.03

Source: Authors' estimation based on data from the NCDC's Monthly Climatic Data for the World.

4.2. Precipitation trends

In contrast to the results for temperatures, there are no clear tendencies with respect to precipitation. A trend analysis like the one performed on temperatures, reveals nine stations with a significant positive trend, two stations with a significant negative trend, and the remaining 25 high-quality stations show no significant trend in precipitation (see Table 7).

⁴ The data used here is not corrected for urban heat effects, but represents the actually experienced changes in temperatures. This is appropriate for a paper evaluating the impacts of climate change, while saying nothing about the causes of climate change (carbon emissions, natural variation, land use change, etc.).

**Table 7: Estimated trends in precipitation (mm/decade)
during 1948-2008 for 36 high-quality stations in Brazil**

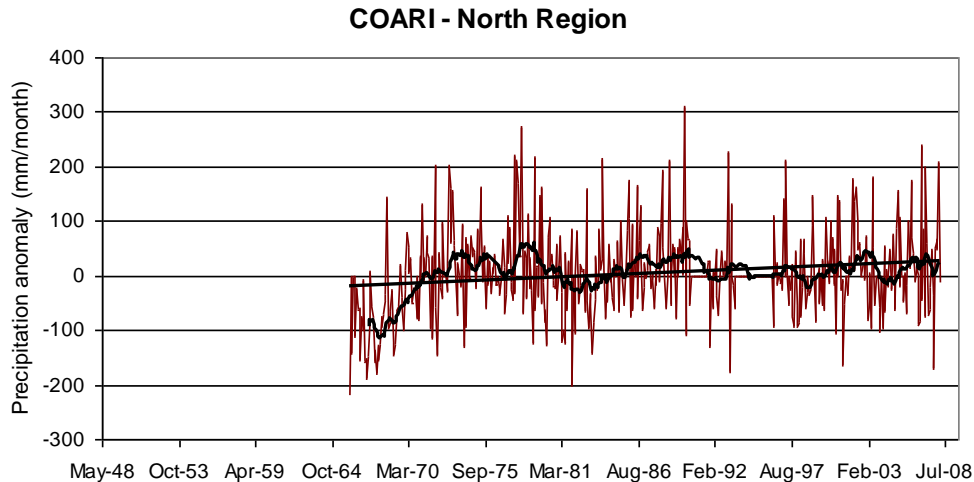
Region	Trend	St. Dev.	t-value	P-value	# obs.
North					
Sao Gabriel Da Cachoeira	0.02	2.41	0.01	0.995	499
Belem	7.37	1.97	3.75	0.000	633
Manaus	4.97	2.36	2.11	0.036	503
Benjamin Constant	-4.43	3.18	-1.39	0.165	360
Coari	12.52	3.27	3.83	0.000	418
Cruzeiro Do Sul	-1.85	2.76	-0.67	0.504	421
Porto Velho	-0.04	2.18	-0.02	0.985	535
Conceicao Do Araguaia	3.49	2.59	1.35	0.177	508
Porto Nacional	1.78	1.91	0.94	0.349	546
Northeast					
Sao Luiz	1.71	2.75	0.62	0.533	518
Fortaleza	6.63	2.37	2.80	0.005	491
Barra Do Corda	-1.13	2.38	-0.48	0.634	477
Quixeramobim	1.29	1.30	0.99	0.321	634
Natal	13.54	3.15	4.30	0.000	376
Floriano	-5.84	3.82	-1.51	0.127	372
Carolina	-1.94	3.99	-0.49	0.626	373
Recife	-0.06	2.54	-0.02	0.988	492
Petrolina	-5.88	2.54	-2.32	0.021	386
Aracaju	-1.34	2.03	-0.66	0.509	579
Salvador	4.19	2.36	1.77	0.077	638
Bom Jesus Da Lapa	-9.67	3.87	-2.50	0.013	390
Caravelas	0.45	1.91	0.24	0.813	630
Centerwest					
Cuiaba	2.43	1.41	1.72	0.086	640
Brasilia	0.99	2.88	0.34	0.731	473
Goiania	0.23	2.48	0.09	0.926	397
Tres Lagoas	-0.01	1.71	-0.01	0.993	526
Ponta Pora	2.06	2.14	0.96	0.337	512
Southeast					
Corumba	-0.84	1.45	-0.58	0.561	498
Araxa	0.77	3.33	0.23	0.817	391
Belo Horizonte	4.21	1.96	2.15	0.032	627
Rio De Janeiro	0.72	2.28	0.31	0.754	492
Sao Paulo	5.03	1.45	3.39	0.001	665
South					
Londrina	-5.89	4.23	-1.40	0.164	362
Curitiba	4.28	2.10	2.04	0.042	550
Porto Alegre	4.96	1.47	3.38	0.001	644
St.Vitoria Do Palmar	2.57	1.67	1.54	0.124	640

