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Climate Change and Infrastructure Investment in Developing Countries

The Case of Mozambique

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Abstract

Climate change may damage road infrastructure to the potential detriment of economic growth, particularly in developing countries. To quantitatively assess climate change's consequences, we construct a climate-infrastructure model based on stressor-response relationships and link this to a recursive dynamic economy-wide modelto estimate and compare road damages to other climate change impact channels. We apply this framework to Mozambiqueand simulate four future climate scenarios. Our results indicate that climate change through 2050 is likely to place a drag on economic growth.../

Keywords: climate change, infrastructure vulnerability, productivity, economic growth, Mozambique

JEL classification: Q54, O44, O55

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and development prospects. The economic implications of climate change appear to become more pronounced from about 2030. Nevertheless, the implications are not so strong as to drastically diminish development prospects. An adaptation policy of gradual evolution towards road designs that accommodate higher temperatures and follows rainfall trends (wetter or dryer) improves outcomes. At the same time, a generalized policy of upgrading all roads does not appear to be merited at this time. Our findings suggest that impact assessments should include the damages on long-run assets, such as infrastructure, imposed by climate change.

Tables and figures appear at the end of the paper.

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1 Introduction

Economic growth is widely held to depend on the quantity, quality, and orientation of a country's backbone infrastructure. Inadequate infrastructure in many developing countries therefore presents a serious constraint to economic development. In order to address this constraint, governments in developing countries often assign a large share of their budget to public infrastructure spending. Moreover, while foreign aid often finances extensions to low-income countries' road networks, local governments frequently cover the cost of maintaining infrastructure after it is installed.

In this paper, we consider the interactions between climate change and investment in economic infrastructure, with an application to Mozambique. We are motivated by two observations. First, as in many countries, much of Mozambique's installed infrastructure is vulnerable to climate change, with the most likely threats being shifts in the frequency, severity, and character of extreme weather events. For example, roads are sensitive to extreme heat. Above certain temperature thresholds, paved roads weaken, causing rapid degradation even under normal or light traffic loads. Perhaps more importantly, a higher frequency and severity of floods will increase road washouts—already a serious problem in many countries. Even under the low-end projections of sea level rise, coastal areas will be subjected to greater inundation as a result of cyclones reaching further inland (Strzepek et al., 2010).

Second, while some manifestations of climate change are already observable in Mozambique, deviations from conditions currently regarded as normal are likely to become far more profound with time. The potential risks to economic infrastructure posed by climate change are likely to be much larger in 2050 than they are today. A simple but pertinent observation is that, in many developing countries, it is highly likely that the bulk of economic infrastructure that will exist in 2050 does not exist today. As a result, the vulnerability of future infrastructure is, to a considerable degree, a matter of choice.

The remainder of this study is structured as follows. Section 2 focuses on road infrastructure, which is typically the largest component of public infrastructure investment. It reviews the literature on roads, economic growth and climate change. Section 3 describes our case country, Mozambique, and presents the four climate change projections selected for our analysis. Section 4 describes the road infrastructure simulation models used to evaluate the consequences of climate change. The first model determines the costs of climate change and the benefits of adapting road designs to cope with climate change. The second model considers the implications of climate changefor road density and evaluates adaptation options under budget constraints. Section 5 estimates the economy-wide cost of climate change in Mozambique. The infrastructure model is directly linked to thedynamic computable general equilibrium (DCGE) model. Finally, Section 6 summarizes and concludes.

2 Roads, growth, and climatechange

2.1 Road infrastructure and economic growth

Numerous studies confirm the importance of road infrastructure for economic growth. Fernald (1999), for example, examined data for the USA for the period 1953–89 and concluded that road investments had a significant causal impact on productivity growth during 1953–73—the period when the interstate highway system was constructed. The author estimated that public investment, principally in roads, 'contributed about one percentage point to total factor productivity growth' (ibid.: 620). To achieve this gain, net road investment exceeded 'a quarter of the value of net non-residential private investment' (ibid.: 619). Public road investmentstherefore contributed to the USA's strong economic performance during the 1950s and 1960s. After 1973, Fernald asserts that the marginal product of road investments declined (i.e., a second interstate highway system is less beneficial than the first).

Developing countries, particularly in Africa, are unlikely to face a declining marginal product of road infrastructure investment due to excess supply since road stocks in these countries are low by almost any measure. Of course, the marginal (and average) product of infrastructure investment can be low for other reasons. Governments can, for example, waste resources constructing poor quality or unnecessary infrastructure. Nevertheless, the empirical evidence is generally favorable to the proposition that public road investments generate reasonable returns. For example, Esfahani and Ramírez (2003) use cross-country panel regressions and find that infrastructure services' contribution to gross domestic product (GDP) is substantial andexceeds the cost of their provision. Similarly, Calderón and Servén (2004) find that growth in Latin America is positively related to infrastructure stocks and that income inequality declines with higher infrastructure quantity and quality. More recently, these authors apply the same techniques to Africa (Calderón and Servén 2008) and reach similar conclusions.

