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# Climate Change and Economic Growth in a Rain-fed Economy: *How Much Does Rainfall Variability Cost Ethiopia?*


**Seid Nuru Ali**

E-mail: snuru@eeaecon.org

**Ethiopian Economics Association**

P.O.Box: 34282
Addis Ababa, Ethiopia
Tel.: (251-11) 6453200
Fax: (251-11) 6453020
E-mail: eea@ethionet.et
Web: www.eeaecon.org



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# Abstract

Climate change may impact economic growth through rainfall variability. This paper, using a simple growth model, demonstrates that the adverse impact of rainfall variability on economic growth depends on the rate of expansion of the amplitude of rainfall variability and frequency of occurrence of extreme events. A co-integration analysis using time series data from Ethiopia shows both inter-annual and within-annual rainfall variations have negative effect on growth. Simulation results on the forgone growth due to rainfall variability for the last five decades implied that mitigation and adaptation strategies towards climate change that reduce the impact of rainfall variability would put Ethiopia on a higher trajectory of growth.


**Key Words**: Economic Growth, Rainfall Variability, Capital, Ethiopia.
**JEL Classification**: O41; Q54

# 1 Introduction

The purpose of this paper is to show how rainfall variability in particular in the face of climate change keeps a poor country in what Nelson (1956) called the 'low-level equilibrium trap.' The paper introduces rainfall variability with widening amplitude into the traditional growth model as a factor that incapacitates capital and demonstrates how dependency on rainfall drags growth. A time series data from Ethiopia is used to empirically support the argument.

In the traditional growth models which accrue long term growth either to exogenous technological change (Solow, 1956; Swan, 1956; Ramsey, 1928; Cass, 1966; Koopmans, 1965) or to savings, human capital, and R and D (Lucas, 1988; Romer, 1986; Romer, 1990; Jones, 1995; Nelson and Phelps, 1966), climate is considered to be part of initial conditions of economies that has only level effects on income (Mankiw, Romer, and Weil, 1992). There are two points that justify the explicit consideration of climate conditions such as rainfall variability in the growth models. First, developing countries whose economy is dependent on rainfall may experience erratic variation in rainfall including extreme events. Such periodic variations have the ability to shape the long-term path of the economy. Second, if climate change is imminent, then it will have more than a level effect on economies because such change is a process rather than being a one period shock.

In terms of addressing the sources of disparities among countries in their level of per capita income, geography has a lot to explain. For example, extreme events such as drought are exceptionally higher for Africa [Bloom and Sachs, 1998]. What makes the rainfall variability an issue is the fact that it is periodic and yet the frequency is unpredictable. For instance, in the period between 1983 and 1995, 29 African countries where about 51 percent of the population of the continent lives experienced drought at least once. In the same period, 24 of them where 28 percent of the African population live experienced drought three times and more (Bloom and Sachs, 1998).

Climate change predictions in particular on precipitation are not generally favorable to Africa (IPCC, 2007; Schreck and Semazzi, 2004; Anyah and Semazzi, 2006; Kaspar and Cubasch, 2008). A recent study by Schlenker and Lobell (2010) shows that aggregate production of five major crops in Sub-Saharan Africa will fall by 8 percent (for Cassava) to 22 percent (for maize) due to climate change in the mid-century. More challenging implication of the study is that the impact of climate change will be more severe for well-fertilized crops of modern seed varieties.

Ethiopia has been experiencing frequent drought. According to Webb, von Braun, and Yohannes (1992), the country faced 11 major drought episodes that led to severe famine between 1953 and 1992. Since then, the drought has become even more frequent: the 1993-94, 2000, 2002-03 droughts are the major ones (EEA, 2004). Given the incidences of droughts that occurred in the years 2007 and 2009, it can be observed that drought is recurring but remain unpredictable.

Incidence of rainfall variability is not only confined to Africa. Asian countries have been challenged by the double hazard of both drought and flooding. For instance, Bangladesh is generally known to be vulnerable to flooding while up to 15 percent of its cultivable land experiences drought every two years (Ahmed et al. 2005). India is also known for being a drought-prone country. The frequency of drought in that country has been increasing (Prabhakar and Shaw, 2008).

Such incidences of rainfall variability would have a bearing on the long-term growth of countries whose economy is dependent on rainfall[1]. There is an attempt by Fankhauser and Tol (2004) to formally introduce climate change into the standard growth models. They predict that climate change represented by overall rise in temperature would have a negative effect on long-term growth. This is basically based on the assumption that all non-market and market impacts of climate change on utility and production are negative. Other studies (Masters and McMillan, 2001; Mendolsohn et al., 1994) show climate change is predicted to have different impacts on different ecological zones bringing positive outcome for temperate zones. The impact of climate change would be different even for different crops within similar agro-ecological zone (Chang, 2002).

Measuring the impact of climate change on growth is tricky for a number of reasons. Primarily, the manifestations of climate change are many and their outcomes vary across different ecological zones. This paper focus on one of such manifestations: it specifically looks into the impact of rainfall variability on economic growth wherever it applies.

There are a number of channels through which rainfall variability affects long term growth. The first channel is savings. Unlike in the neoclassical growth models, saving rate has an impact on long-run growth in the AK variant of the endogenous growth models (Lucas, 1988). In particular, the importance of saving in triggering growth in developing countries which are far from the world technology frontier is significant (Hicks, 1965; Lewis, 1954; Nurkse, 1953). Frequent drought or flooding erodes savings.

The other channel through which climate change affects growth is tech-

[1] There are countries which are characterized by low variability of rainfall such as those in the equatorial region of Africa. In such cases where it rains all year round, variation in monthly rainfall is expected to increase output. Future studies may focus on general cases in which rainfall variability can also have positive effect on growth.

nology. Technology transfer is the most likely way of ensuring convergence for developing countries (Jones, 2004; Lee, 2001; Stiglitz, 1999). Technology transfer requires human capital (Jones, 2004) that can "scan globally and invest locally" (Stiglitz, 1999). It also requires openness to international trade so that capital goods which are technology carriers can be imported. Both human capital formation and ability to import capital goods are negatively affected by rainfall variability. During severe drought, youths struggle to survive rather than invest in education. During such bad times, what a poor country can afford to import at best are food and medicine rather than capital goods.

Uncertainty is another route through which rainfall variability affects economic growth. Agents in particular farmers tend to invest in low risk but low return activities in the face of unpredictable climatic conditions. Lingering pessimism among economic agents due to frequent extreme events retards economic growth.

Rainfall variability also affects growth by directly impacting productivity of capital. That is, for an economy which is heavily dependent on rainfall, the productivity of capital inputs such as land, fertilizer, and tractor-hours depends on the availability of timely rainfall. The theoretical framework of this paper is based on this line of argument. Rainfall variability enters the aggregate production function as a factor incapacitating capital with an ultimate growth-drag effect[2]. Hence, in a developing 'rain-fed economy,' erratic rainfall with widening variability becomes part of the story of the economy.

The remaining sections of this paper are organized as follows. Section two gives a theoretical basis for the impact of rainfall variability on growth. Section three presents an empirical support to the impact of rainfall variability on growth based on Ethiopian data for the period 1961-2008. The last section concludes.

# 2 Theoretical Framework: A Simple Model of Rain-fed Economy

The basis for the theoretical framework is the Ramsey-Cass-Koopmans model of growth which makes saving rate endogenous in a dynamic setup. The major modification in the model is the introduction of rainfall variability as a factor that incapacitates capital. The outcome of the optimization of

[2]The term 'growth-drag' is borrowed from Romer (2006, pp. 38-42) where he discussed growth with resource and land inputs.

the dynamic model is that growth in the long-run depends on the rate of technological change and rate of change of rainfall variability in terms of both amplitude and frequency.

## 2.1 The Production Function

Assume that agents in the economy combine labor and capital to produce output. Let the economy-wide production function be given by:

$$Y(t) = A(t)K(t)^{\alpha}L(t)^{(1-\alpha)} \tag{1}$$

where $Y(t)$ = output, $K(t)$ = capital, $L(t)$ = labor, $A(t)$ = a variable containing technology.

In the growth literature, $A(t)$ is most often regarded as a variable representing level of technology. It is customary to assume that technology, $A(t)$, grows at a constant rate of $g$ according to $A(t) = A_0e^{gt}$. Normally, the constant $A_0$ represents country specific factors such as resource endowment, institutions, and climate (Mankiw, Romer, Weil, 1992). But if one or more components of the factors that are lumped in this parameter are not constant over a fairly long period of time, they become part of the dynamics of the production function. Some of such variables may possibly have a growth-drag effect.