Source: Authors' estimation based on data from the NCDC's Monthly Climatic Data for the World.

Coari, located in the middle of the Amazon, is the station that shows the most pronounced positive trend, but a visual inspection of the data (see Figure 7) suggests that this trend is due to a substantial increase in the beginning of the period (1966-72), with no significant trend from 1972 onward. The estimated trend is thus very sensitive to the starting year. If

they had started measuring precipitation at Coari just five years later, the data would not have showed a positive trend, and if they had started measuring five years before, it is likely that the trend had at least been less steep.

Figure 7: Precipitation anomalies for Coari – North Region, 1948-2008.



With the mixed evidence from Table 7, it is difficult to say anything solid about the trends in precipitation in Brazil. Since more than 2/3 of the most reliable stations show no significant trends in precipitation over time, we will assume that this is generally so across all of Brazil. Therefore we concentrate on temperature changes in the simulations of the impacts of climate change in Section 5.

4.3 Additional considerations

The climate analysis in this section has been based on average monthly temperatures, whereas the affected population might be more concerned about extreme temperatures. Farmers may be particularly concerned about unusual frost episodes, like those that killed most of their coffee and orange crops in 1975 and 1994 (Marengo et al., 1997; Pezza and Ambrizzi, 2005), while health and crime researchers are more worried about unusually hot days, which have been shown to bring about increased mortality (e.g. Michelozzi et al, 2004; Gouveia, Hajat & Armstrong, 2003) as well as increased violent crime (e.g. Anderson, 1989).

Using daily minimum and maximum temperatures instead of monthly averages, Marengo & Camargo (2008) have made a more detailed analysis of temperature changes between 1960 and 2002 in Southern Brazil. They find that the general warming trend is mainly explained by increasing daily minimum temperatures (night temperatures), while there is only a weak positive trend in daily maximum temperatures. This means that the diurnal temperature range has systematically decreased; a trend which has been confirmed by studies from neighboring areas in Argentina (Rusticucci & Barrucand, 2004) and in southeastern South America (Vincent et al, 2005). In addition, Marengo & Camargo (2008) found that winter temperatures have generally increased more than summer temperatures.

Together these two findings suggest that while there is a general trend towards warming, there is not a clear trend towards hotter summer days or colder winter days. Indeed the Marengo & Camargo index of hot summer days seems to have peaked in 1986. This means that we can use changes in average temperatures as a summary measure of climate change, without being afraid that we would be underestimating the impacts of the real and more complex ways the climate change.

5. Simulating the impacts of recent climate change

In this section, we use the models estimated in Table 3 above to simulate the likely impacts of the climate change experienced during the last 50 years on per-capita income and life expectancy in each of the 5,507 municipalities in Brazil.

In Section 4 we saw that precipitation does not appear to have changed in any systematic way, but that temperatures have been increasing all over Brazil. The temperature trends reported in Table 6 corresponds to the following change over the last 50 years:

**Table 7: Temperature change (°C)
between 1958 and 2008**

Region	Temperature change
North	1.55
Northeast	1.00
Centerwest	1.15
Southeast	1.45
South	0.75
Brazil	1.20

To find 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 municipality, whereas the No Climate Change temperatures are the actual temperatures minus the temperature changes from Table 7.