A litany of methodological problems haunts the cross-country regression literature (see, for example, Roodman 2009). However, country level studies are also generally positive. In a study of Nepal, Jacoby (2000) finds that 'providing extensive road access to markets would confer substantial benefits on average, much of these going to poor households' (ibid.: 713). Also for Nepal, Dillon et al. (2011) conclude that rural roads are one of the most productive public expenditures. Fan and coauthors conduct detailed studies to estimate the returns to public investment in China, India, and Uganda (Fan et al. 2004; Fan and Chan-Kang 2008; Fan and Hazell 2001; Fan and Zhang 2008). They consistently find positive returns to road investments, particularly rural roads. These and other findings led Ndulu (2006)to call for a 'big push in promoting infrastructure' in Africa in order to overcome under-development and sustaineconomic growth.

Both theory and evidencetherefore suggest that infrastructure investments are important determinants of economic growth and poverty reduction. In most developing countries, these investments represent commensurately large shares of public budgets and total investment. If the stock of public capital in general, and the road stock in particular, is material to growth and poverty reduction, then the rate of depreciation of that stock is also material. We next review the literature on the implications of climate change for the stock of roads.

2.2 Road infrastructure and climate change

The literature on climate change impacts and adaptation in the infrastructure sector is primarily qualitative, emphasizing broad recommendations and warnings based on general weather studies. Research by the Transportation Research Board in the USA, the Scottish Executive, and Austroads in Australia are notable examples (TRB 2008; Galbraith et al. 2005; AUSTROADS 2004). The authors compare weather-related disasters and their perceived severity with predicted climate change impacts. More focused studies estimate specific impacts of temperature, rain, snow, ice, wind, fog, and coastal flooding on roads (CCSP 2006). Further studies address areas where climate change may threaten infrastructure unique to that locale. For example, Canadian roads are particularly vulnerable to rising temperatures (Industrial Economics 2010). Similarly, northern climates may face greater infrastructure degradation due to increased freeze-thaw cycles (Jackson and Puccinelli 2006).

Mills and Andrey (2002) provide a general framework for considering climate impacts on transportation. They enumerate baseline weather conditions and episodic weather-influenced hazards that determine the environment in which infrastructure is built, maintained, and used. The authors note that climate change will alter the weather-related context, affecting the frequency, duration, and severity of hazards. These hazards can affect transportation infrastructure itself; its operation; and the demand for transportation services. The latter might include climate effects on agriculture that alter the location of production and, thus, the need and mode for shipping agricultural products.

A limitation of the above studies is their focus on a narrow potential impact of climate change, and their lack of specific estimates of costs or damages that may result from climate change. In response to this limitation, Chinowsky et al. (2011) document the potential costs of climate change on road infrastructure in ten geographically and economically diverse countries. They illustrate the opportunity costs of diverting infrastructure resources to climate change adaptation. This response methodology has been extended to estimate climate change impacts on bridges (Stratus Consulting 2010) and roads in northern climates (Industrial Economics 2010).

Greater attention is now being paid to the potential impact of climate change on infrastructure in Africa. As mentioned, planning for climate change in the African context is taking place in the context of inadequate existing infrastructure. For instance, in 1997, Africa (excluding South Africa) contained 171,000 kilometers of paved roads, which was 18 percent less than Poland—a country roughly the size of Zimbabwe (IRF 2009). Despite continued investments, road stocksstill lag behind the rest of the world. Moreover, in 2008, only 25 percent of Sub-Saharan Africa’s primary roads were paved, compared to a global rate of 50 percent and a 67 percent rate in North America. In terms of per capita road stocks, the paved road length in Sub-Saharan Africa of 0.79 kilometers per thousand inhabitants is less than half of that of South Asia and only a fifth of the world average. Finally, there is significant variability in the quality of primary transport corridorsacross Africa, with Central Africa having only half of its primary roads in good condition, while all of South Africa’s roads are in good condition (Gwilliam et al. 2008). Similarly, in terms of rural roads, which comprise a majority of roads in Africa, more than 70 percent of rural roads are in fair or poor condition (Foster and Briceno-Garmendia 2010). On the one hand, the possibility that climate change will further deteriorate the limited existing road infrastructure in African countries is of considerable concern. On the other hand, African nations have the advantage of building a large share, if not the majority, of their infrastructure backbone while bearing in mind the potential implications of climate change.

3 Mozambique

3.1 Economic characteristics

Mozambique has experienced both a struggle for independence and a subsequent civil war. However, since the mid-1990s the country's development trends have improved considerably. The economy has grown rapidly (even if the large-scale capital-intensive 'mega-project' investments are excluded anddespite a recent downward adjustment to past agricultural growth; see Arndt et al. 2011a). Improved economic conditions have been felt by most segments of the population, albeit not in equal measure. The national poverty headcountfell from 69 to 55 percentduring 1997–2009, and infant mortality rates fell from 149 to less than 100 during 1996–2008. Education levels have also improved dramatically, thanks to high economic growth and large foreign aid inflows.