In the presence of noticeable climate change, one such component which can be explicitly modeled is the climatic condition of a country. Let $B(t)$ in $Y(t) = B(t)K(t)^{\alpha}L(t)^{1-\alpha}$ contain a purely technological component $A(t)$ with a property of growth spur-effect and $D(t)$ with growth drag -effects. In this context, $D(t)$ represents particularly rainfall variability. A Harod-neutral technology is assumed in the sense that $A(t)$ augments labor. However, $D(t)$ is assumed to disable capital from contributing to output at its full capacity up to a scalar $\gamma$. The parameter $\gamma$ can be considered as the degree of dependency of the economy on rainfall.

There is an optimum level of rainfall variation $\bar{R}$ which can be thought of as the level of rainfall variation which is consistent with maximum output. Deviation from the optimum level discounts capital and hence causes output to decline. Let the deviation from the optimum variation of rainfall be represented by:

$$D(t) = \left|R(t) - \bar{R}\right| \tag{2}$$

The production function under Equation (1) can thus be rewritten as:

$$Y(t) = \left(\frac{K(t)}{(1 + D(t))^{\gamma}}\right)^{\alpha} (A(t)L(t))^{(1-\alpha)} \tag{3}$$

It is apparent to observe that Equation (3) reduces to the standard production function when either there is no deviation from the optimum level of rainfall variation ($D(t) = 0$) or the economy does not significantly depend on rainfall ($\gamma = 0$).

In addition to the mathematical convenience, the specification that rainfall variability is greater than one is also theoretically intuitive. Rainfall variability could cause meteorological, agricultural, and hydrological droughts. A one period decline in rainfall might have impacts on water resources, and water-soil balance which do have longer-run effects. Hence, there might be some sort of hydrological drought even during a period when a normal mean annual rainfall is observed (Rosenzweig and Hilel, 1998; Bloom and Sachs, 1998) which is equivalent to a zero deviation.

As usual, Equation (3) can be expressed in terms of effective labor by dividing both sides of the equation by $A(t)L(t)$. Output per effective labor is thus a function of capital per effective labor with a 'capital-incapacitating' factor $D(t)$:

$$\tilde{y}(t) = D(t)^{-\gamma\alpha}\tilde{k}(t)^{\alpha} \tag{4}$$

One important aspect that has to be emphasized is that the deviation $D(t)$ is periodic in nature. For instance, the major droughts in Ethiopia had been occurring almost every ten years at least until 2000. Such periodic deviations can be better represented by sinusoidal functions. In practice, the annual pattern of rainfall variability does not follow a well-behaving sine or cosine curves. Nevertheless, these less perfect patterns can be represented by combinations and interactions of sine and cosine functions (Cox, 2006). To make the analysis tractable, let such deviations be represented by the typical sinusoidal function:

$$D(t) = |a_1 sin(2\pi ft) + a_2 cos(2\pi ft)| = |acos(2\pi ft + \epsilon)| \tag{5}$$

where $a_1, a_2$, and $a$ are amplitudes, $f$ = frequency, $t$ = time, and $\epsilon$ is some arbitrary constant.

This representation implies that rainfall variation oscillates along the optimal mean rainfall over time with constant amplitude $a$, and frequency $f$. Such formulation with constant amplitude may not be consistent with climate change. To account for the increasing variation in rainfall variability, the model should be re-specified with at least varying amplitude expanding exponentially at a rate of $h$:

$$D(t) = \left|e^{ht}\left[a_1 sin\left(2\pi ft\right) + a_2 cos\left(2\pi ft\right)\right]\right| \tag{6}$$

Because what matters in representing climate change is the amplifying component, the amplitudes can be normalized to unity ($a_1 = a_2 = 1$) so that

Equation (6) can be rewritten as:

$$D(t) = \left| e^{ht} \left[ sin(2\pi ft) + cos(2\pi ft) \right] \right| \tag{7}$$

Introducing Equation (7) to the production function in Equation (4) makes the production function non-differentiable at points where deviations are supposed to be zero. Ignoring this inconvenience has an intuitive advantage in explaining the double-hazard effect. That is, in this setting, because incidences of near zero deviations from the mean annual rainfall are less frequent than the occurrence of both negative and positive deviations (extreme events), the equation demonstrates how a rain-fed economy could be plunged into a more frequent cycles of extreme events rather than a cycle between drought and normal years.

Nonetheless, the differentiability issue can be restored by redefining the deviation $D(t)$ as a cycle of swings between normal and extreme events. Keeping the amplitude above zero requires an upward shift by the magnitude of the amplitude. Thus, Equation (7) can be re-specified as:

$$D(t) = e^{ht} \left\{ 1 + \left[ sin(2\pi ft) + cos(2\pi ft) \right] \right\} \tag{8}$$

Substitution of Equation (8) for $D(t)$ in Equation (4) gives:[3]

$$\tilde{y}(t) = \left\langle e^{ht} \left\{ 1 + \left[ sin(2\pi ft) + cos(2\pi ft) \right] \right\} \right\rangle^{-\gamma\alpha} \tilde{k}(t)^{\alpha} \tag{9}$$

## 2.2 The Path of Capital Accumulation

In the production function represented by Equation (9), there is only one factor input, capital per effective worker. The path of this variable is one of the determinants of the path of the per capita income. Assuming that technology grows at instantaneous rate of $g$ according to $A(0)e^{gt}$, and that labor grows at a rate of $n$ according to $L(0)e^{nt}$, it is standard to show that accumulation of capital per effective worker over time is governed by:[4]

$$\begin{aligned} \dot{\tilde{k}}_t \equiv \frac{d\tilde{k}_t}{dt} &= f\left(\tilde{k}_t\right) - \tilde{c}_t - (n + \delta + g)\, \tilde{k}_t \\ &= D^{-\gamma\alpha}(t) \tilde{k}^{\alpha}(t) - \tilde{c}(t) - (n + \delta + g)\, \tilde{k}(t) \end{aligned} \tag{10}$$

[3] Here, $D(t)$ as represented by the sinusoidal function enters the production function instead of the term $(1 + D(t))$. This however does not change the result because if $D(t)$ follows a sinusoidal function, then $(1 + D(t))$ is simply the original function shifted one unit upward which is also a sinusoidal function.

[4] See Appendix A for the derivation. Also see Acemoglu (2009), Barro and Sala-i-Martin (2004).

where $\tilde{c}(t) = \frac{c(t)}{A(t)}$, $c(t)$= per capita consumption, $(n+g)$ = growth rate of effective worker, and $\delta$ = rate of depreciation.

The first term in Equation (10) is output as a function of capital per effective worker so that the term $(f(\tilde{k}(t)) - \tilde{c}(t))$ represents investment per effective worker. The last term in the equation is an allowance for depreciation and expansion of labor. Thus, the rate of capital accumulation is equal to the net investment made at a point in time. What is new in this relation is the presence of the term $D(t)^{-\gamma\alpha}$ which can be shown to adversely affect capital accumulation for a given level of consumption $\tilde{c}(t)$.

## 2.3 The Problem of the Social Planner

Suppose that each representative household has one member and each household is altruistic towards the next generation. Let the utility function for each individual of the $n$ population can be aggregated. The aggregate preference can be represented by a constant-relative-risk-aversion utility function (also known as constant intertemporal elasticity of substitution):

$$U = \int_0^\infty e^{-(\rho-n)t}\left(\frac{c(t)^{1-\theta}-1}{1-\theta}\right)dt = \int_0^\infty e^{-rt}\left(\frac{c(t)^{1-\theta}-1}{1-\theta}\right)dt \tag{11}$$

where $c(t)$ = per capita consumption, $\rho$ = subjective discount rate so that $r = (\rho - n)$ represents effective discount rate. The problem of the social planner is to maximize the aggregate utility function subject to the resource constraint under Equation (10) and the usual transversality conditions. The Hamiltonian of the problem is thus given by:

$$H = e^{-rt}\left(\frac{\tilde{c}(t)^{1-\theta}-1}{1-\theta}\right) + \lambda(t)\left[D(t)^{-\gamma\alpha}\tilde{k}(t)^{\alpha} - \tilde{c}(t) - (n+\delta+g)\,\tilde{k}(t)\right] \tag{12}$$

Applying the usual first order conditions and making substitutions, it is possible to derive the two important paths for consumption and capital per effective worker, respectively:[5]

$$\dot{\tilde{c}}(t) = \frac{\tilde{c}(t)}{\theta}\left[\alpha D(t)^{-\alpha\gamma}\tilde{k}(t)^{\alpha-1} - (n+\delta+g\theta+r)\tilde{k}(t)\right] \tag{13}$$

$$\dot{\tilde{k}}(t) = D(t)^{-\alpha\gamma}\tilde{k}(t)^{\alpha} - \tilde{c}(t) - (n+\delta+g)\tilde{k}(t) \tag{14}$$

[5] See Appendix B for the derivations. Also see Chiang (1992), and Dixit (1990).

