Welfare consequences of persistent climate prediction errors on the insurance markets against natural hazards[1]

Abstract: This paper proposes a two-period model of private insurance under climate uncertainty with endogenous prices to explain how the coexistence of agents' heterogeneity regarding ability to predict future occurrence of natural events may deviate market prices from the fundamentals, leading to reduction in social welfare in the long run. Based on survey data related to self-insurance against floods and perception on change in local climate parameters, coupled with historical meteorological data from local weather stations, we identified the existence of a group of individuals making persistent errors in the anticipation of climate events. Econometric models further suggest that the probability of belonging to this group varies significantly by sociodemographic and geophysical attributes of the sampled respondents. This empirical finding of heterogeneity within and between groups helps explain why there is no market supply of information on natural events. The absence of firms providing this type of information occurs because price discrimination via product differentiation is economically unfeasible in private markets. Therefore, we propose a theoretical model with heterogeneous agents and taxation to finance a public technology providing information on natural events. Results from our insurance model with incomplete markets show that the group with accurate expectations price the insurance as the fundamentals, while agents with inaccurate expectations distort insurance prices in the long run. The closed form solution suggests that agents making persistent mistakes on the process of anticipation of climate events are not driven out from the market. By including a central planner providing a technology for access to accurate information, our example illustrates that public intervention (via taxation) would only be feasible if public expenditure in the provision of this technology did not exceed 9.188% of the aggregate income earned by agents with inaccurate expectations. This threshold is computed based on a relative measure of social welfare that is robust to scale transformations.

Key-words: Natural disasters, climate change, errors in climate prediction, private insurance model under uncertainty, heterogeneity in agents' priors

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1. Introduction

Climate change has altered agents' ability to anticipate the future occurrence of events with high degree of accuracy (PARKER, 2010; DASGUPTA, 2008; REGAN et al., 2005). This subjective anticipation may be inaccurate, leading to Pareto inferior choices when compared to a situation where agents have rational expectations (SAVAGE, 1951; YOHE et al., 2004; PRATO, 2008). In this case, market equilibrium and demand for insurance are better understood using models that explicitly incorporate agents' heterogeneity in the degree of prediction accuracy.

Most models used in insurance economics with heterogeneous agents up to now try to explain market allocation of insurance using differential information. These models' results focus on issues related to adverse selection and moral hazard (MIRLEES, 1971; ATKISON; STIGLITZ, 1972; LAFFONT; TIROLE, 1987). These types of heterogeneity, as used in Crocker and Snow's (1985) and Picard's (1987) models, consider differences in the consumer's information structure, but not in their subjective probabilities directly. In this case, market failures arise due to a supply shortage caused by negative profit or demand shortage due to excessively high prices.

In markets where contractual insurance is not available, moral hazard and adverse selection are of little relevance for market allocation. Many studies that analyze the trade-off between the demand for insurance, self-insurance, and self-protection[1] reinforce this argument, either looking at agents' reservation price or taking insurance price as actuarially fair (EHRLICH; BECKER, 1976; DIONNE; EECKHOUDT, 1985; LAKDAWALLA; ZANJANI, 2005; SNOW, 2011; ALARY et al., 2013). Most of the previous models look at effect of information asymmetry on the demand for insurance using a representative agent. By doing this, they ignore the influence of this effect on equilibrium prices, which would be the most interesting economic problem to be studied. The scarcity of studies on insurance models with endogenous prices is mainly explained by the difficulty in obtaining the price solutions.

Another important issue to be considered in insurance models is the role played by a central planner to attenuate the effect of information asymmetry in market allocation

[1] In a seminal study, Ehrlich and Becker (1976) defined *self-insurance* as a reduction in the size of a loss and *self-protection* as a reduction in the probability of a loss. These private insurance choices occur when there are no firms providing contractual insurance to hedge against hazards. In certain situations, self-protection can lead to a reduction in the size of a loss, making these alternative choices intertwined. For instance, if a person moves from an area close to a river prone to floods to a neighborhood located in a hill, the potential loss is declined along with its probability. Note that the definitions given by the authors ignore the situation where agents make mistakes on the probability of the realization of the states of nature, the precise case studied in this paper.

(CAILLAUD et al., 1988). Arnott and Stiglitz (1990), for instance, show that taxation and subsidization policies providing incentives to avoid and reduce losses are not effective in markets in which moral hazard arises from information asymmetry. When public intervention is used to solve the insurability problem using increased taxation (as discussed by Mangan, 1995), risk can increase in the long run. Additional pressure on the government to increase coverage keeping the risk premiums unaltered is also a likely moral hazard consequence of taxation (DIONNE et al., 2000). This situation is similar to a market with mandatory insurance acquisition, with prices financed by the government. However, we show that it is still possible to implement a public technology supported by a tax levy to correct information asymmetry represented by errors in the probabilities on natural events. Since intervention affects information on selected groups instead of on insurance directly, the problem of moral hazard is irrelevant and can be ignored.

This paper has four main goals. First, we study the welfare consequences of the friction between two groups, with and without rational expectations, in an incomplete insurance market. We validate this friction by seeking empirical evidence of persistent error in a subsample of individuals regarding the perception of change in local climate parameters. Second, we test the existence of additional heterogeneity in the probability of belonging to the group who makes persistent mistakes on the anticipation of climate events using econometric models. Third, we develop a two-period model of private insurance under uncertainty with endogenous prices[2] to explain how the coexistence of these groups may deviate market prices from the fundamentals, leading to reduction in social welfare in the long run. Our proposed model differs from Stiglitz's (1976) by considering heterogeneous beliefs and income taxation to correct market failures (information asymmetry). The tax burden[3] is employed to finance a public technology that provides accurate information to those agents making persistent mistakes[4]. The levy only on agents without rational expectations is a way to avoid moral hazard behavior among those with rational expectation (MIRLEES, 1971; ATKISON; STIGLITZ, 1972). Finally, we solve the proposed model algebraically with a closed form solution and simulate the taxation threshold as a proportion of the agents' income that Pareto improves any market allocation without government intervention.