Mozambique is a large country with a total area of more than 800,000 square kilometers. About 70 percent of the population lives in rural areas and this population is fairly evenly spread throughout the country. Population density is low at 27 persons per square kilometer (compared with 259 people per square kilometer in Vietnam, a close geographic analog in Asia). Connecting sub-national regions poses a serious challenge, especially given infrastructure losses during the civil war. With agriculture accounting for about a quarter of GDP and three-quarters of employment, improved rural infrastructure is often viewed as critical to future economic growth and poverty reduction. Poor infrastructure, large distances, and associated weak market development generate large differences between farm-gate and urban prices for agricultural products. Tarp et al. (2002) show that reducing these marketing margins results in strong poverty reductions, particularly if agricultural productivity rises simultaneously. Recent work shows that high marketing margins, slow agricultural growth, and external terms of trade shocksexplains the slowdown in poverty reduction despite rapid national economic growth over the period 2002/03 to 2008/09 (Arndt et al. 2011a).

Given Mozambique's infrastructure deficit, infrastructure investment, particularly in roads, has amounted to around 15 percent of total government expenditure (i.e., about five percent of GDP). Since Mozambique lies at the end of numerous transnational river basins, flooding in its deltas is a perennial threat to farmers and infrastructure. In 2000, for example, severe flooding in the south of the country destroyed road links between the capital city Maputo and the rest of the country for nearly a year. The rail line to Zimbabwe was also destroyed. This loss of road infrastructure and connectivity between sub-national regions caused per capita economic growth to decline to about one percent in 2000, which was the slowest growth rate registered in two decades. In 2001, with infrastructure largely restored, economic growth rebounded bringing Mozambique back close to pre-flood growth trends. The growth performance in 2001 without doubt reflected some snapback from the depressed levels observed in 2000. At the same time, substantial increments to development assistance also helped to repair damage relatively rapidly and implied few tradeoffs with other investment options. Overall, the experience of the 2000 flood illustrates the potentially large economic impacts of floods (see also Christie and Hanlon 2001).

3.2 Climatecharacteristics and climate change scenarios

Mozambique's climatic characteristics are region-specific. The country's northern and central regions' climate is mainly subtropical, whereas steppe and dry arid desert conditions exist in the south.There is also a strong coastal-to-inland orographic, or elevation gradient, effect on weather patterns. Weather patterns change as they move west from the southeastern, low-elevation, coastal belt into the central and northcentral plateau regions of the country.

Mozambique has a distinct rainy season lasting from October to April, with an annual average precipitation for the whole country of around 1032 mm. Annual rainfall along the coast is usually 800–1000 mm, but this falls to 400 mm at the southern border with South Africa and along the eastern border with Zimbabwe. Rainfall averages 500–600 mm in the southern mountains, whereas inland central and northern regions experience annual rainfall of 1000–2000 mm due to northeast monsoon and high mountains. Average annual evapotranspiration ranges from 800 mm along the Zimbabwean border to more than 1600 mm in the middle of the Mozambican portion of the Zambezi basin. Coastal evapotranspiration is consistently higher at 1200–1500 mm annually.

The impact of climate change on Mozambique is explored using four scenarios based on different pairings of general circulation models (GCM) and global emission scenarios.Thesefour scenarios were selected to represent the total possible variability in future climate moisture within Mozambique. The NCAR-CCSM sres_a1b represents a 'Global Wet' scenario and CSIRO-MK3.0 sres_a2 represents a'Global Dry' scenario. While these GCM/emission scenario pairings represent the wettest and driest scenarios globally, they are not necessarily the wettest or driest for Mozambique. Therefore, the wettest and driest GCM/emission scenarios for Mozambique are also included. Specifically, the UKMO-HADGEM1 sres_a1b is the 'Mozambique Dry' scenario, and IPSL-CM4 sres_a2 is the 'Mozambique Wet' scenario.

Table 1 shows that all sub-national regions in Mozambique are expected to experience a 1–2 ºC increase in temperature by 2050. This increase occurs under both wet and dry scenarios, and reflects the general consensus that temperatures will rise as a result of climate change (IPCC 2007). We find greater variation in average precipitation changes in our four scenarios for Mozambique reflecting a lack of consensus amongst GCMs over precipitation projections at localized scales (IPCC 2007). Differences in precipitation patterns across projections are even more pronounced at daily and monthly time scales. Overall, the GCMs suggest that Mozambique's climate will become hotter and more variable as a result of climate change.