## 2.4 Growth in the Long-run

Complete solutions for the two paths are complicated by the non-linearity of the term $\tilde{k}(t)^{\alpha}$. Nonetheless, because the primary interest is in the long-run solutions, the steady-state level of capital per labor and income per labor can be easily derived. At a steady state where income, capital, consumption, and population are assumed to grow at the same rate, capital and consumption per effective labor cease to grow. That is, $\dot{\tilde{k}}(t) = \dot{\tilde{c}}(t) = 0$. Exploiting the fact that at steady- state $\dot{\tilde{c}}(t) = 0$, Equation (13) can be solved to give capital per effective labor:

$$\tilde{k}^{*}(t) = D(t)^{\frac{-\gamma\alpha}{1-\alpha}} \left(\frac{\alpha}{n+\delta+\theta g+r}\right)^{\frac{1}{1-\alpha}} \tag{15}$$

Substituting Equation (15) into Equation (4) and noting that the level of per capita income is the product of level of technology $A(t)$ and the income per effective labor, per capita income at the steady-state becomes:

$$y^{*}(t) = A(t)D(t)^{\frac{-\gamma\alpha}{1-\alpha}} \left(\frac{\alpha}{n+\delta+\theta g+r}\right)^{\frac{\alpha}{1-\alpha}} \tag{16}$$

Substituting Equation (8) for $D(t)$ in Equation (16), and applying the derivative after taking the logarithm of Equation (16), long-term growth in per capita income can be shown to be:

$$\frac{dy_t^{*}}{dt}/y_t^{*} \equiv \frac{\dot{y}_t^{*}}{y_t^{*}} = g - \eta h - \varphi\,(f.\psi) \tag{17}$$

where $\eta = \left(\frac{\gamma\alpha}{1-\alpha}\right)$, $\varphi = \left(\frac{2\alpha\gamma\pi}{1-\alpha}\right), \psi = \left[\frac{sin(2\pi ft)-cos(2\pi ft)}{1+sin(2\pi ft)+cos(2\pi ft)}\right]$. Equation (17) shows that long-term growth depends on two forces: rate of technological change and rate of widening of the amplitude of rainfall variability. While technological change spurs sustainable growth, unfavorable rainfall variability drags it. The parameter $\eta$ measures the lost output in the long-run for a unit expansion rate $h$.

The impact of rainfall variability on growth also depends on the frequency $f$ of variability and the particular cycle in which the economy is found, $\psi$. That is, the magnitude of the rate of long-term growth depends on whether it is measured back from a period of sustained 'good' rainfall or a period of extreme events.

The adverse impact of excessive rainfall variability on economic growth has been simulated using the production function under Equation (9). Three scenarios are used for the simulation: favorable rainfall variability, unfavorable rainfall variability with constant amplitude, unfavorable rainfall variability with amplified amplitude. The initial parameters are summarized as follows:

| | |
|---|---|
| Initial capital stock: | $k_0 = 10$ |
| Share of capital: | $\alpha = 0.33$ |
| Rate of expansion of amplitude: | $h = 0.12$ |
| Investment rate: | $s = 0.10$ |
| Depreciation rate: | $\delta = 0.05$ |
| Path of capital per labor: | $k(t) = k(t-1) + sy(t-1) - \delta k(t-1)$ |
| Rainfall variability: | |
| Constant amplitude | $D(t) = 2 * \{1 + [sin\,(2\pi * 0.09 * t)]\}$ |
| Amplified amplitude | $J(t) = 2 * e^{ht}\,\{1 + [sin\,(2\pi * 0.09 * t)]\}$ |
| Degree of rainfall dependency: | $\gamma = 1$ |
| Path of per capita income: | $y_1(t) = 10 * k(t)^{\alpha}$ |
| | $y_2(t) = 10 * D(t)^{-\gamma\alpha} k(t)^{\alpha}$ |
| | $y_3(t) = 10 * J(t)^{-\gamma\alpha} k(t)^{\alpha}$ |

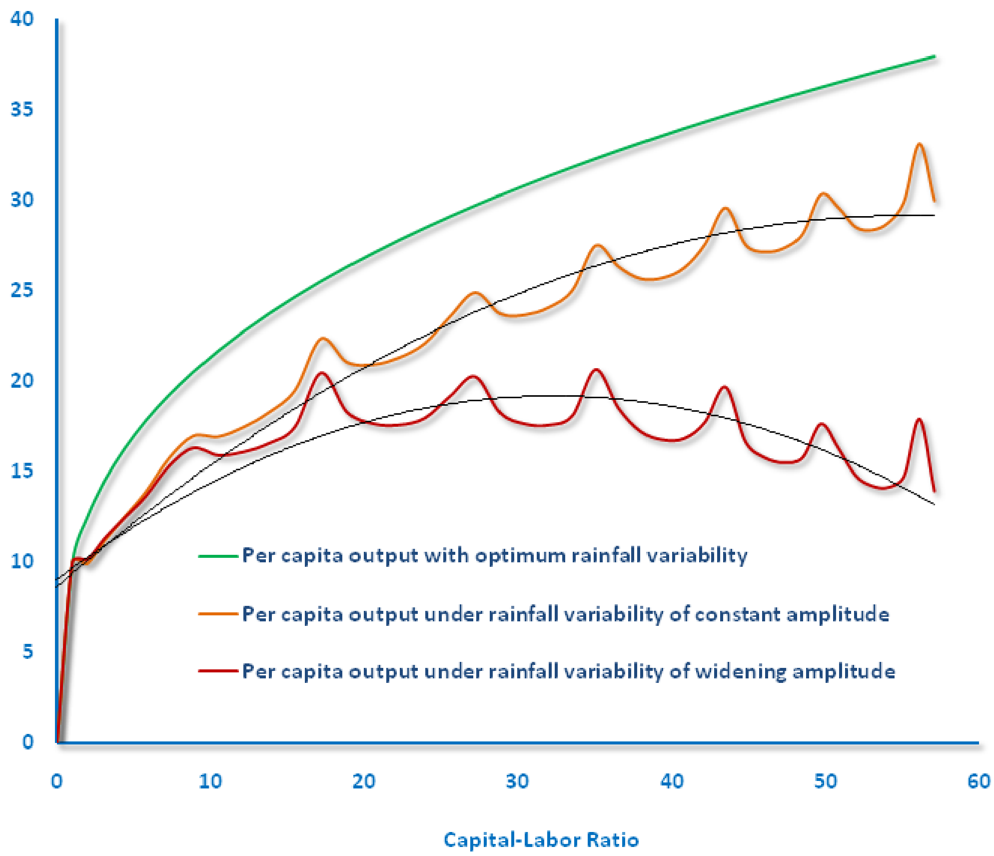


Figure 1: Production Function with Rainfall Variability

## 2.5 Welfare Implication

The implication on welfare can be shown by solving for steady-state level of consumption using Equation (14). Substituting the steady-state value of capital per effective labor in Equation (14) by setting $\tilde{k}(t)^{\alpha}$ to zero, the steady-state level of per capita consumption becomes:

$$c^*(t) = D(t)^{\frac{-\alpha\gamma}{1-\alpha}} A(t) \left[ \left( \frac{\alpha}{n+\delta+\theta g+r} \right)^{\frac{\alpha}{1-\alpha}} - \left( \frac{\alpha}{n+\delta+\theta g+r} \right)^{\frac{1}{1-\alpha}} (n+\delta+g) \right] \quad (18)$$

In the traditional growth models, at the balanced growth path, both per capita consumption and per capita income grow at the rate of technological change $g$. A simple differentiation of the steady-state level of per capita consumption under Equation (18) with respect to time shows that consumption is proportionally reduced by rainfall variability so that steady-state level of per capita consumption grows at the same rate of growth of steady-state level of per capita income. That is:

$$\frac{d\left(c^{*}(t)\right)}{dt} = g - \eta h - \varphi\left(f.\psi\right) \tag{19}$$