2. Empirical evidence on agents' heterogeneity

[2] Our model considers two periods in the long run in which we assume that at this point expectations are already stationary.

[3] The tax burden used in our theoretical model is not mandatory. Thus, only those in need of precise information would be willing to pay. Ex post, however, the tax burden becomes a tax levy for the agents without rational expectations, since this tax would Pareto improve the social welfare.

[4] The use of a model with taxation to attenuate information asymmetry justifies because agents without rational expectations are not driven out from the market (DE LONG et al., 1990). If nothing is done, a welfare loss would be observed in the long run because of inefficiencies in the insurance market.

2.1. Climate Data

To understand the evolution of objective climate parameters we use climate data (precipitation and temperature) from all the six meteorological stations located in the municipality of Governador Valadares, Brazil. Data were provided by the Center of Weather Forecast and Climate Studies (CPTEC), at the Brazilian Institute for Spatial Research (INPE), and by the Brazilian Institute of Meteorology (INMET). Different stations were pooled together, since not all had valid information for the same time window. Station data pooling allowed us to recreate the time series of climate information after some forecasting and data smoothing.

Some decision rules were taken to interpolate the data: (1) when there was only one information available for a climate parameter (from 1 station only), this information was used to create the time series; (2) when more than one station provided data for the same parameter at the same date, the average of these measures were used. The spatial location of meteorological stations shows no geophysical barrier[5], which could affect climate parameters through heat island or humidity alteration effects. Thus, simple average for the parameters could be used with no significant estimation bias (ASHRAF; LOFTIS; HUBBARD, 1997).

For this study, we selected temperature and precipitation parameters. These data were measured in a daily basis, with different temporal gaps per station. The decision rules previously described allowed us to recreate historical climate series data from 1960 to 2014 for precipitation. Daily data were transformed into monthly averages. Precipitation data were classified in: (a) intensity and (b) frequency (Figure 1). Precipitation intensity was measured as the annual average of monthly precipitation (in mm/month). Precipitation frequency was measured as the number of monthly precipitation events higher than 1 or 2 standard deviations of the annual average[6]. Figure (1) suggests an increase in rainfall intensity and frequency from 1960 to 1983, followed by decreased parameters from 1983 to 2014.

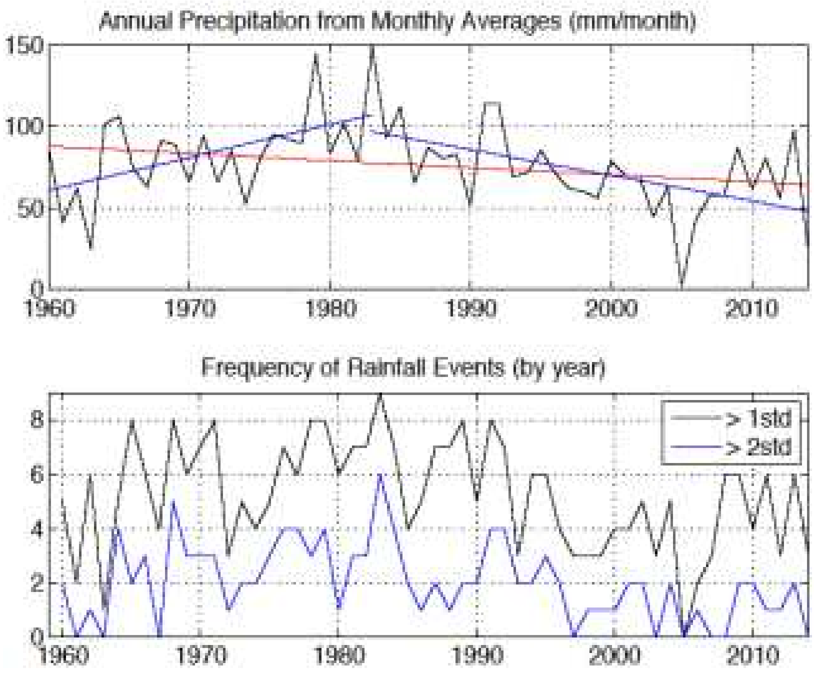
Since we compare perceptions of local climate change with objective climate data to proxy the agents' prediction errors, we may incur in the risk of perceptions related to long periods backward being contaminated by memory bias. Thus, assuming that memory bias is small from 1990 on (only 25 years of contrasts), trends in climate parameters look different. Figure (1) reveals that between the late 1990's and 2005 rainfall frequency and intensity declined, with the opposite trend being observed for the more recent period (2005 to 2014). This recent trend mirrors the trend observed for 1960 to 1983. Our analyses then were based

[5] To check that, we georeferenced all stations within QGis and overlaid them with the satellite base image for the city.
[6] Additional analyses were performed, yielding a variance analysis with moving average of different window size (5, 10, and 12 years). Results suggest that precipitation variance increased until 1983, declining since then.

on three time windows: **full memory** (1960-1983 - 1984-2004 - 2005-2015), **long-term memory** (1960-1983 /1984-2014) and **short-term memory** (1990-2004 / 2005-2014). The empirical results using these three time windows suggest different degrees of precision in the anticipation of the true probabilities. This justifies the analysis of a spectrum of errors in the probabilities in our numerical example (described later in the text).