We use historical monthly climate data (0.5°×0.5°) from the Climate Research Unit for 1951–2000 to produce a baseline 'no climate change' scenario for each sub-national region. Our baseline scenario assumes that future weather patterns will retain the characteristics of historical climate variability. It should be noted that the purpose of the baseline scenario is not to predict future weather patterns, but to provide a counterfactual for the climate change scenarios. Taking the baseline scenario, we overlay a ten-year moving average of the monthly deviations in temperature and precipitation predicted by the GCMs. For example, if the ten-year moving average for rainfall around January 2031 increases by 10 percent for a given GCM, then the historical realizations for precipitation in January 1981 are multiplied by 1.1. This procedure produces four ‘synthetic’ climate projections containing both current climate variability (i.e., the historical baseline) and future climate changes.

Climate change is expected to lead to greater rainfall intensity. Note that, when the GCMs predict greater rainfall, the procedure described above, both increases the volume of rainfall and the variance of the precipitation series. This can lead to a greatly increased probability of severe flooding events. Consider an analysis of flood return periods for two of the selected GCMs for the north of Mozambique taken from Strzepek et al. (2010). The results are presented in Figure 1 in the form of flood return periods with the maximum return period set at a 100 year flood. Results vary strongly by GCM. The UKMO (Moz dry) scenario results in a small increase in the average flood return period but no appreciable increase in the probability of extreme flooding relative to the baseline. For the CSIRO scenario (global dry), on the other hand, the probability of extreme flooding events rises dramatically.

As the experience of the 2000 floods illustrated, major flooding events have substantial economic implications. The next section will estimate the impact of these climate changes on road infrastructure.

4 Assessing climatechange impacts on road infrastructure

4.1 General approach

Climate change impacts are determined by a ‘stressor-response’ methodology,in which exogenous factors (i.e., stressors) have a direct effect on and subsequent response by focal elements. In the context of climate change and infrastructure, the exogenous factors are changes in precipitation levels, temperatures, storm frequency, and wind speeds. The focal elements are infrastructure types, including roads, railways, water systems, power distribution, and public buildings amongst others. A stressor-response value is the quantitative impact that a specific stressor has on a particular infrastructure element. We draw on previously determined stressor-response relationshipsto estimate the impact on infrastructure of climate change stressorsof different intensities. For example, increased precipitation has a specific quantitative impact on the lifespan and maintenance costs of unpaved roads.

Our approach diverges from previous studies that emphasize qualitative statements rather than quantitative estimates (see Section 2). A combination of material science reports, usage studies, case studies, and historic data are used to develop response functions for different infrastructure categories. Where possible, data from material manufacturers was combined with historical data to obtain an objective response function. However, when these data were not available, response functions were extrapolated based on performance data and case studies from sources such as Mozambique’s Department of Transportation and other government ministries. Two climate stressors are examined in particular—temperature and precipitation. Road construction and maintenance costswere determined using both commercial cost databases and country-specific data.

Stressor-response factors are separated into impacts on new construction costs and impacts on maintenance costs. New construction cost factors reflect the change in costs required to adapt the design and construction of new infrastructure or to rehabilitateinfrastructure in response to climate changes expected to occur over the asset's lifespan. Climate change may generate increases or decreases in new construction and maintenance costs. Costs are estimated such that an infrastructure's design life span is retained. This premise was established as a baseline requirement due to the preference for retaining infrastructure for as long as possible rather than replacing infrastructure on a more frequent basis. Achieving this goal may require a change in the design standard for new construction or an increase/decrease in maintenance for existing infrastructure. In our analysis, we realize this strategy for the individual infrastructure categories.

4.2 Stressor response relationships: precipitation and temperature

As indicated, infrastructure costs can be separated into new construction costs (CC) and maintenance costs (CM). Below we derive formulae for estimating how climate change affects these two cost components.

Separate stressor-response values for new construction costs from temperature and precipitation effects are derived for paved and unpaved roads. For paved roads, estimates of stressor-response values are based on the cost associated with a change in building codes. The building code approach assumes that new paved roads will be subject to design updates if it is anticipated that a significant climate change stressor will occur during their projected lifespan. A major update of design standards is required when temperature of precipitation changes pass given thresholds. The available data suggest thresholds levels of 10 cm increases in annual precipitation or a 3 ºC maximum temperature increase (Lea International, L.D. 1995; NOAA 2009). Each time a threshold is exceeded, it results in a 0.8 percent increase in construction costs (FEMA 1998).

The stressor-response relationship for these types of infrastructure is expressed as follows

$$CC_P = 0.008 \cdot NT \cdot BC_P \qquad (1)$$

where CC_P is the change in construction costs for paved roads associated with a climate stressor, NT is the number of precipitation or temperature thresholds exceeded, and BC_P is base construction costs for paved roads.