Since the relationship between temperatures and life expectancy was found to be weak and not statistically significant at the 95% confidence level, we will only simulate the effects of past climate change on income levels and not on life expectancy.

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

$$\Delta_{CC} y_i = \frac{y_{i,CC}}{y_{i,NCC}} = \frac{\exp\{\hat{\beta}_1 \cdot t_{i,CC} + \hat{\beta}_2 \cdot t_{i,CC}^2\}}{\exp\{\hat{\beta}_1 \cdot t_{i,NCC} + \hat{\beta}_2 \cdot t_{i,NCC}^2\}}$$

After estimating this ratio for each municipality, the percentage change in income levels that can be attributed to climate change can be calculated. At the national level, the simulation indicates that per-capita income is now about four percent lower than it would have been if temperatures had stayed at the level it was 50 years ago. The simulations suggest that it is the northern municipalities that have lost most, while several southern municipalities may have felt a slightly positive impact (see Table 8)

**Table 8: Impact of climate change 1958 – 2008
on per-capita income, by macro-region**

Region	Impact on per capita income (% change)
North	-11.6
Northeast	-6.7
Centerwest	-5.3
Southeast	-1.6
South	+0.7
Brazil	-3.7

The range of estimated impacts on income is quite large. According to the simulations, some municipalities have lost as much as 16.5 percent, while others have gained up to 8.5 percent.

At the municipal level, there is a strong positive relationship ($\rho = 0.45$) between the initial level of income and subsequent gains from climate change, indicating that initially richer municipalities have lost less from climate change than initially poorer municipalities. This implies that the climate change experienced over the last 50 years has contributed to increasing inequality between Brazilian municipalities.

The simulation shows that virtually all of the poorest municipalities (99.75% of the municipalities with average monthly per-capita income below \$100) have seen deteriorations in income due to recent climate change. This means that the rising temperatures experienced over the last 50 years have tended to contribute to an increase in poverty in Brazil, all other things equal. The magnitude of the impacts on poverty is difficult to estimate, however, since it depends on the income distribution in each municipality.

6. Expected future climate change in Brazil

Having quantified the impacts of climate change during the last 50 years, we now turn to an assessment of the possible impacts of 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 faster in the northern part of Brazil than in the southern part. This corresponds well to the pattern observed in the past. It also corresponds to the projections reported by Working Group 2 for Latin America (see Table 9). According to this table, it is reasonable to expect a 2.5°C increase in temperatures in the northern part of Brazil, and a 2.0°C increase in the southern part of Brazil during the next 50 years.

Table 9: Temperature changes predicted by the climate models used by IPCC 4

Changes in temperature (°C)		2020	2050	2080
Central America	Dry season	+0.4 to +1.1	+1.0 to +3.0	+1.0 to +5.0
	Wet season	+0.5 to +1.7	+1.0 to +4.0	+1.3 to +6.6
Amazonia	Dry season	+0.7 to +1.8	+1.0 to +4.0	+1.8 to +7.5
	Wet season	+0.5 to +1.5	+1.0 to +4.0	+1.6 to +6.0
Southern South America	Winter (JJA)	+0.6 to +1.1	+1.0 to +2.9	+1.8 to +4.5
	Summer (DJF)	+0.8 to +1.2	+1.0 to +3.0	+1.8 to +4.5
Change in precipitation (%)				
Central America	Dry season	-7 to +7	-12 to +5	-20 to +8
	Wet season	-10 to +4	-15 to +3	-30 to +5
Amazonia	Dry season	-10 to +4	-20 to +10	-40 to +10
	Wet season	-3 to +6	-5 to +10	-10 to +10
Southern South America	Winter (JJA)	-5 to +3	-12 to +10	-12 to +12
	Summer (DJF)	-3 to +5	-5 to +10	-10 to +10

Source: Magrin et al. (2007, p.594).