The quality of historical temperature data is worse than data on precipitation, with more missing records over the period here considered. Daily data from 1960 to 2015 were transformed into monthly averages. After transformation, some months had missing information for some years. To smooth the time series we used ARMA models with different windows for the auto-regressive [AR(1,2,3)] and moving average [MA(1,2,3)] components. To reduce forecast error we only used the predicted values if in a particular year at least 6 complete monthly data were available. After climate data were cleaned and smoothed, we performed a time analysis of temperature evolution (minimum, average, maximum) for each one of the 12 months with complete information7. Finally, monthly data were transformed into yearly averages. From the 56-years window (1960 to 2015) we obtained reliable data (complete or with high levels of prediction accuracy) for the following sub- periods: 1960-1978, 1995-2004, 2007, and 2010-2015. Treated temperature data series shows a tendency of local cooling until the 1980's, followed by average temperature increase (Figure 2).

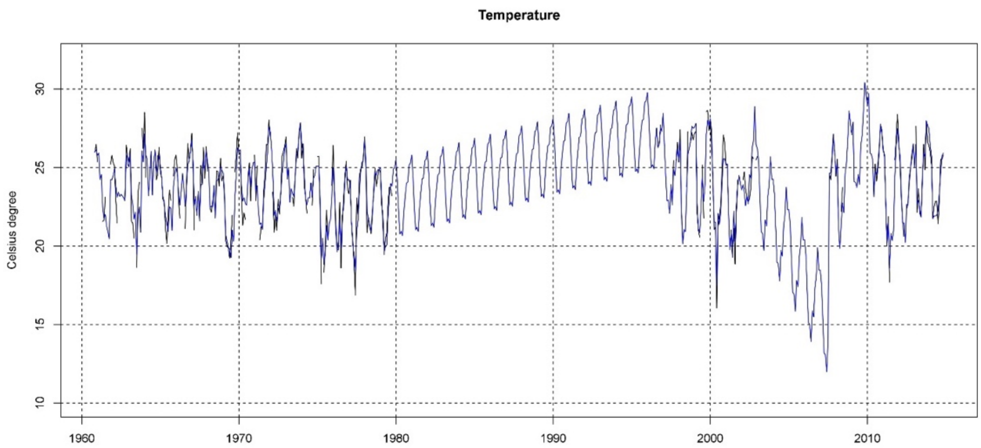
Figure 1: Average Monthly Precipitation Intensity and Frequency - Governador Valadares, Brazil - 1960 to 2014



Source: Data from INPE/CPTEC (2015); INMET (2015)

These local climate data were used as an objective criterion for comparison with individuals' perception of local climate change for Governador Valadares. Perceptions were derived from survey data collected in the region. These two sources of climate data combined proxy the parameters from our theoretical model represented by the objective (π_s^{ι}) and subjective (π_s^i) probabilities, respectively. These contrasts were used within an econometric framework to seek evidence of a subgroup of sampled individuals making persistent mistakes in the anticipation of occurrence of natural events.

Figure 2: Temperature Trend, Governador Valadares, Brazil (1960-2014)



Source: Data from INPE/CPTEC (2015); INMET (2015)

2.2. Survey Data

To seek empirical evidence of heterogeneity in agents' prior beliefs, we make use of novel survey data collected in Governador Valadares, Brazil. The survey data here used come from a pioneering research project in Brazil addressing environmental attitude, awareness, and behavior at the local level, with detailed questions on climate change perception and adaptive measures under risk of flood hazards. Data are part of the research project entitled "Migration, Vulnerability, and Environmental Change in Rio Doce Valley", funded by the Minas Gerais Research Foundation (FAPEMIG Grants CSA-APQ-00244-12, CSA-PPM-00305-14 and CSA APQ-01553-16), the Brazilian Research Council (CNPq Grants 4837/2012-7, 472252/2014-3 and 431872/2016-3), and the Brazilian Network on Global Climate Change Research (Brazilian Ministry of Science, Technology, and Innovation). The project was approved by the Research Ethics Committee at the Universidade Federal de Minas Gerais (Protocols CAAE 12650413.0.0000.5149 and 55007116.7.1001.5149).

Interviews were conducted in the urban area of Governador Valadares between 2014 and 2015, using a multi-stage sampling design. The sample was based on clusters of neighborhoods, with clustering based on geographic proximity and socioeconomic status of the neighborhood. Within each cluster, sample was stratified by sex and age groups, and within each stratum households were randomly selected. A minimum sample size was estimated of 1,069 households, based on a significance level of 5% and a tolerance of 3% for sample proportions. Variance estimate was 0.25, yielding the most conservative minimum sample size (GROVES et al., 2011). Because of additional budget resources granted, sample size was increased to 1226 households.

2.3. Comparative Analysis

In order to compare the local climate parameters (temperature and precipitation) with population perception we used the following items available in the survey questionnaire: (a) temperature: “In your opinion, since you started living in Governador Valadares, the city is: (1) as hot as in the past, (2) hotter than in the past, (3) cooler than in the past, (4) I don’t know”; (b) precipitation: “In your opinion, since you started living in Governador Valadares, it rains: (1) as often and with same intensity, (2) more often, but with same intensity, (3) more often and intensively, (4) less often, but with same intensity, (5) less often and less intensively, (6) more often, but with less intensity, (7) less often, but with same intensity, (8) it is impossible to know, (9) did not answer.

Based on these two questions and the climate data, we created a dummy variable for each climate parameter: (1) Perception and climate data differ (mismatch); (0) no mismatch. We ground our descriptive analysis on two different sets of dependent variables: (1) perception of any change in climate parameters from survey data, and (2) perception mismatch (survey versus climate data). For the first set, we split the analysis into rain pattern and temperature change perception[7]. The second set comprises descriptive association between covariates and the dependent variable (mismatch) for the three time windows considered: full memory, long memory, and short memory.

We then moved to a regression-based association, with two main models: (1) model of perceived change (survey data), (2) models of mismatch (survey versus climate data). Since questions on perception of temperature and precipitation change were answered by the same respondent, they are probably correlated on unobserved determinants. Because of this potential conditional correlation, we model the two dummy variables within a bivariate probit system of equations. To estimate sociodemographic patterns related to the contrasts (convergence and divergence between perception and measurement), we used the following

[7] The first discriminated the following rain pattern categories: more frequent, less frequent, more intense, less intense, and missing information. The second discriminated the following temperature pattern categories: same, hotter, cooler, and missing information.

covariates: age, age variance of household members, sex, individual income, education, time of residence, network distance to the Doce River, if the household is located in a flood-prone area, if any household member was ever hit by a river flood in the city, and if there is serious lack of green areas in the household surroundings.