For unpaved roads, a direct approach is used for estimating the cost impact of changes in climate stressors. The stressor-response relationship associates the change in construction costs with changes in maximum monthly precipitation. Ramos-Scharron and MacDonald (2007) attribute about 80 percent of unpaved road degradation to precipitation, while the remaining 20 percent is attributed to factors such as the tonnage of traffic and traffic rates. Given this attribution to precipitation and the focus on retaining design lifespan, we assume that base construction costs for unpaved roads increase by 80 percent of the total percentage increase in maximum monthly precipitation, rounded to one percentage point increments.For example, if the maximum monthly precipitation increases by 10 percent in a given location, then we assume an 8 percent ($0.8 \times 0.1 = 0.08$) increase in base construction costs. Available data suggests that there is no relationship between temperature and the cost of building unpaved roads. Our approach is summarized as follows

$$CC_U = 0.8 \cdot MIP \cdot BC_{\mathrm{U}} \tag{2}$$

where CC_{U} is the change in construction costs for unpaved roads associated with a unit change in climate stress or design requirements, MIP is the increase in maximum monthly precipitation, and BC_{U} is base construction costs for unpaved roads.

As with the stressor-response values for new construction costs, two basic methodologies were adopted for maintenance costs. The first approach, used for paved roads, is based on the cost of preventing a reduction in lifespan that may result from changes in climate-related stress. It is assumed that any lifespan reduction caused by an incremental change in climate stress is equal to the percent change in climate stress, scaled for the stressor's effect on maintenance costs. Miradi (2004) estimates that ongoing precipitation-related maintenance for paved roads accounts for 4 percent of maintenance costs and temperature-related maintenance accounts for 36 percent of costs. After estimating the potential reduction in lifespan associated with a given climate stressor, the costs of avoiding this reduction in lifespan are calculated as the product of (i) the potential percent reduction in lifespan and (ii) the base construction costs of the asset. Therefore, a 10 percent reduction in lifespan has an estimated increase in maintenance costs of ten percent over base construction costs.

As shown in Equations (3) and (4), we implement our approach to maintenance costs in two stages: (i) estimating the lifespan decrement that would result from a unit change in climate stress, and (ii) estimating the costs of avoiding this reduction in lifespan. It is assumed that such a reduction in lifespan caused by an incremental change in climate stress (L_{P})is equal to the percent change in climate stress, scaled for the stressor's effect on maintenance costs, as shown below

$$L_{\mathrm{P}} = \sum\nolimits_{\mathrm{i}} \frac{\Delta S^i}{{S_0}^i} \cdot SMT^i \tag{3}$$

where L_{P} is potential percent change in lifespan for existing paved roads associated with a unit change in climate stress, ΔS is change in climate stress, S_0 is base level of climate stress without climate change, and SMT is the share of existing paved road maintenance associated with a given climate stressor, and the set *i* has elements [precipitation, temperature].

The total change in maintenance costs is then as follows

$$CM_{\mathrm{P}} = L_P \cdot BM_P \tag{4}$$

where CM_{P} is change in maintenance costs for existing paved roads associated with a unit change in climate stress, andBM_P is base original construction cost of the paved road segment.

Finally, to estimate the stressor-response values for unpaved road maintenance costs, we follow the approach outlined above for unpaved roads' new construction costs. Changes in unpaved road maintenance costs are associated with a 1 percent change in maximum monthly precipitation. As indicated above, 80 percent of road degradation can be attributed to precipitation, while the remaining 20 percent is due to traffic rates and other factors. This implies that unpaved road maintenance costs increase by 0.8 percent with every 1 percent increase in the maximum monthly precipitation values projected for any given year. The general form of the maintenance equation is as follows

$$CM_U = 0.8 \cdot MIP \cdot BM_U \tag{5}$$

where CM_U is the change in maintenance costs for unpaved roads associated with a unit change in climate stress or design requirements, MIP is the percentage increase in maximum monthly precipitation, and $BM_U$is the baseline maintenance costs for unpaved roads.

4.3 Stressor response relationships: flooding

As with precipitation and temperature, flooding damage is calculated using stressor-response functions. Road flood losses are calculated based on flood return periods projected by GCM for northern, central, and southern Mozambique in Strzepek et al. (2010). An assessment of the nature of the flooding is also germaine. Gradually rising and then gradually receding flood waters can often leave roads, particularly paved roads, essentially intact. Running flood waters, on the other hand, quickly result in the complete destruction of underlying roads generating repair costs that are close to new road construction costs. Translating the return periods illustrated in Figure 1 into damage costs requires two steps: (i) determining the amount of road kilometers damaged, and (ii) estimating the specific costs implied by these damages.

Figure 2 illustrates the damage functions employed for the analysis. The damage functions are derived based on COWI (2009), Strzepek et al. (2010), and the assessment of the authors. While minor flooding events have minor or no impact, major flooding events can have substantial impact. A 100-year flood is assumed to damage 30 percent and 10 percent of unpaved and paved roads, respectively in the region in which it occurs (north, south, center). The extent of damage is presented in Table 2. Costs of repairing damaged roads vary by road class (primary, secondary, and tertiary) and by road type (unpaved and paved). Flood damage costs are also variable as a share of new construction costs. These cost estimates are also based on COWI (2009) and the assessment of the authors.[1]

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[1] Flood damages/costs vary dramatically depending upon the type of the flood. If floodwaters are moving rapidly, damage to roads can be extensive making flood repair costs commensurate with new road construction costs. On the other hand, slowly rising and then slowly falling floodwaters can leave infrastructure largely intact (especially paved roads). The economic analyses for Mozambique in Strzepek et al. (2010) and Arndt et al.