The direction of the impact of the rainfall variability $D(t)$ can be shown to be negative. Taking the derivative of Equation (18) with respect to $D(t)$, we have:

$$\frac{d\left(c^{*}(t)\right)}{dD(t)} = -\frac{\alpha\gamma}{1-\alpha}.D(t)^{\frac{\alpha(1-\gamma)-1}{1-\alpha}} A(t)\Delta \tag{20}$$

where $\Delta = \left[\left(\frac{\alpha}{n+\delta+\theta g+r}\right)^{\frac{\alpha}{1-\alpha}} - \left[\left(\frac{\alpha}{n+\delta+\theta g+r}\right)^{\frac{1}{1-\alpha}}(n+\delta+g)\right]\right.$. Since $\alpha < 1$ and $D(t)$ is expressed in absolute value, the only way $\frac{d(c^{*}(t))}{dD(t)}$ can be negative is if $\Delta > 0$. For $\alpha < (n+\delta+(+)r)$,it should hold that $\left(\frac{\alpha}{n+\delta+g\theta+r}\right)^{\frac{\alpha}{1-\alpha}} > \left(\frac{\alpha}{n+\delta+g\theta+r}\right)^{\frac{1}{1-\alpha}}$. Multiplication of the last term by $(n+\delta+g)$ ensures that $\Delta > 0$ even for a higher $\alpha$ since it holds that $0 < (n+\delta+g) < 1$. Thus, for intuitive values of the parameters, it holds that $\frac{dc^{*}(t)}{dD(t)} < 0$.

# 3 Empirical Evidence: The Ethiopian Data

The empirical part of this paper makes use of Ethiopian data that runs from 1961 to 2008. Ethiopian economy is a typical rain-fed economy on two grounds. First, about 45 percent of GDP comes from rain-fed agriculture. Second, about 99 percent of electrical energy in the country on which the industrial and service sectors depend is generated by hydroelectric power which in turn depends on the volume of rainfall.

Ethiopia has been known to be hit by frequent drought which usually translates into famine (Webb, von Braun, and Yohannes, 1992; EEA, 2004). Rainfall variability in particular in the form of drought and flooding had claimed many lives in the past and it has still been threatening millions of people. Such variability is witnessing a widening pattern in recent years. For instance a drought that was expected to occur in Ethiopia once in ten years has recently begun to strike the country more frequently (EEA, 2004).

The agriculture sector is most hit by the frequent extreme events thus resulting in a deteriorating income of rural households. The rainfall variability that has long characterized the Ethiopian agriculture became part of the factors which shape the dynamics of the Ethiopian economy. Moreover, in recent years, the country is experiencing power rationing due to insufficient water in the dams and reservoirs. The power rationing adversely affected the non-agricultural sector of the economy. Thus, the periodic prevalence of such extreme events is believed to have had a negative impact on the overall Ethiopian economy. This section shows empirically that rainfall variability, in particular frequent drought, dragged long-term growth in Ethiopia.

For the empirical part of the study, a time series data of 48 years (1961-2008) is used. The source for the GDP and gross investment data is the Ministry of Finance and Economic Development (MoFED). Rainfall data collected from nine major meteorological stations on a monthly basis over the last five decades (1955-2008) was obtained from the Meteorological Agency and Central Statistical Agency (CSA). Data for labor force and land under major crops were obtained from CSA.

## 3.1 Rainfall Variability and Trends in Real Per Capita GDP

For the period between 1961 and 2004, growth in real per capita GDP was nearly zero. The high growth episode in the last four years since 2005 has pushed the long-run growth in per capita GDP to a mere 0.35 percent. Most deep shocks in real GDP in the country are associated with extreme meteorological events in particular drought. Even if major low growth records in Ethiopia are associated with drought, it was not and does not have to be the case that a relatively high rainfall records were paralleled by bumper harvest. Rather, the best crop harvests in the country were recorded at level of rainfall roughly equal to the long-term average of the mean annual rainfall.

In Figure 2, even though the rainfall data appears to be stationary, incidences of extreme events are apparent to see where drought years tend to be characterized by lower annual rainfall over time[6]. The other pattern that can be inferred from Figure 2 is that while major droughts occurred almost on regular cycle (1963, 1973, 1985, 1992, and 2003), noticeable bumper harvests were registered roughly midway between consecutive drought episodes.

Previous studies on precipitation in Ethiopia (Seleshi and Zanke, 2004) showed that there was no trend in the annual rainfall in the major crop producing areas for the period 1965 - 2002. Nevertheless, it is possible that

[6]The line in red is a fitted value of rainfall as a function of time (in years). As an approximation to sinusoidal function, higher degree of polynomial is used. In this particular case, up to a maximum degree of 5 best fits the cycle.

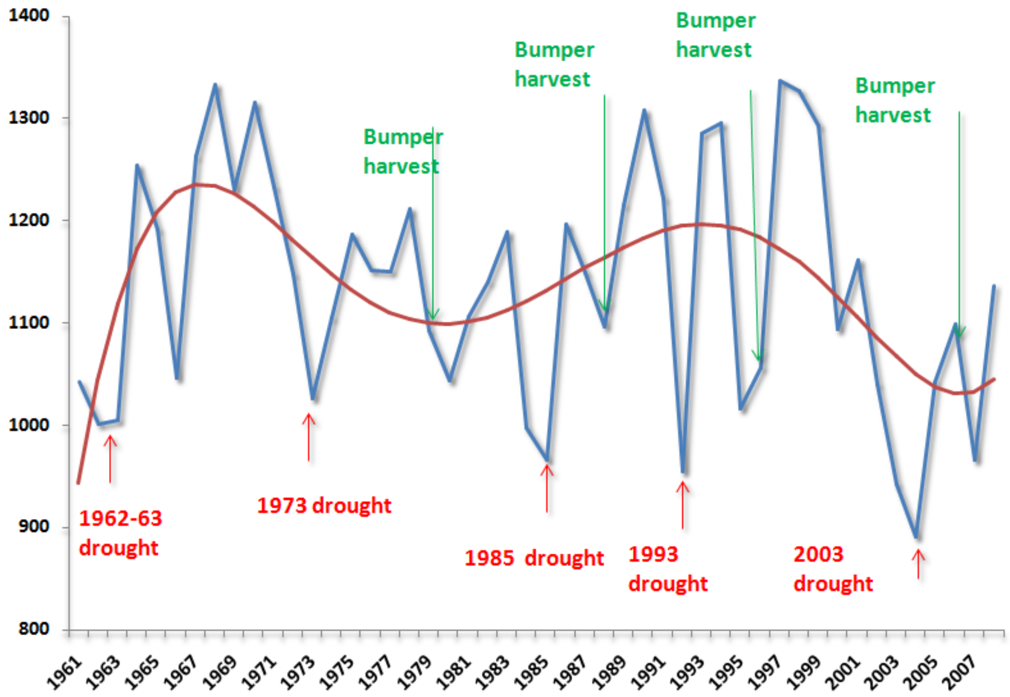


Figure 2: Patterns of Mean Annual Rainfall (1961-2008)

rainfall variability could increase with alternate extreme values while keeping the long-term average stable. As Katz and Brown (1992) argued, rainfall variability is more important to crop production than the changes in the average rainfall. The absence of a highly significant reduction in mean annual rainfall does not imply a lesser probability of occurrence of drought. This is because the impact of even a small decline in rainfall on the probability of incidence of drought is aggravated by an increase in potential evapotranspiration (Rosenzweig and Hilel 1998; Katz and Brown, 1992, Rind, et al., 1990).

In this study, three aspects of rainfall variability are considered. The first is mean annual rainfall variation which is the deviation from the long-term average of mean annual rainfall. The second aspect is monthly variation within a year. The third aspect is spatial variation in rainfall.

A simple plot of time series data from 1955 to 2008 shows that mean annual rainfall variability tends to increase over time in Ethiopia. However, the distribution of rainfall over months within a year has increased only for the North Eastern part of the country. Another important trend that has been observed is the September rainfall. Except for the Western part of the country, the volume of rainfall for the month of September has been declining over time. This is critical because in the Ethiopian case, crops in most crop producing areas are in their flowering stage in the month of September.

Whether the observed changes in the trend and patterns of rainfall are indicative of a climate change or even technically valid indicators of significant change is not the objective of this paper. The focus of the paper is rather to show that the observed changes in rainfall patterns in terms of inter-annual variation and within a year variation have been strong enough to adversely affect the Ethiopian economy.

Figure 3 shows the growth rate in per capita income and the absolute value of deviation of mean annual rainfall from its long-term average. There emerged a more systematic pattern of relationship between the two variables indicating a possible non-linear relationship between them.