2.4. Descriptive Results

Our survey data (Table 1) showed that 65.8% of respondents identify some change in the local temperature since they started living in GV (58.3% think the temperature increased and 7.5% believe that the city is cooler than in the past). Only 26.7% perceived no change in local temperature over the years. Less than 8% of respondents did not answer the question. The lower panel of Table 1 shows that sociodemographic patterns differ depending on how temperature change is perceived. On average, women, younger, longer residents, less educated, and those living closer to the Doce River, but out of the flood-prone areas, are more likely to perceive an increase in local temperature over the years (compared to temperature cooling). The younger but with a larger within-household age variance, more recent residents, those living further from the Doce River and those not having been directly affected by the river floods are the ones most likely to perceive any change (against no perception of change).

Descriptive data on perception of precipitation change also reveal interesting patterns: age is not very relevant, although those perceiving rainfall as more frequent and intense are slightly younger[8]. While women perceive more frequent rainfall, men are more likely to perceive increase in rainfall intensity over the years. Women, however, are more likely to perceive less frequent and intense rain than men over time. Time of residence seems to be linked to increased likelihood of temperature perception mismatch, regardless of the time window. For precipitation, however, newer immigrants are less likely to have a divergent perception for the shorter period, the opposite holding for the long time window. This is likely to reflect a mix of acclimatization and endogeneity between perception and place attachment (GROTHMANN; PATT, 2005).

Those living in less educated households are less likely to perceive more intensive rain patterns as do women; these patterns may reflect both vulnerability and exposure to worse locational conditions. Those living further away from the Doce River, but within the flood-prone area, and those ever directly affected by a river flood in town are more likely to perceive increased intensity and frequency. These patterns may be explained by two quite different reasons: while those far from the river may seek environmental cues on change in the water level while raining, those directly affected by the experience with an extreme event may trigger

[8] This is consistent with the short-memory analysis of climate data discussed above.

what is known as the magnified perception of risk (PIDGEON; KASPERSON; SLOVIC, 2003). Those that are less likely to have noticed any change in precipitation patterns are quite younger, living in households with a smaller age variance of residents, more likely to be a more educated migrant household, located close to the Doce River within flood-prone areas and with very low probability of ever having been hit by a river flood in town.

Table 1: Descriptive analysis of sociodemographic attributes and its relation to perception of change in local climate parameters – GV, Brazil, 2014/2015

Covariates	Rain Pattern				
	More Frequent	Less Frequent	More Intense	Less Intense	Doesn't Know
Male	39.7	45.7	55.0	43.7	46.7
Age	38.9	41.0	38.5	40.9	34.8
Std. Dev. of age in Household	15.0	15.6	15.0	15.5	12.4
Incomplete high school	34.5	31.3	27.5	33.1	16.7
Incomplete college	44.8	47.0	50.3	46.8	51.7
Complete college	20.7	21.7	22.1	20.0	31.7
Near distance to river (km)	1.7	1.4	1.6	1.4	1.2
Household in flood-prone area	22.4	19.8	20.8	19.2	25.0
Any in household ever hit by flood	29.3	27.9	28.9	24.4	1.7
Sample* (%)	6.8	82.3	16.9	57.0	5.3

Covariates	Temperature			
	Same	Hotter	Cooler	Doesn't Know
Male	46.4	44.1	48.1	48.8
Age	43.0	40.4	42.6	36.8
Std. Dev. of age in Household	14.7	15.6	16.2	12.6
Incomplete High School	33.6	30.6	33.8	13.8
Incomplete College	44.2	47.7	40.3	60.0
Complete College	22.3	21.7	26.0	26.3
Near distance to river (km)	1.4	1.4	1.7	1.3
Household in flood-prone area	24.5	15.8	31.2	33.8
Any in household ever hit by flood	29.6	25.5	23.4	7.6
Sample (%)	26.7	58.3	7.5	7.5

Source: Data from survey data (GV, 2014/2015)

Although interesting by itself, the comparison of sociodemographic groups by type of perceived change, it is less likely to provide a more solid clue on prior beliefs. A better way to look at it descriptively is to check if those patterns hold in terms of perception mismatch. Table 2 presents bivariate summary measures for the three time windows previously discussed. If we look at persistent relations, regardless of the time window, we find that more educated men, and those with some experience with floods from the Doce River are more likely to perceive a different trend in local climate parameters than what is suggested by the meteorological data. Age is only important for the full and long memory time windows, as older people are more likely to mismatch their perceptions with climate data. As anticipated, memory bias seems to be reduced for the short memory time window. These patterns hold for both, precipitation and temperature.

When we look at the geophysical markers however, some differences arise. Although not important for precipitation, those living further from the river seem to be more likely to match perception of temperature change. Since climate data suggests an increase in local temperature for recent years, proximity to the River and the riverbank vegetation may exert a cooling effect, making it more difficult for nearby residents to perceive subtle changes over the years. Also coherent with the previous descriptive findings for perceived change, those living in river flood-prone areas and having experienced episodes of floods are more likely to mismatch precipitation change. It may be that the experience with floods may exacerbate the sensitivity to shorter, intense rainfall, causing the myopic bias effect typically seen in insurance demand behavior (KUNREUTHER et al., 2013).