Some intuition on the implications of these numbers is valuable. Combining the damage functions and the cost estimates, using shares of baseline national road extension by road class and road type and using the flood damage costs in Table 2, we find that a 100-year flood causes damages equivalent to about 9 percent of the value of the road stock in the region in which the flood occurs. Based on these figures, we would estimate that the floods in the south of Mozambique in 2000 caused about US$122 million in damages to road and related infrastructure. While we have been unable to locate any formal ex post evaluations of the infrastructure costs of the 2000 floods against which to compare this number, the available evidence would suggest that this estimate is reasonable.

The relationships developed above are incorporated into a dynamic road network simulation model labeled ‘CLIROAD’. The simulation model tracks the road stock broken by age since construction (or 20-year rehabilitation), road class (primary, secondary, tertiary), road type (paved or unpaved), region (north, south, center, and urban) for each year over a simulation period from 2003–50. It also tracks all costs to the same level of detail over the simulation period. The model is constructed in GAMS and is available upon request.

4.4 Simulations

The stressor-response relationships discussed aboveallow us to determine the impact of climate change on the maintenance of paved and unpaved roads. In the first set of simulations, we estimate the costs of maintaining a given road network across all climate change scenarios relative to the baseline climate scenario. In the second set of simulations, the budget for building and maintaining roads is held constant across all climate change scenarios while the length of the road network is allowed to vary.

In addition, these simulations are run with and without adaptation. In the ‘without adaptation’ scenarios, no actions are taken to mitigate the effects of climate change on paved and unpaved roads. In other words, Mozambique continues to build and maintain roads according to the design standards established without climate change. This is the engineering equivalent of the classic ‘dumb farmer’ approach where the individual employs the same cropping patterns and techniques despite changing climate conditions. In terms of roads, this classic model is modified to a ‘dumb engineer’ model whereby the engineers continue to design and maintain roads in the same manner despite an evolving climate. The result being that as temperatures increase and precipitation patterns change, maintenance needs often increase as the roads are not designed to withstand the changes in stressors. Concurrently, these same roads are maintained in a reactive manner meaning that each year the affected roads are maintained to ensure continued lifespan. No pro-active steps are taken to reduce climate change impacts.

In contrast, adapting to climate change requires a ‘design strategy’ that enhancesthe design standards for roads to reflect the risk of new and/or increased climate change stressors. In our

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(2011b) assumed that floodwaters were moving rapidly and thus repair costs were approximated by new road construction costs. The current analysis assumes that only a share of floods are strongly damaging. Hence, overall flood damages are less than in previous analysis.

modeling, adaptation proceeds on the basis of rules. Two adaptations are modeled. First, as observed temperature rises and precipitation levels change, road designs are assumed to be adjusted to reflect revised conditions. More specifically, surface design standards evolve with a moving average of the preceding ten years of temperature and precipitation (i.e., road engineers learn from recent experience). Although road construction and maintenance unit costs remain the same, the revised design standards imply that precipitation and temperature thresholds are breeched less frequently. Second, we assume that planners take steps to counter an enhanced probability of flooding by investing in adaptation at the per kilometer costs given in Table 2. These adaptations reduce flood damages by 50 percent.

In the simulation modeling, all adaptations are assumed to occur either at new road construction or at 20-year road rehabilitation implying that these are gradualist adaptation policies. The road network gradually evolves to become more robust as the share of roads that have undergone adaptation (e.g., newly constructed or completely rehabilitated roads) under the new policy increases.

4.5 Results: withoutadaptation scenarios

The scenarios presented in this section both begin from the road infrastructure in Mozambique in 2003, which comprised about 26,000 and 6,300 kilometers of unpaved and paved roads, respectively. The upper panel of Table 3 illustrates the costs of maintaining exactly this road network without adaptation. As shown in the Table, discountedmaintenance costs (the discount rate is 5 percent) increase in three of the four climate change scenarios relative to the base. The global dry scenario (CSIRO) is the least favorable to the road network. Even though the global dry (CSIRO) scenario exhibits less overall precipitation than the Mozambique wet (NCAR) scenario, the scenario exhibits greater precipitation intensity within the trans-boundary river basin and so leads to a larger number of flooding events (see Strzepek et al. 2010 and Figure 1). In the most strongly affected scenarios, climate change costs amount to a discounted value of about US$641 million. As damage to primary roads is the most expensive to fix, primary roads represent the most expensive road class. However, because the quantity of unpaved roads is so much larger, costs to maintain unpaved roads are larger in all scenarios. Discounting (of course) disguises cost rises that occur in the 2030s and 2040s. Total maintenance costs with no discounting rise in all scenarios (not shown). For the strongly affected scenarios, the majority of maintenance cost increases are due to flooding (also not shown).