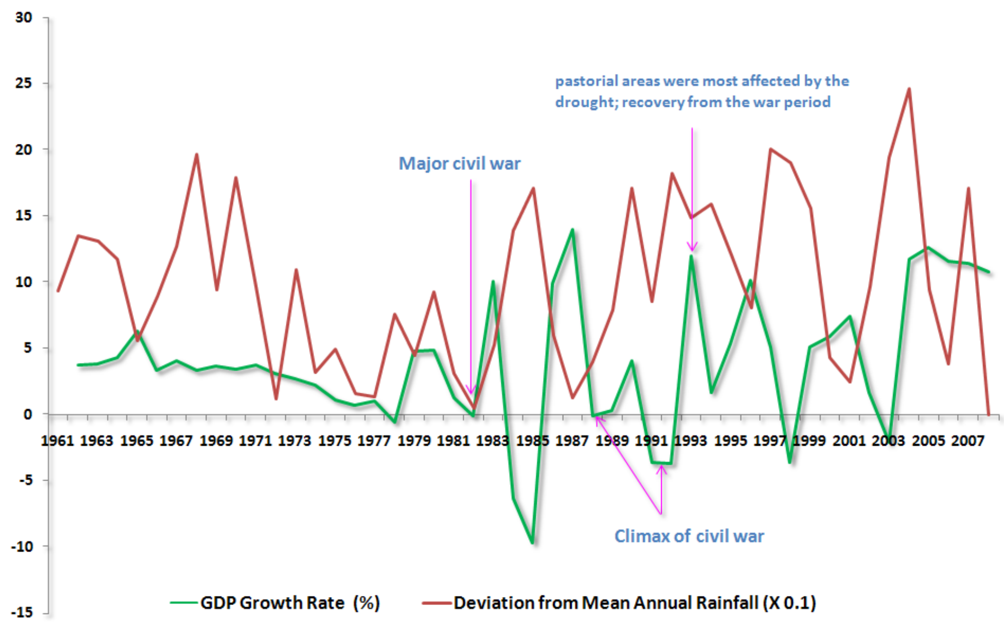


Figure 3: Deviations from Long-term Mean Annual Rainfall, and Growth in Per Capita GDP

There are, however, some exceptions to the systematic pattern of the rainfall and per capita GDP growth in particular in the year 1982, and the period 1989-1993. It appears that even if mean annual rainfall was almost 'optimal' in 1982 as deviation from the long-term average mean annual rainfall was nearly zero, there was no growth in per capita income. One possible reason could be the large scale war between the Ethiopian government and the then Eritrean insurgents - the so-called 'Operation Red Star'. The period 1989-1992 was characterized by the climax of the civil war that culminated with deposing the military regime. Thus, the economy during those years was more explained by war-related uncertainty than climatic conditions. Part of the seemingly high growth rate observed in the year 1993 was a recovery from recessions during the preceding war periods.

## 3.2 Econometric Analysis

This section investigates the impact of rainfall variability on the level of per capita income and calculates the cost of such variability in terms of income for Ethiopia at least for the past five decades. As a first step in modeling the determinants of long-term per capita income ($lnPCGDP_t$), mean annual rainfall ($lnRF_t$), square of mean annual rainfall ($lnRF_t^2$), and coefficient of variation of monthly rainfall ($lnMRCV_t$)[7] are used as regressors along with other control variables in particular capital labor- ratio ($lnk_t$), and land-labor ratio ($lnl_t$).

One of the control variables that are used in the econometric analysis is capital stock. This variable is not readily available in the national accounts of Ethiopia. In this study, the level of capital stock is estimated by perpetually accumulating net investment starting from an initial level of capital stock for the year 1961. The initial level of capital stock was estimated using the then level of output and capital-output ratio. The capital-labor ratio was in turn calculated by invoking the Harrod-Domar model that relates growth with saving rate and capital-labor ratio.

The augmented Dickey-Fuller test with two lags suggested that per capita income, capital-labor ratio, and land-labor ratio are non-stationary all integrated of order 1. That is, the variables are I(1). However, mean annual rainfall and coefficient of variation of monthly rainfall, which are the variables of interest, are somehow stationary. The null for unit root was not rejected for these variables when the Dickey-Fuller test with no lag was applied.

While the existence of non-stationary (I(1)) variables in the model necessitates the application of co-integration analysis, the presence of stationary (I(0)) variables requires some special handling. The mixed result of the unit root test for the rainfall variables may also justify the application of the stan-

[7]The coefficient of variation, a measure of relative variability (McGregor and Nieuwolt, 1998), is calculated by dividing the standard deviation of rainfall in a particular year by the mean of the mean annual rainfall over the entire period under consideration.

dard Johansen procedure for the tests may over-reject the null of unit root (Harris and Sollis, 2003).

### 3.2.1 The Model

Taking the logarithm of both sides of Equation (16) gives an estimable function that relates per capita income with the climate related variable, $D_t$:

$$lny_t = \beta_0 + \beta_1 lnD_t + \beta_2 lns + \beta_3 ln\left(n + \delta + \theta g + r\right) \tag{21}$$

where $\beta_0 = lnA_t$, $\beta_1 = \frac{-\gamma\alpha}{1-\alpha}$, $\beta_2 = \beta_3 = \frac{\alpha}{1-\alpha}$, $s$ = saving rate (representing contribution of capital, $\alpha$). Such a model can be estimated for a panel of countries as Mankiw, Romer, and Weil (1992) did. This study focuses on a single country and hence relies on time series analysis. A particular variable of interest is $D_t$. It is represented by mean annual rainfall, and coefficient of monthly rainfall variation. The control variables include capital-labor ratio, and land-labor ratio.

Let $Z_t$ represent the variables entering the co-integration vector without a priori distinction as endogenous or exogenous variables. The vector error correction model is given by:

$$\Delta Z_t = \alpha\beta' Z_{t-1} + \sum_{i=1}^{p} \Gamma_i \Delta Z_{t-i} + \epsilon \tag{22}$$

where $\alpha$ = vector of parameters of adjustment coefficients, $\beta$ = vector of parameters of long-run coefficients, $\Gamma_i$ = vector of parameters of short-run dynamics, $\epsilon_t$ = vector of innovations.

The inclusion of stationary variables in the co-integrating vector creates nuisance parameters which affect the trace statistics used in determining the co integration rank (Rahbek and Mosconi, 1999) under the Johansen procedure. Rahbek and Mosconi (1999) suggested a modified version of Equation (22) by including the cumulated values of the $I(0)$ variables $X(t)$, and linear trend $t$. The critical value of the trace statistics is adjusted accordingly as suggested by Harbo et. al (1998). Given the cumulated value of the $I(0)$ variables $\sum_{i=1}^{t} X_i$, Equation (22) can be re-written as:

$$\Delta Z_t = \alpha\beta^{*'} \begin{pmatrix} Z_{t-1} \\ \sum_{i=1}^{t} X_i \\ t \end{pmatrix} + \sum_{i=1}^{p} \Gamma_i \Delta Z_t + \sum_{i=1}^{p} \delta_i X_i + \epsilon_t \tag{23}$$

where $\beta^*$ can be decomposed into the long-run coefficient of the proper $I(1)$ variables ($\beta$) and that of the cumulated stationary variables. A restriction test can be applied on whether the cumulated values and linear trend are statistically significant (Rahbek and Mosconi, 1999).

### 3.2.2 Estimation and Results

In the model, the stationary variables namely mean annual rainfall, the square of mean annual rainfall, and coefficient of variation of monthly rainfall entered the co-integration vector restricted as exogenous. Per capita GDP, land-labor ratio, and capital - labor ratio were the endogenous variables. The appropriate lag length in the co-integration vector was determined using the Akaike's information criterion (AIC), Hannan and Quinn information criterion (HQIC), and Schwarz's Bayesian information criterion (SBIC). While the AIC favors a lag length of 3, the rest two suggested a lag length of 2. For this particular study, a two-period lag length is used. The trace statistics of the Johansen test rejected the null of no co-integration among the variables. The null for the existence of a maximum of one co-integrating vector was not however rejected at 1 percent level of significance (Table 1, model (1)).