Table 2: Descriptive analysis of sociodemographic attributes and its relation to divergence between perceived and objective change in local climate parameters – GV, Brazil, 2014/2015

Covariates	**Rain Pattern**		**Temperature**	
	Mismatch	No Mismatch	Mismatch	No Mismatch
	Full Memory			
Male	45.9	42.5	46.2	39.4
Age	43.9	29.7	41.0	39.7
Std. Dev. of Age in Household	15.3	16.1	15.6	14.4
Years continuously living in GV	30.4	20.4	30.4	15.8
Incomplete High School	31.9	30.6	31.8	30.3
Incomplete College	43.8	53.4	45.8	46.2
Complete College	24.4	16.1	22.4	23.5

Near distance to river (km)	1.5	1.4	1.4	1.7
Household in flood-prone area	20.0	19.2	18.8	25.8
Any in household ever hit by flood	27.3	24.9	26.9	26.5
Sample (%)	78.6	21.4	85.3	14.7

Covariates	Long Memory			
Male	46.1	42.1	46.5	37.5
Age	44.1	30.6	40.8	41.1
Std. Dev. of Age in Household	15.4	15.7	15.5	15.2
Years continuously living in GV	31.5	18.1	30.4	16.4
Incomplete High School	32.8	27.8	32	29.4
Incomplete College	43.0	54.6	45.6	47.1
Complete College	24.2	17.6	22.4	23.5
Near distance to river (km)	1.5	1.4	1.4	1.7
Household in flood-prone area	19.0	22.2	19.1	23.5
Any in household ever hit by flood	27.8	23.6	27.1	25.0
Sample (%)	76.1	23.9	84.9	15.1

Covariates	Short Memory			
Male	46.4	43.9	46.5	37.5
Age	40.4	41.2	40.8	41.1
Std. Dev. of Age in Household	15.2	15.7	15.5	15.2
Years continuously living in GV	25.2	31.4	30.4	16.4
Incomplete High School	28.8	34.5	32.0	29.4
Incomplete College	45.3	46.4	45.6	47.1
Complete College	25.9	19.1	22.4	23.5
Near distance to river (km)	1.5	1.4	1.4	1.7
Household in flood-prone area	22	17.6	19.1	23.5
Any in household ever hit by flood	29.2	24.3	27.1	25
Sample (%)	50.7	49.3	84.9	15.1

Source: Data from survey data (GV, 2014/2015); INPE/CPTEC (2015); INMET (2015)

2.5. Econometric results

Table 3 shows the bivariate probit coefficients using the same covariates described in Tables 1 and 2. Overall, the Wald test and LR test for a non-zero ρ were significant for both types of models, justifying the efficiency gain in the use of correlation on conditional unobservables for estimation purposes. When we look at the models for perceived change (no matter if matched with climate data), we found that the younger are less likely to identify change in precipitation, but more likely to perceive change in temperature. Education was only marginally significant. Those in river flood-prone areas are less likely to perceive change in temperature. In all, the model for perceived change fits very poorly and shed almost no insight on patterns related to agents' prior beliefs.

If we look, however, to the models for mismatch in perceived change, interesting patterns arise. For both, long and short memory models, male are more likely to mismatch trends in local temperature, but not in rainfall. The descriptive results had pointed to that direction, as men were less likely to perceive the local temperature getting hotter over the years (Table 1), mirroring the findings in the literature (SHAO et al., 2014). Also coherent with the descriptive findings, younger individuals are less likely to mismatch perception with climate trend. The age effect is more important for precipitation than for temperature and looses statistical significance in the short memory model, reinforcing the argument on memory bias. The weaker age effect on temperature may relate to that vulnerability to extreme temperature peaks on the younger and on the elderly, leading both age groups to be more sensitive to actual change in temperature conditions (KAHNEMAN, 1979; HAJAT et al., 2014). The effect of education on perception mismatch is intriguing and might reflect the fact that more educated households are more adapted to climate change, being less sensitive to gradual local change in climate parameters. This type of result was also found in other studies, where individuals who are more educated are more likely to respond to climate change, but less likely to perceive further changes after adaptation (SJOGERSTEN et al., 2013). It may be that education is also capturing a more general trend observed in macro studies, which suggest that education would be positively related to perceptions of climate change, inducing adaptation (SHAO et al., 2014).

Among the geophysical attributes, we found significant effects for proximity to the Doce River and lack of green spaces in the surroundings. These are predominantly important for explaining mismatch on perceived temperature change and have opposite effects. Households closer to the river are more likely to mismatch temperature change, possibly reflecting the cooling effect of water bodies and riverbank forests. The lack of green spaces, on the other hand, increases the likelihood of mismatch. Although counter-intuitive, since we would expect those living in more urbanized areas to be more likely to perceive the increased temperature change in recent years, this effect may be explained by our own data construction strategy. Since we model the probability of mismatch and the temperature trend reflects a cooling period until the mid-1980s and increasing temperature since then, someone perceiving a continuous increased temperature would be classified as having a different perception of change. The almost double size of the coefficient for the short-memory model suggests that this would be the case, with those individuals projecting their amplified perception of a warming environment

Table 3: Estimated Coefficients on the Probability of Perceived Change and Divergence between Perception and Objective Change in local Climate Parameters – GV, Brazil, 2014/2015

Covariates			Mismatch (Observed x Perceived)					
	Any Perceived Change		Full Memory		Long Memory		Short Memory	
	Rain Pattern	Temperature	Rain Pattern	Temperature	Rain Pattern	Temperature	Rain Pattern	Temperature
Sex (1=Male)	0.054	-0.042	0.146	0.167	0.157	**0.212***	0.054	**0.206+**
	[0.137]	[0.088]	[0.104]	[0.107]	[0.100]	[0.106]	[0.086]	[0.106]
Age (years)	**0.037+**	**-0.005+**	**0.028****	**0.013***	**0.031****	0.007	**-0.009+**	0.006
	[0.022]	[0.003]	[0.007]	[0.006]	[0.006]	[0.006]	[0.005]	[0.006]
Age Square	**-0.0004+**							
	[0.000]							
Std. Dev. of Age in Household	**0.014+**	0.006	**-0.038***	**0.038***	-0.018	0.023	**-0.028***	0.022
	[0.008]	[0.005]	[0.016]	[0.016]	[0.015]	[0.016]	[0.013]	[0.016]
Interaction (Age x Std. Dev.)			**0.001***	**-0.001+**	0.000	0.000	**0.000+**	0.000
			[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Incomplete College (Base = Incomplete high school)	-0.101	0.025	**0.204+**	0.010	0.071	-0.057	0.094	-0.035
	[0.174]	[0.106]	[0.122]	[0.128]	[0.119]	[0.127]	[0.102]	[0.127]