Turning to Table 4, the upper panelreports the impact of climate change on road network length for a given budget without adaptation in 2050. All scenarios assume about a 3.6 percent annual increase in the real budget devoted to road infrastructure during 2003–50.[2]The budget is first allocated to cover the maintenance of existing roads, including the costs of rebuilding roads washed out by flooding. Any remaining budget is then allocated to the construction of new roads. For new road construction, constant allocation shares are applied across road types

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[2] The applied budget is in fact obtained from the base run CGE scenario (introduced in the next section). Hence, the base runs for CliRoad as a standalone model and as incorporated directly into the CGE produce the same outputs.

(paved/unpaved), road class (primary, secondary, tertiary), and location (north, south, center, and urban). If the total budget is insufficient to meet maintenance costs in a given year, then the share of roads not maintained is assumed to be equal to the percentage budget shortfall. So if, for example, the budget is only sufficient to meet 95 percent of total maintenance costs, then 5 percent of roads (for all types, classes and locations) are assumed not to receive any maintenance. Maintained roads do not depreciate while unmaintained roads depreciate at a 10 percentannual rate.

The total road network length is lower in 2050 in all of the four climate change scenarios we consider (see the columnlabeled 'totals' in the upper panel). Results vary widely across scenarios, road types (paved vs. unpaved), road classes, and sub-national regions. For instance, while the UKMO (Mozambique dry) scenario has the smallest overall effect, it isrelatively unfavorable to roads (as currently designed) in the south. Net effects on road extension are complicated as both the distribution of road classes and types and climate change impacts vary by region. For example, the CSIRO scenario generates a particularly large amount of flooding. With events concentrated in the north and center. The north, in particular, has a high proportion of unpaved roads, and unpaved roads are more strongly affected by flooding. As a result, damage to the overall unpaved network is strongest in the CSIRO scenario. The other scenarios reduce the paved network by relatively more because their flooding events are concentrated in center and the south. The large unpaved network in the north is left largely intact. Overall, even with constant road budgets, the implications of climate change, particularly the increased frequency of flooding events, are potentially large and negative for road networks *as currently designed*. This underscores the need to consider adaptation measures.

4.6 Results: adaptation scenarios

In our adaption scenarios, we first consider the costs of maintaining a given road network when design standards are allowed to adjust (the lower panels of Tables 3 and 4). The costs of adaptation compared to the potential impacts that result without adaptation may or may not justify up-front expenditures to avoid significant costs later due to inaction. As indicated earlier, adaptation occurs either at new road construction or at 20 year rehabilitation. The first adaptation measure involves building or rehabilitating roads to evolving precipitation and temperature standards using 10-year moving averages of precipitation and temperature realizations (labeled 'design standard evolution'). The second adaptation involves investing more in new roads and rehabilitated roads in line with the adaptation cost figures in Table 2. The interesting question is whether increased rehabilitation costs pay off in terms of reduced maintenance costs.

Under 'design standard evolution' in Table 3, discounted total costsare lower with adaptation in all climate scenarios (see the final column of Table 3). This adaptation policy leaves costs essentially unchanged under current climate. Hence, the results are favorable to evolving design standards. At the same time, the second adaptation measure, 'Flood Investments', which increases the robustness of roads to flooding events but at the costs given in Table 2, raises discounted costs across the board. Turning to the lower panels of Table 4,we find road extension results that are similar to the cost results even though the cost numbers are the net present value in 2003 while the road kilometers measure focuses exclusively on 2050. Design standard evolution results in a longer road network by 2050 for the same cost. Hence, this adaptation measure appears to provide clear benefits both in terms of discounted costs to 2050 and in terms of road network extension by 2050. At the same time, across the board road robustness policies increase costs and/or reduce road network extent. These results imply that more selective investment policies are required. Greater robustness to flood events could easily be worthwhile for selected flood prone areas and for unpaved roads.

5 Economy-wideimplications of climate change with focus on road infrastructure

Figure 3 illustrates the integrated modeling framework employed to consider the impacts of climate change and alternative adaptation options on an economy-wide basis. Arndt et al. (2011b) and Strzepek et al. (2010) describe the river basin, water resources, crop, and hydropower models employed to analyse sector impacts. In this paper, we have focused on the infrastructure model developed above (CLIROAD). We now introduce the DCGE model employed in the framework to estimate economy-wide impacts. This section focuses on the interface between the road infrastructure and DCGE models.

5.1 Recursive dynamic CGE model

Our DCGE model belongs to the structural neoclassical class of CGE models (see Dervis et al. 1982). These models are well-suited to analysing climate change. First, they simulate the functioning of a market economy, including markets for labor, capital, and commodities, and can therefore evaluate how changing economic conditions are mediated via prices and markets. Second, these models ensure that all economy-wide constraints are respected, which is crucial for long-run climate change projections. Finally, CGE models contain detailed sector breakdowns and provide a ‘simulation laboratory’ for quantitatively examining how the individual impact channels of climate change influence the performance and structure of the whole economy.