Table 1: The Johansen Test for Cointegration

| $H_0 : rank \leq$ | Trace (1) | Trace (2) |
|---|---|---|
| 0 | 37.825** | 23.166** |
| 1 | 14.536 | 1.704 |
| 2 | 0.6998 | - |

The long-run parameters (the $\beta$-coefficients) and the measures of adjustments (the $\alpha$-coefficients) were also estimated. A zero-restriction tests on the $\beta$-coefficients is rejected for all variables entering the co-integration vector. A zero-restriction test on the $\alpha$-coefficient (adjustment coefficient) for per capita GDP is rejected only at 10 percent level of significance. The $\alpha$ coefficients for the variables land-labor ratio, and capital - labor ratio were not statistically significant (Table 2, model (1)).

A co-integration test was also implemented by restricting land-labor ratio as exogenous. In this case, because there are only two endogenous variables-per capita GDP and land-labor ratio-the issue was on whether there exist co-integration among the variables rather than determining the number of co-integrating vectors. Under this scenario, the existence of co-integration between per capita GDP and land-labor ratio was not rejected (Table 1, model (2)). Upon zero coefficient restriction tests on the $\alpha$-coefficients, the coefficient for per capita GDP was significantly different from zero at 1 percent level while that of capital-labor ratio was not indicating that capital-labor ratio is weakly exogenous (Table 2, model (2)).

Table 2: Estimates of long-run parameters and adjustment coefficients

| | (1) | (2) | |
|---|---|---|---|
| Variable | coefficient | coefficient | Restriction |
| | $\beta$ | | Wald |
| $lnPCGDP_t$ | 1 | 1 | 8.896** |
| $lnk_t$ | -0.984 | -0.717 | 15.415** |
| $lnl_t$ | -0.524 | -0.260 | 3.485 |
| $lnRF_t$ | -99.13 | -72.08 | 11.275** |
| $lnRF_t^2$ | 7.066 | 5.137 | 11.266** |
| $lnMRCV_t$ | 0.588 | 0.481 | 5.465* |
| | $\alpha$ | | |
| $lnPCGDP_t$ | -0.120 | -0.263 | 9.229** |
| $lnk_t$ | 0.022 | 0.036 | 3.668 |
| $lnl_t$ | 0.285 | - | - |
| Diagnostic | Tests (Vector) | | |
| AR 1-2 : | F(18,76) = 1.229 | | F(8,62) = 1.355 |
| Normality : | $\chi^2(6) = 5.606$ | | $\chi^2(4) = 3.632$ |
| Heteroskedasticity: | F(102,75) = 0.652 | | F(45,54) = 0.771 |

Normalizing the variables by per capita GDP, coefficients for capital - labor ratio, land - labor ratio and level of mean annual rainfall are found to be positive while the coefficients for the square of mean annual rainfall and monthly coefficient of variation were negative. In particular the positive coefficient of the level of mean annual rainfall and the negative coefficient for its square support the argument that there is an optimum level of rainfall so that deviation from that optimum level reduces output.

While the estimated $\beta$-coefficients (possibly elasticities) for capital - labor ratio, land - labor ratio, and monthly coefficient of variation of rainfall are intuitive to explain, the coefficient for mean annual rainfall is not directly interpretable without further computations. Using the coefficients for the mean annual rainfall and its square (72.08 and -5.137, respectively), the optimum level of mean annual rainfall was calculated to be 7.016 in logarithmic scale. This is roughly equal to the mean of mean annual rainfall of the major meteorological stations of the country for the last five decades.

A test for existence of co-integration was carried out by replacing the level of mean annual rainfall and its square by the absolute value of the deviation of mean annual rainfall from the 'optimum' value ($lnARD_t$). The null for no co-integration was rejected in this case as well. [Results are not reported].

Finally, structural parameters were estimated by employing the vector error correction model. The first difference of the logarithm of per capita GDP ($\Delta lnPCGDP_t$) was regressed on the differences of the logarithm of capital - labor ratio ($\Delta lnk_t$), land-labor ratio($\Delta lnl_t$), mean annual rainfall ($\Delta lnRF_t$), square of mean annual rainfall ($\Delta lnRF_t^2$), monthly coefficient of variation ($\Delta lnMRCV_t$), and a one period lag of the cointegration vector-a measure of last period disequilibrium ($CV_{t-1}$). The error correction model was also re-estimated by replacing the differences in the mean annual rainfall and its square by the absolute value of the deviation from the optimum level of mean annual rainfall ($lnARD_t$).

A convenient property of the natural logarithm is that the first difference of the variable in logarithm is a measure of growth rate. Hence, the estimated model relates growth rate in per capita GDP ($\Delta lnPCGDP_t$) to rate of changes in the various determinants of growth.

In the first scenario of the model, differences in mean annual rainfall, its square, and the change in the monthly coefficient of variation are significant with expected signs: the coefficients for the first difference of mean annual rainfall and its first and second lags are positive while that of its square and change in monthly coefficient of variation are negative. This may indicate that variations in rainfall is important for growth but excessive variability in rainfall retards it. The adverse impact of the erratic nature of rainfall on growth is also supported by the negative sign and significance of the change in the monthly coefficient of variation of rainfall ($\Delta lnMRCV_t$). As it has been discussed in Section 3.1, monthly variation in rainfall in Ethiopia tends to be erratic in recent years. In particular, the rainfall for the month of September, which is critical for crop productivity, shows a declining trend. The fact that the first and second lags of the change in mean annual rainfall are positive while the squared values are negative may indicate the importance of the cumulative effect of rainfall variability.

In the second scenario where deviation from the optimum mean annual rainfall is used as a regressor, both deviations from mean annual rainfall and change in monthly rainfall variations were significant with negative coefficients. The results confirmed the double-hazard of rainfall at least in the Ethiopian context addressing one of the central themes of this paper. That is, both excessive and below average rainfall have adverse impact on growth.

The (vector) error correcting term, the first lag of the linear combination of the variables involved normalized with per capita GDP ($CV_{t-1}$), is negative and significant. It can be interpreted as the speed of adjustment towards the long-run level of per capita GDP after a shock in the GDP per capita is about 67 percent.

Table 3: Error Correction Model-Recovering the Structural Parameters
Dependent variable: Growth in per capita income ($\Delta lnPCGDP_t$)

| | (1) | | (2) | |
|---|---|---|---|---|
| Variable | Coefficient | Std. Error | Coefficient | Std. Error |
| $\text{lnARD}_t$ | - | - | -0.016 | 0.007** |
| $\Delta lnRF_t$ | 21.855 | 6.383** | - | - |
| $\Delta lnRF_{t-1}$ | 16.084 | 6.766* | - | - |
| $\Delta lnRF_{t-2}$ | 14.458 | 6.458* | - | - |
| $\Delta lnRF_t^2$ | -1.553 | 0.456** | - | - |
| $\Delta lnRF_{t-1}^2$ | -1.144 | 0.481* | - | - |
| $\Delta lnRF_{t-2}^2$ | -1.026 | 0.460* | - | - |
| $\Delta lnMRCV_t$ | -0.170 | 0.053** | -0.188 | 0.0481** |
| $\Delta lnk_t$ | 1.670 | 0.492** | 1.765 | 0.5148** |
| $\Delta lnk_{t-2}$ | -1.267 | 0.419** | -1.263 | 0.433** |
| $\Delta lnl_t$ | 0.187 | 0.058** | 0.173 | 0.061** |
| $\Delta lnl_{t-2}$ | -0.145 | 0.060* | -0.126 | 0.065* |
| $\Delta lnPCGDP_{t-1}$ | 0.436 | 0.224 | 0.510 | 0.021* |
| $\Delta lnPCGDP_{t-2}$ | -0.249 | 0.142 | -0.263 | 0.129* |
| $\Delta lnPCGDP_{t-3}$ | 0.414 | 0.146** | 0.390 | 0.142** |
| $\text{CV}_{t-1}$ | -0.663 | 0.269* | -0.671 | 0.254* |
| Intercept | -0.004 | 0.0087 | 0.063 | 0.031* |
| $R^2 = 0.74$ | | | $R^2 = 0.63$ | |
| F(15,28) = 5.38** | | | F(10,33) =5.695** | |
| Diagnostic | Tests | | | |
| AR 1-2: | F(2,26) | = 0.550 | F(2,31) = 0.699 | |
| ARCH: | F(1,26) | = 0.207 | F(1,31) = 0.832 | |
| Normality: | $\chi^2(2)$ | = 1.537 | $\chi^2(2) = 0.055$ | |
| Heterosk.: | $\chi^2(30)$ | = 36.939 | F(20,12) = 0.671 | |
| RESET-test: | F(1,27) | = 0.900 | F(1,32) = 0.005 | |

** Significant at 1 per cent level. * Significant at 5 per cent level.

Based on the estimates reported on Table 3, growth in per capita GDP was simulated. The average of the predicted growth rates of per capita GDP was 1.095 percent for the period 1965-2008 which is the same as the actual average growth of per capita GDP for the same period. More importantly, however, Figure 4 shows that the simulated growth rates somehow mimic the trend in the actual growth rates of per capita GDP.