Complete College (Base = Incomplete high school)	-0.342+	0.041	0.422**	0.003	0.245+	-0.056	0.283*	-0.016
	[0.190]	[0.123]	[0.154]	[0.150]	[0.146]	[0.148]	[0.120]	[0.148]
Near distance to the river (km)	-0.011	0.051	0.049	-0.136**	0.063	-0.136**	0.072+	-0.125*
	[0.067]	[0.042]	[0.050]	[0.052]	[0.048]	[0.051]	[0.041]	[0.051]
Household in flood-prone area (1=Yes)	0.063	-0.247*	-0.052	-0.239+	-0.270*	-0.183	0.094	-0.143
	[0.191]	[0.118]	[0.143]	[0.140]	[0.136]	[0.139]	[0.117]	[0.139]
Anyone in household ever hit by flood (1=Yes)	-0.009	-0.043	0.010	0.130	0.157	0.166	0.114	0.144
	[0.170]	[0.107]	[0.129]	[0.132]	[0.126]	[0.131]	[0.104]	[0.129]
Serious lack of green spaces in the household surroundings				0.279*		0.288*		0.434**
				[0.135]		[0.135]		[0.134]
Constant	0.798+	0.657**	-0.433		-0.651*	0.745*	0.237	0.706*
	[0.478]	[0.183]	[0.317]		[0.305]	[0.324]	[0.266]	[0.326]
Atanh-rho	0.304**		-0.092		0.347**		-0.363**	
	[0.089]		[0.079]		[0.073]		[0.070]	
Observations	940	940	891		891	891	891	891

Source: Authors' estimation based on Survey Data (Governador Valadares, 2014/2015) and data from INPE/CPTEC (2015); INMET (2015) back in time. Thus, local climate change may be more salient for this group. Previous experience with floods was not statistically associated with perception mismatch.

3. The Model of Private Insurance Market

Our empirical analysis found evidence of friction between two groups: one making persistent mistakes and another with accurate expectations. Even among those without rational expectation, we found additional evidence of heterogeneity. These findings provide us guidance in proposing a model of private insurance market with heterogeneous beliefs, based on Stiglitz (1976). Our proposed model differs from Stiglitz's by considering endogenous insurance price, heterogeneous beliefs, and income taxation to correct information asymmetry.

Suppose a market described by a set of I individuals, with a typical element denoted by $i \in I$. Assume that an agent has a utility function $u^i: \mathbb{R}_+ \to \mathbb{R}_+$ representing the benefit of consumption. Further assume that individuals have a periodic income, or endowment, denoted by e^i. A finite set, S, includes all possible states of nature. In this study, this set represents the intensity of a natural disaster. Agents with inaccurate beliefs will be granted access to a certain public technology that provides information about the true probabilities of the states of nature, π^ι. This technology is implemented using a tax rate τ^i, measured as a fixed amount given in units of the good. At the optimal choices, agents with accurate expectations choose $\tau^\iota = 0$.

Write $(\pi_s^i)_{s\in S}$ as the long run subjective probability distribution describing the law governing the realization of all possible states of nature. Assume that agents run a risk of a gross loss of l_s good units in each state, $s \in S$, and that a certain contract (insurance, for instance) is available to transfer the total estate across states of nature. This contract has a unitary price $p \in \mathbb{R}_{++}$, taken as given. A unit of this contract allows the agent to receive an amount t_s, conditioned on each realization of a state of nature, s.

According to these premises, the level of consumption depends on the realization of each s. Hence, individuals choose the optimal consumption plan contingent to the realization of exogenous events. A contingent consumption plan, $\left(c_s^i\right)_{s\in S}$, is said to be feasible, given the price p, when an amount of insurance units, θ^i, exists such that:

$$c_s^i + p\theta^i \le e^i - l_s - \tau^i + \theta^i t_s \ for\ all\ s \in S \qquad (1)$$

Write $b^i(p, \tau^i)$ as the set of all feasible consumption plans and insurance choices. Agents' indirect utility[9] is then defined as:

[9] Agents' indirect utility represents the benefit of the optimal choice.

$$v^i(\pi^i, p, \tau^i) = \max\{\sum_{s\in S} \pi_s^i u^i(c_s) \colon \exists \theta^i \in \mathbb{R}_+ \; such\ that\ (c_s^i, \theta^i) \in b^i(p, \tau^i)\ \forall\, s \in S\} \quad (2)$$

The value $v^i(\pi^i, p, \tau^i)$ represents the optimal expected benefit among all feasible consumption plans, given price p, subjective probability π^i and tax rate τ^i. Here we assume that when there is no loss there is no transfer, that is, $l_s' = 0\ implies\ t_s' = 0$. The insurance is in net supply of ϑ units, offered inelastically by the firms. The agents' optimal choices are described by:

$$(\tilde{c}^i(\pi^i, p, \tau^i), \tilde{\theta}^i(\pi^i, p, \tau^i)) = \operatorname{argmax}\left\{\sum_{s\in S} \pi_s^i u^i(c_s) \colon \exists \theta^i \in \mathbb{R}_+ \; such\ that\ (c_s^i, \theta^i) \in b^i(p, \tau^i)\ \forall\, s \in S\right\}$$

We present bellow the definition of equilibrium in which the consumption market clearing need not be exhibited, because in a setting with two markets the equilibrium of the first implies the equilibrium of the second (Walras' Law).