With respect to precipitation there is little agreement as to the direction of change, as the confidence intervals all include zero change. Christensen et al. (2007) conclude that “It is uncertain how annual and seasonal mean rainfall will change over northern South America, including the Amazon forest.” “The systematic errors in simulating current mean tropical climate and its variability and the large intermodel differences in future changes in El Niño amplitude preclude a conclusive assessment of the regional changes over large areas of Central and South America. Most MMD models are poor at reproducing the regional precipitation patterns in their control experiments and have a small signal-to-noise ratio, in particular over most of Amazonia (AMZ).”

Our simulations of the effects of future climate change will therefore assume no change in precipitation, just like our simulations of past climate change.

7. Simulating the impact of expected future change

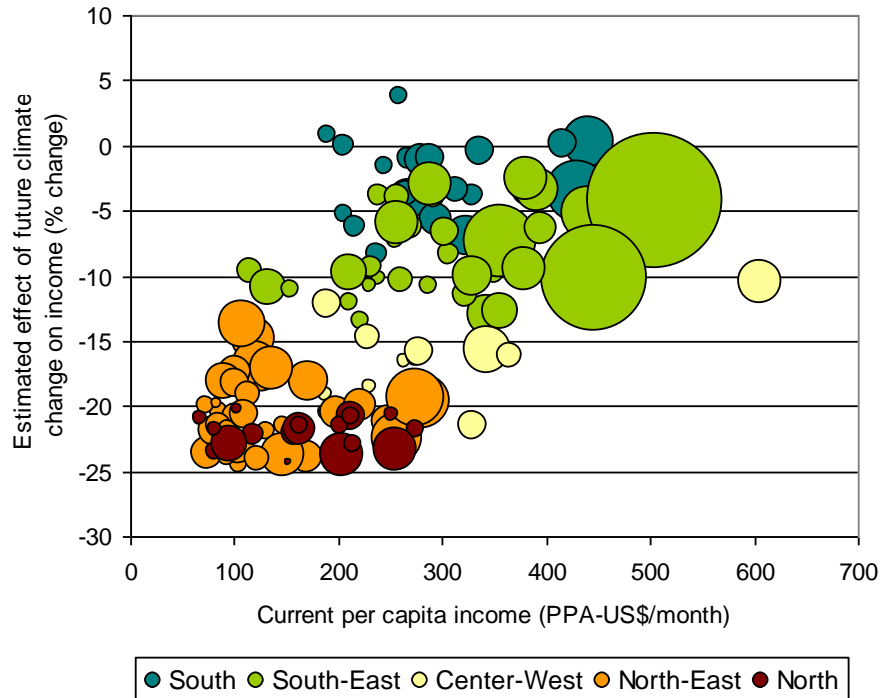
For the simulations in this section we will assume that temperatures in the South and Southeast (51% of all municipalities) will increase by 2.0°C over the next 50 years and that in the rest of Brazil (49% of all municipalities) will increase by 2.5°C, corresponding to the findings in the previous section. Using the formulas presented in Section 5, we find that the expected temperature increases over the next 50 years would tend to cause a 12 percent decrease in average per-capita income across Brazil, with the northern states losing considerably more than average and the southern states losing less (see Table 10).

Table 10: Impact of climate change 2008 - 2058 on per-capita income, by macro-region

Region	Impact on per capita income (% change)
North	-22.5
Northeast	-19.8
Centerwest	-15.6
Southeast	-7.2
South	-2.9
Brazil	-11.9

The highest estimated loss for any individual municipality was 29 percent for the municipality Uiramutã in Roraima in the northern part of the Amazon, and the biggest gain was 8.6 percent in the municipality Campos de Jordão in the State of São Paulo. At the municipal level, there is a strong positive relationship ($\rho = 0.58$) between the current level of income and the subsequent gains from climate change, indicating that currently richer municipalities will likely lose less from future climate change than currently poorer municipalities (see Figure 8). This implies that future climate change can be expected to cause an increase in inequality between Brazilian municipalities. Future temperature increases will also work towards increasing poverty, as the currently poorest regions are all set to see substantial income reductions due to temperature increases.