The second aspect which this paper attempts to address is quantifying the forgone output as a result of rainfall variability. To accomplish this,

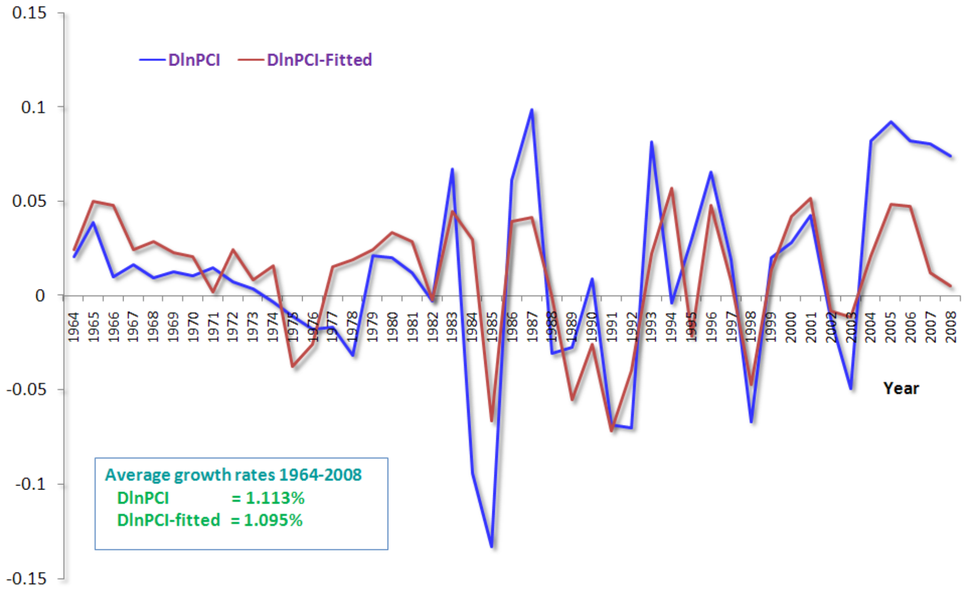


Figure 4: Growth Rate in Per Capita GDP-Actual and Fitted (1961-2008)

a growth path was simulated by reducing rainfall variability by half and keeping monthly coefficient of variation of rainfall at the value of that of Western Ethiopia. The result shows that if rainfall variation was only half of what has been witnessed and monthly variation was as stable as that of the Western part of the country, then the Ethiopian economy would have grown at a rate of 4.7 percent per annum for the period 1965-2008. The implication of this exercise is that mitigation and adaptation strategies of developing countries towards climate change in the form of, for example, water harvesting, reducing seasonal dependency of agricultural activities, and reducing the dependency of the economy on rainfall would put such countries on higher growth trajectories.

What could have been the level of per capita income of Ethiopia in 2008 had the 4.7 percent growth rate been realized through the wisdom of the policy makers in reducing the economy's dependency on rainfall? Simple computation shows that leaving aside the cost of extreme events that the country has incurred long before 1960s, the level of income of an average Ethiopian in the year 2008 would have been at least four times higher than the current actual level had the economy grown at the simulated rates of growth of per capita GDP starting from the level of income recorded in 1965.

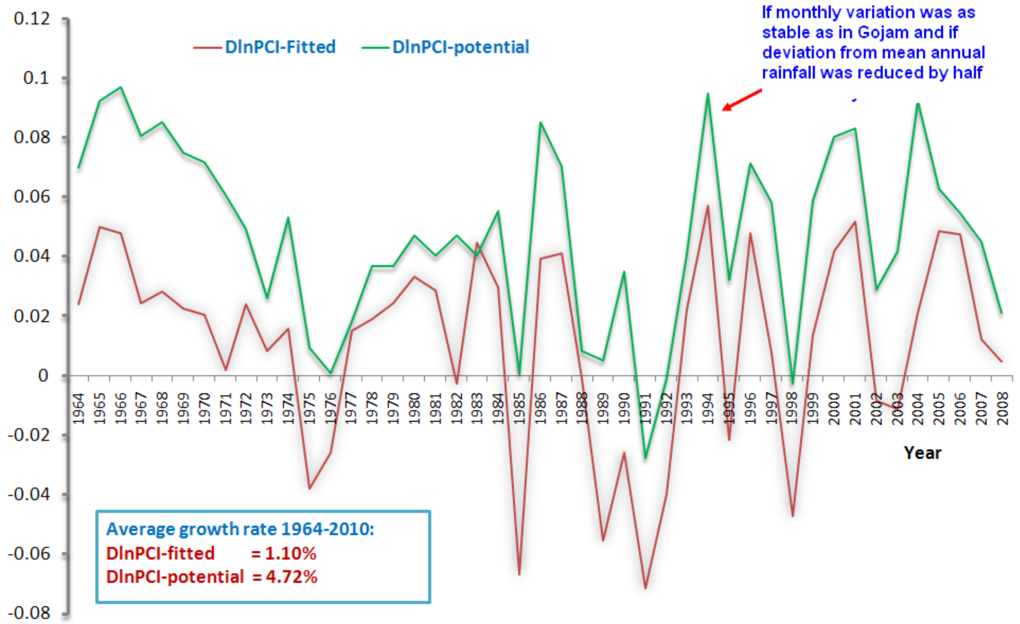


Figure 5: Simulated Growth under Less Variability of Rainfall

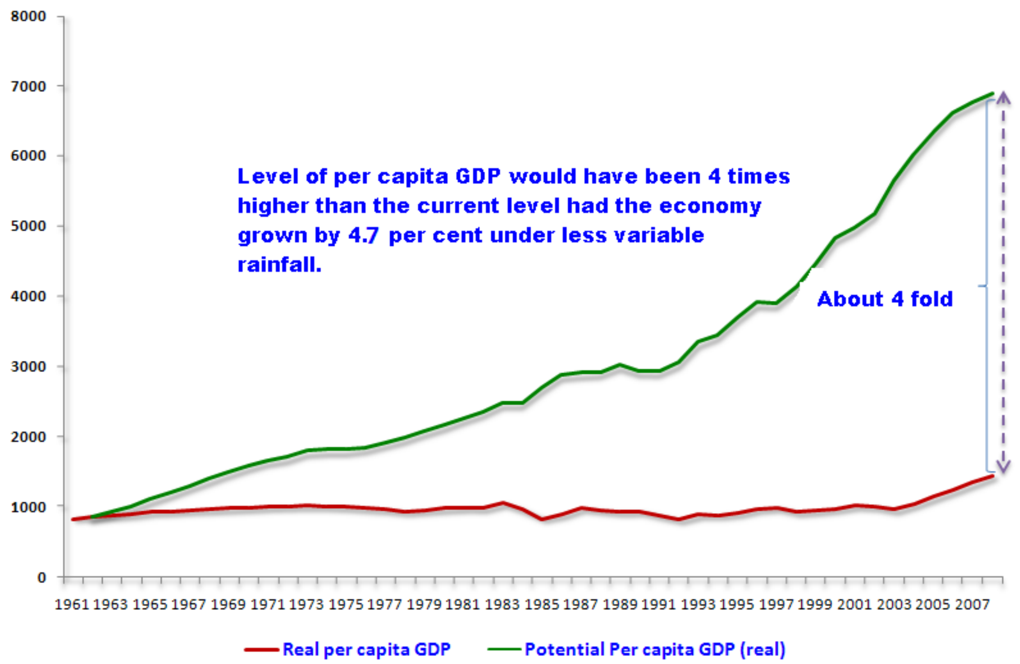


Figure 6: Level of Potential Per Capita GDP under Less Rainfall Variability

The lost growth could be translated into the level of poverty that could have been avoided. Assuming poverty elasticity of growth for Ethiopia to be 1 percent (a conservative figure for a country with low base income and relatively low level of income disparity), it is not difficult to see how the predicted growth over the last five decades would have reduced the level of poverty to a bearable level today.[8]

# 4 Conclusion

Modeling the impact of climate change on economic growth by type of manifestation of climate change and region would help recommend effective specific adaptation strategy than a blanket policy. This paper formally incorporates rainfall variability into the traditional growth model as a factor which incapacitates capital to contribute to output. The result shows that for an agrarian economy dependent on rainfall, variability in rainfall has a long-term growth-drag effect through changes in its amplitude and frequency.