Definition: The equilibrium is given by a profile of consumption, insurance choices and taxation, $(c^i, \theta^i, \tau^i)_{i\in I}$, and a price p such that:

1. $\sum_{i\in\{1,2\}} \tilde{\theta}^i(\pi^i, p, \tau^i) = \vartheta$
2. $c^i \in \tilde{c}^i(\pi^i, p, \tau^i)$ and $\theta^i \in \tilde{\theta}^i(\pi^i, p, \tau^i)$

Condition 1 implies that the net supply of insurance is ϑ. Condition 2 represents the optimality choices. Given the model setting, we present an example with a closed form solution and exhibit a numeric threshold on the taxation to illustrate how the market failure resulted from information asymmetry can be corrected.

Example: Consider $u^i(c) = ln(\alpha^i + c)$ and $S = \{1,2\}$, with $s = 1$ representing the state of low intensity for the natural disaster. Given that risk aversion is defined as $r_a(c) = -u_i''(c)/u_i'(c) = 1/(\alpha^i + c)$, we assign $\alpha^i = 0$ for high risk-averse agents, $\alpha^i = 10$ for agents with intermediate level of risk aversion, and $\alpha^i = 50$ for those with a low level of risk aversion.

For the interior solution, Equation (1) becomes:

$$\tilde{c}_s^i(\theta^i, \tau^i) = (t_s - p)\theta^i + e^i - l_s - \tau^i\ for\ all\ s \in S \quad (3)$$

The concavity of u^i assures that the first order condition (F.O.C.) on θ^i is enough to find the optimal choice if it is an interior solution[10].

[10] Satisfying the INADA conditions.

If $\tilde{\theta}^i(\pi^i, p, \tau^i)$ is the optimal insurance choice, then the optimal solution calculated at $\tilde{\theta}^i(\pi^i, p, \tau^i)$ satisfies

$$\sum_{s\in S}(t_s - p)\pi_s^i u'\left((t_s - p)\tilde{\theta}^i(\pi^i, p, \tau^i) + e^i - l_s - \tau^i\right) = 0 \qquad (4)$$

Assuming $u^i(c) = \ln(\alpha^i + c)$ and $S = \{1,2\}$, we get the following solution representing the optimal demand for insurance:

$$\tilde{\theta}^i(\pi^i, p, \tau^i) = \frac{(p - t_{s_1})\pi_{s_1}^i(\alpha^i + e^i - \tau^i - l_{s_2}) + (p - t_{s_2})\pi_{s_2}^i(\alpha^i + e^i - \tau^i - l_{s_1})}{(p - t_{s_1})(p - t_{s_2})} \qquad (5)$$

The optimal consumption is given by

$$\tilde{c}_s^i(\pi^i, p, \tau^i) = \frac{(t_s - p)[(p - t_{s_1})\pi_{s_1}^i(\alpha^i + e^i - \tau^i - l_{s_2}) + (p - t_{s_2})\pi_{s_2}^i(\alpha^i + e^i - \tau^i - l_{s_1})]}{(p - t_{s_1})(p - t_{s_2})} + e^i - \tau^i - l_s$$

The equilibrium price, p, is given in the appendix. The relative welfare loss, wl, is evaluated as

$$wl = \frac{v^i(\pi^\iota, p, \tau^\iota) - \sum_{s\in S}\pi_s^\iota u^\kappa\left(\tilde{c}_s^\kappa(\tilde{\theta}^\kappa(\pi^\kappa, p, \tau^\iota))\right)}{v^i(\pi^\iota, p, \tau^\iota)}$$

This measure represents the long run welfare loss when agents make persistent mistakes on the probabilities. By the Law of Large Numbers, the benefit of the agent with inaccurate expectations is given by the summation in the numerator of wl. Hence, wl represents the asymptotic welfare loss of the agent with inaccurate expectations relative to the one with rational expectations.

The optimal tax levy is the tax implemented by the government to assure at most the same level of welfare loss when agents with inaccurate beliefs adopt the accurate information bought at this optimal tax level. That is, it represents the tax that makes $wl^G = wl$, where:

$$wl^G = \frac{v^i(\pi^\iota, p, \tau^\iota) - \sum_{s\in S}\pi_s^\iota u^\kappa\left(\tilde{c}_s^\kappa(\tilde{\theta}^\kappa(\pi^\iota, p, \tau^\kappa))\right)}{v^i(\pi^\iota, p, \tau^\iota)}$$

The optimal tax levy, τ^i, is obtained numerically[11].

[11] We simulate the solution with the following parameters for all $i \in I = \{\iota, \kappa\}$: total endowment: $e^i = 1200$; risk aversion parameter: $\alpha^i = 0$; Insurance net supply: $\vartheta = 100$; level of gross loss for state s_2: $l_{s_2} = 800$; unitary transfer for state s_2: $t_{s_2} = 8$; true probabilities: $\pi_{s_1} = 0.7; \pi_{s_2} = 0.3$; inaccurate probabilities: $\pi_{s_1} \in [0.1, 0.9]; \pi_{s_2} = 1 - \pi_{s_1}$. In the second and third simulations, we keep all the previous parameters constant, except for the decrease in the parameter of risk aversion (now set to $\alpha^i \in \{10, 50\}$ for intermediate and low levels, consecutively). This simulation was performed to check how sensitive are the results when risk aversion changes among agents. The use of different levels of risk aversion in our simulations is based on many

Table 4: Optimal tax rate, price allocation, insurance choice, and welfare loss under varying inaccurate beliefs and levels of risk aversion