Figure 8: Current per-capita income versus expected future impacts of climate change, by meso-region



8. Conclusions

In this paper we used a municipality level cross-section database to estimate the general relationship between climate and income in Brazil. This relationship was found to be hump-shaped with incomes being maximized for average annual temperatures around 19 °C and for moderate amounts of precipitation (about 60 cm/year), other things being equal.

Similarly, we estimated the relationship between climate and life expectancy. We found that life expectancy tends to decrease with temperature, but that the relationship is not statistically significant at the 95% level. The relationship between precipitation and life expectancy is hump-shaped, and statistically significant, with the optimal amount of rain being about 70 cm/year.

These estimated relationships were then used to simulate the effects of both past (1958-2008) and future (2008-58) climate change. Past changes in climates were analyzed using historical data from a large number of meteorological stations from all over Brazil, and estimating average trends for each of the five macro-regions. We found that average temperatures have increased about 1.2°C over the last 50 years, with northern regions having warmed more than southern regions. No systematic trends in precipitation were found.

The impacts of the temperature increases experienced over the last 50 years were estimated to be a four percent reduction in per-capita incomes at the national level. However, the warmer and poorer northern municipalities were found to experience bigger losses than the cooler and richer southern municipalities, implying that past climate change has likely contributed to an increase in inequality between Brazilian municipalities, as well as an increase in poverty.

For the assessment of future climate change, we used the projections from the Fourth Assessment Report of the IPCC, which suggests a 2°C increase in temperatures for the southern part of Brazil and a 2.5°C increase for the northern part over the next 50 years. The report did not provide any conclusive evidence concerning the direction of precipitation changes, so we assume that future precipitation will maintain the same irregular patterns as in the past. According to our simulations, such a 2-2.5°C increase in temperatures would tend to reduce the average level of income in Brazil by about 12 percent. Here there were substantial differences between municipalities, with the hardest hit municipality losing as much as 29 percent of incomes and the most fortunate municipality gaining 9 percent. In general, it is the presently poorest and hottest municipalities in the north and northeast that are likely to suffer most if temperatures increase as indicated by the IPCC models, while the cooler and richer southern municipalities are likely to lose much less. This again implies that climate change can be expected to contribute to increasing inequality and poverty in Brazil (all other things equal).

Some qualifications to this overall picture are in order. First of all, in order to isolate the effects of climate change, the simulations assume that everything else remains the same. In reality much has changed over the last 50 years and much will likely change over the next 50 years. For example, atmospheric CO₂ concentrations are likely going to increase from the current level of 387 ppm to somewhere between 500 and 600 ppm 50 years from now, depending on how effective Kyoto and Post-Kyoto policies are at reducing emissions. If CO₂ concentrations increase considerably, as seems almost inevitable, crop productivity may increase significantly, as indicated by almost all studies of CO₂-fertilization (e.g. Allen et al 1987; Baker et al 1989; Poorter 1993; Rozema et al 1993; Wittwer 1995; Torbert et al 2004). In addition, education levels, income levels and urbanization rates are all likely to increase, which may make people less vulnerable to climate change (Dell, Jones & Olken 2008).

Second, 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 from the warm northern regions to the cooler southern regions. Simulations carried out by Assunção & Feres (2008) for Brazil indicate that the estimated impacts of climate change on poverty are almost 40% lower when people are allowed to migrate. The potential for this is somewhat limited, however, as the south already has much higher population densities than the north, and also higher than optimal urbanization rates, so it may be difficult to accommodate a large number of “climate migrants” in the South and South-East cities.

It is worth pointing out that the estimated models indicate that there are other factors than climate that are far more important for development, notably education. Our findings indicate that while a 2°C increase in temperatures may cause a reduction in average incomes of about 12 percent, a two year increase in average education levels is associated with a 94 percent increase in average incomes. This implies that the negative effects of temperature increases on incomes could, at least theoretically, be counteracted by increases in education levels.

Finally, it should be warned that the impacts found for Brazil cannot be generalized to apply 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. In neighboring Bolivia, for example, the poorest parts of the population are located in the cold highlands, while the warmer lowlands are much more prosperous, which implies that future warming might contribute to a reduction in poverty and inequality rather than an increase (Andersen & Verner, 2009).

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