Empirical analysis using data from Ethiopia shows that deviation from the long-term mean annual rainfall and erratic distribution of rainfall within a year adversely affected growth. Simulation results show that the country would have been much better in terms of per capita income without variable and erratic rainfall.

Looking ahead, IPCC predictions indicate that precipitation would increase for the sub-region to which Ethiopia belongs. But there is no guarantee that such increase would not be a result of too much rain beyond the optimum level. It is not clear either whether regular patterns would replace erratic conditions. If the future is blink in terms of these meteorological aspects, Ethiopia being dependent on rain-fed agriculture would suffer from extreme events. In particular in the case of drought, shifting the economy from agriculture to industry and service may not rescue the country from the impact because such transformation under the dependency on hydroelectric power (HEP) means shifting the economy from rain-fed agriculture to rain-fed industry.

More importantly, however, predictions show that meteorological events for different regions across the world will not be the same. To that end, the results of this paper demonstrate how the long-term growth of developing countries whose economies are dependent on rainfall would be retarded

[8]With a poverty elasticity of growth of 1 percent, a country that can sustain a 3 percent annual growth of per capita income can reduce poverty from 50 percent to 10 percent in head counts over 50 years, assuming other things such as level of inequality will remain the same.

further by climate change if the outcome of the change is not favorable.

Given the current adverse impact of erratic annual rainfall on growth, one of the adaptation strategies may focus on the option of producing or water harvesting as it rains instead of waiting for the traditional seasons of agricultural activities at least in the case of some crops. The other adaptation strategy might be reducing the high dependency of the economy on rainfall. Global efforts to foster conservation endeavors in developing countries could be part of the long-run solutions.

Future research that aims at looking into the impact of rainfall variability in particular extreme events on growth might consider the channels such as savings, human capital, and uncertainty. Macroeconometric type of model on a sectorally disaggregated data would help better estimate the impact. Moreover, extending the model to many countries or regions using a panel data would give better predictions.

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# 6 Appendix

## 6.1 Deriving Capital Accumulation per Effective Labor

Given the production function as represented by Equation (3), consumption $C(t)$ and allowance for depreciation $\delta K(t)$, the path of capital accumulation is given by:

$$\frac{dK(t)}{dt} = D(t)^{-\gamma\alpha} K(t)^{\alpha} (A(t)L(t))^{(1-\alpha)} - C(t) - \delta K(t) \tag{24}$$

Define capita per effective labor as:

$$\tilde{k}(t) = \frac{K(t)}{A(t)L(t)} \tag{25}$$

The rate of capital accumulation per effective worker is thus:

$$\frac{\tilde{k}(t)}{dt} = \frac{d\left(\frac{K(t)}{A(t)L(t)}\right)}{dt} \tag{26}$$

$$= \frac{dK(t)}{dt} . \frac{1}{(A(t)L(t))} - \frac{K(t)}{(A(t)L(t))^2} \left( \frac{L(t)dA(t) + A(t)dL(t)}{dt} \right)$$

But $\frac{dL(t)}{L(t)dt} = n$ and $\frac{dA(t)}{A(t)dt} = g$ . Thus, we have:

$$\frac{d\tilde{k(t)}}{dt} = \frac{dK(t)}{dt} . \frac{1}{(A(t)L(t))} - \tilde{k}(t) - (n+g) \tag{27}$$

Substituting (24) into the last Equation:

$$\begin{aligned} \frac{d\tilde{k}(t)}{dt} &= \frac{D^{-\gamma\alpha}(t)^{\alpha}}{K} (t) \left(A(t)L(t)\right)^{1-\alpha} - C(t) - (t)(A(t)L(t)) - \tilde{k}(t)\left(n+g\right) \\ &= D(t)^{-\gamma\alpha} \tilde{k}(t)^{\alpha} - \tilde{c}(t) - (n+\delta+g)\,\tilde{k}(t) \end{aligned} \tag{28}$$

where $\tilde{c}(t) \equiv \frac{C(t)}{A(t)L(t)}$.

## 6.2 Deriving the Paths for Consumption and Capital

Given the Hamiltonian of the optimization problem in Equation (12): $H = e^{-rt}\left(\frac{c^{\theta}(t)-1}{1-\theta}\right) + \lambda\left[D(t)^{-\gamma\alpha}\tilde{k}(t)^{\alpha} - \tilde{c}(t)\left(n+\delta+g\right)\tilde{k}(t)\right]$, the first-order conditions are:

$$\frac{\partial H}{\partial c(t)} = e^{-rt} c^{\theta}(t) - \frac{\lambda(t)}{A(t)} = 0 \Rightarrow \lambda(t) = A(t) e^{-rt} c^{-\theta}(t) \tag{29}$$

(Because $\tilde{c}(t) = \frac{c(t)}{A(t)}$

$$\frac{d\lambda(t)}{dt} = -\frac{\partial H}{\partial \tilde{k}(t)} = -\lambda(t)\left[\alpha D(t)^{-\gamma\alpha} \tilde{k}^{\alpha-1}(t)\right] - (n+\delta+g) = 0 \tag{30}$$

$$\frac{\partial H(t)}{\partial \lambda(t)} = \frac{d\tilde{k}(t)}{dt} = D(t)^{-\gamma\alpha} \tilde{k}(t)^{\alpha} - \tilde{c}(t) - (n+\delta+g)\,\tilde{k}(t) = 0 \tag{31}$$

Recalling that $A(t) = A(0)e^{gt}$ and taking the derivative of (29) with respect to time:

$$\begin{aligned}
\frac{d\lambda(t)}{dt} &= A(0)e^{(g-r)t} \frac{d\lambda(t)}{dc(t)} . \frac{dc(t)}{dt} + \frac{d\left(A(0)e^{(g-r)}\right)t}{dt} c^{-\theta}(t) \\
&= -A(0)^{(g-r)t} c^{(\theta+1)(t)} \frac{dc(t)}{dt} + (g-r)\,A(0)e^{(g-r)t} c^{-\theta}(t) \\
&= -A(0)^{(g-r)t} c^{(\theta)(t)} \left[\theta c^{-1} \frac{dc(t)}{dt} - (g-r)\right]
\end{aligned} \tag{32}$$

Combining (29), (30) and (32),

$$\frac{dc(t)}{dt} = \frac{c(t)}{\theta}\left[\alpha D^{-\gamma\alpha}(t) \tilde{k}^{\alpha-1}(t) - (n+\delta+r)\right] \tag{33}$$

Let $\tilde{c}(t) \equiv \frac{C(t)}{A(t)L(t)} \equiv \frac{c(t)}{A(t)}$. Then,

$$\frac{d\tilde{c}(t)}{dt} = \frac{A(t)dc(t)}{A(t)dt} - \frac{dA(t)}{A(t)dt} . \frac{c(t)}{A(t)} \tag{34}$$

Multiplying the first term of Equation (34) by $\frac{c(t)}{c(t)}$,and denoting $\frac{dA(t)}{A(t)dt} = g$, and $\frac{c(t)}{A(t)} = \tilde{c}(t)$:

$$\frac{d\tilde{c}(t)}{dt} = \left(\frac{dc(t)}{c(t)dt} - g\right)\tilde{c}(t) \tag{35}$$

Combining Equations (33) and (35),

$$\begin{aligned}
\frac{d\tilde{c}(t)}{dt} \equiv \dot{\tilde{c}}(t) &= \frac{\tilde{c}(t)}{\theta}\left[\alpha D^{-\gamma\alpha}(t) \tilde{k}(t)^{\alpha-1} - (n+\delta+r)\right] - g\tilde{c}(t) \\
&= \frac{\tilde{c}(t)}{\theta}\left[\alpha D^{-\gamma\alpha}(t) \tilde{k}(t)^{\alpha-1} - (n+\delta+r+\theta g)\right]
\end{aligned} \tag{36}$$

We thus have the two differential equations:

$$\begin{cases} \dot{\tilde{c}}(t) = \dfrac{\tilde{c}(t)}{\theta}\left[\alpha D^{-\gamma\alpha}(t)\tilde{k}(t)^{\alpha-1} - (n+\delta+r+\theta g)\right] \\ \dot{\tilde{k}}(t) = D(t)^{-\gamma\alpha}\tilde{k}(t)^{\alpha} - \tilde{c}(t) - (n+\delta+g)\,\tilde{k}(t) \end{cases} \tag{37}$$

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