PANEL A: high level of risk aversion $[\alpha^i = 0;\ \pi^\iota = (0.7; 0.3)]$				
Expectations $(\pi^2_{s_1}; \pi^2_{s_2})$	Tax % (τ^2)	Equilibrium Price (p)	Demand % $(\theta^1; \theta^2)$	Welfare loss %
(0.3; 0.7)	9.439	5.072	(49.967; 50.033)	5.000
(0.4; 0.6)	6.896	4.660	(49.976; 50.024)	2.718
(0.5; 0.5)	2.978	4.226	(49.989; 50.011)	1.217
(0.6; 0.4)	0.516	3.769	(49.998; 50.002)	0.319
(0.7; 0.3)	0.000	3.289	(50.000; 50.000)	0.000
(0.8; 0.2)	-1.039	2.789	(50.004; 49.996)	0.418
PANEL B: Intermediate level of risk aversion $[\alpha^i = 10;\ \pi^\iota = (0.7; 0.3)]$				
Expectations $(\pi^2_{s_1}; \pi^2_{s_2})$	Tax % (τ^2)	Equilibrium price (p)	Demand % $(\theta^1; \theta^2)$	Welfare loss %
(0.3; 0.7)	8.936	5.056	(49.970; 50.030)	4.996
(0.4; 0.6)	6.719	4.645	(49.977; 50.023)	2.713
(0.5; 0.5)	2.934	4.211	(49.990; 50.010)	1.214
(0.6; 0.4)	0.511	3.755	(49.998; 50.002)	0.318
(0.7; 0.3)	0.000	3.277	(50.000; 50.000)	0.000
(0.8; 0.2)	-1.037	2.778	(50.004; 49.996)	0.412
PANEL C: Low level of risk aversion $[\alpha^i = 50;\ \pi^\iota = (0.7; 0.3)]$				
Expectations $(\pi^2_{s_1}; \pi^2_{s_2})$	Tax % (τ^2)	Equilibrium price (p)	Demand % $(\theta^1; \theta^2)$	Welfare loss %
(0.3; 0.7)	6.989	5.000	(49.977; 50.023)	4.957
(0.4; 0.6)	6.039	4.589	(49.980; 50.020)	2.692
(0.5; 0.5)	2.767	4.157	(49.991; 50.009)	1.206
(0.6; 0.4)	0.494	3.705	(49.998; 50.002)	0.316
(0.7; 0.3)	0.000	3.231	(50.000; 50.000)	0.000
(0.8; 0.2)	-1.031	2.738	(50.003; 49.997)	0.409

Table 4 shows the numerical results. Simulated values for insurance demand present small differences because the parameters scale was chosen to preclude corner solutions. We call pessimistic agents those who attribute higher probability to the occurrence of natural disasters; the other agents are called optimistic. The computed relative welfare loss can be viewed as a type of deadweight loss because it was evaluated after the implementation of a tax levy to attenuate the information asymmetry in the insurance market.

Table 4 suggests four main findings. First, among pessimistic agents the higher the error in the probabilities the larger the welfare loss, regardless of the level of risk aversion. In this case, agents making larger errors would be willing to pay a higher tax rate relative to their income. Second, markets with higher levels of risk aversion yield higher insurance prices due to the increase in the reservation price. Third, when agents act optimistically government intervention becomes unfeasible. Welfare loss, in this situation, is higher than when the same agents act pessimistically with the same error magnitude. Finally, the average threshold for the tax rate would be 9.188% for the larger error in the probabilities. However, this upper limit

empirical findings for the USA (LIGHT and AHN, 2010), the Netherlands (TERPSTRA and LINDELL, 2013), and Brazil (GUEDES et al., 2015).

varies by level of risk aversion. In our example, it ranges from 9.439% of aggregate agents' income (in a market with high levels of risk aversion) to 6.989% (when risk aversion is low).

Concluding Remarks

This paper had four main goals. First, we study the welfare consequences of the friction between two groups, with and without rational expectations, in an incomplete insurance market. We validate this friction by seeking empirical evidence of persistent error in a subsample of individuals regarding the perception of change in local climate parameters. Second, we test the existence of additional heterogeneity in the probability of belonging to the group who makes persistent mistakes on the anticipation of climate events using econometric models. Third, we develop a two-period model of private insurance under uncertainty with endogenous prices to explain how the coexistence of these groups may deviate market prices from the fundamentals, leading to reduction in social welfare in the long run. Our proposed model differs from Stiglitz's (1976) by considering heterogeneous beliefs and income taxation to correct market failures (information asymmetry). The tax burden is employed to finance a public technology that provides accurate information to those agents making persistent mistakes. The levy only on agents without rational expectations is a way to avoid moral hazard behavior among those with rational expectation (MIRLEES, 1971; ATKISON; STIGLITZ, 1972). Finally, we solve the proposed model algebraically with a closed form solution and simulate the taxation threshold as a proportion of the agents' income that Pareto improves any market allocation without government intervention.

Based on the survey data, we identified the existence of a group of individuals making persistent errors in the anticipation of climate events. The econometric models further suggest that the probability of belonging to this group varies significantly by sociodemographic and geophysical attributes of the sampled respondents. This empirical finding of heterogeneity within and between groups helps explain why there is no market supply of information on natural events. The absence of firms providing this type of information occurs because price discrimination via product differentiation is economically unfeasible in private markets. Therefore, we propose a theoretical model with heterogeneous agents and taxation to finance a public technology providing information on natural events. Results from our insurance model with incomplete markets show that the group with accurate expectations price the insurance as the fundamentals (STIGLITZ, 1976), while agents with inaccurate expectations distort insurance prices in the long run. The closed form solution suggests that agents making persistent mistakes on the process of anticipation of climate events are not driven out from the market, as in Blume and Easley (2006). By including a central planner providing a technology for access to accurate information, our example illustrates that public intervention (via taxation) would only be feasible if public expenditure in the provision of this technology did not exceed 9.188% of the aggregate income earned by agents with inaccurate expectations. This threshold is computed based on a relative measure of social welfare that is robust to scale transformations.

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