Economic decision-making in the DCGE model is the outcome of decentralized optimization by producers and consumers within a coherent economy-wide framework. A variety of substitution mechanisms occur in response to variations in relative prices, including substitution between factors, between imports and domestic goods, and between exports and domestic sales. The Mozambique model contains 56 activities or sectors, including electricity generation, transport services and 24 agricultural subsectors (see McCool et al. 2009). Five factors of production are identified: three types of labor (unskilled, semi-skilled, and skilled), agricultural land, and capital. The agricultural activities and land are distributed across the three sub-national regions (north, center, and south). This sector and regional detail captures Mozambique’s economic structure and influences model results.

The long timeframe over which climate change will unfold implies that dynamic processes are important. The recursive dynamic specification of our CGE model allows it to capture annual changes in the rate of physical and human capital accumulation and technical change. So, for example, if climate change reduces agricultural or hydropower production in a given year, it also reduces income and hence savings. This reduction in savings displaces investment and lowers production potential. Similarly, higher road maintenance costs imply less infrastructure investment and shorter road networks both now and in the future. Extreme events, such as flooding, also destroy infrastructure with lasting effects. Generally, even small differences in accumulation can cause large differences in economic outcomes over long time periods. The DCGE model is well-suited to capture these path dependent effects.

5.2 Modeling climate change impacts on roads and other sectors

As shown in Figure 3, climate change affects economic growth and welfare in the DCGE model via four principal mechanisms. First, productivity changes in rain-fed agriculture are taken from detailed crop models and the DCGE then determines how much resources should be devoted to each crop given their profitability relative to other activities (i.e., 'endogenous adaptation'). Second, the DCGE model directly incorporates fluctuations in hydropower production based on a river flow model (see Arndt et al., 2011b). River flows also affect crop production if the irrigated area available for planting exceeds the maximum potential area that could be irrigated given water availability constraints. Third, the DCGE model incorporates the effects of sea level rise by reducing the total amount of cultivable land in each region by the land inundation estimates from the 'DIVA' model (i.e., dynamic and interactive vulnerability assessment—see Strzepek et al. (2010) for details on the application to Mozambique).

Finally, the road model, CLIROAD, is incorporated directly into the recursive DCGE model. CLIROAD interacts with the DCGE model through two mechanisms. First, the budget allocated to roads (investment and maintenance) grows along with government spending on commodities. Second, road extension in any given time period is assumed to influence the underlying rate of Hicks-neutral factor productivity (HFP) growth. Specifically, the following formula is employed

$$HFPGr_t^i = HFPGr_t^{base} * (\frac{road_t^i}{road_t^{base}})^{\frac{1}{2}} \qquad (6)$$

where $HFPGr$refers to the total factor productivity (TFP) growth rate, i refers to the climate scenario, base is the no climate change climate, $road$ refers to the overall extent of roadstock in kilometers, and t refers to the time period. Note that the linkages to between CLIROAD and the DCGE imply feedback. If climate change generates a more severe flooding event than under the baseline climate scenario, the growth rate is slowed for two reasons. First, the flooding event reduces road extent which reduces HFP growth via the formula above. Second, through time, the reduced rate of economic growth caused by the reduction in HFP growth implies a reduced rate in the growth of the road network due to a reduction in the rate of growth of government investment in infrastructure, which also implies lower HFP growth. Other economic impacts from climate change which reduce the economic growth rate, such as broad-based reductions in crop yields, will also eventually reduce the rate of HFP growth through the infrastructure investment channel.

The rate of TFP growth is higher than the growth in HFP due to the assumption of labor force upgrading (biased technical change in favor of labor and particularly skilled labor). The rate of

HFP growth in the baseline is 0.8 percent per year in agriculture and 1.2 percent per year in non-agriculture.

These assumptions imply that if, in scenario *i*, the road network extent falls to 90 percent of the baseline, HFP growth is reduced by about 5 percent. Recall that Fernald (1999) estimated that road investment in the USA added a full percentage point to US TFP growth over the period 1953–73, which means that road investment contributed nearly two thirds of US TFP growth over the period. The benefit/cost ratios estimated by Fan and his coauthors also imply similarly large TFP gains to investments in roads in a number of developing country contexts (Fan et al. 2004; Fan and Chan-Kang 2008; Fan and Hazell 2001; Fan and Zhang 2008). As noted, these relationships do not hold in all places at all times. Poorly implemented investments are unlikely to yield high returns. And, eventually, road investments, like all other investments, suffer diminishing returns. Nevertheless, relative to these benchmarks, the formulations described above would appear to be a conservative estimation of the economic implications of road infrastructure damage caused by climate change.

5.3 Results: linked CLIROAD DCGE impacts on infrastructure

The sets of assumptions discussed in the preceding paragraphs, including the other impact channels (crop models, hydropower models, and reduction in available cropping area due to sea level rise), were incorporated into the linked CLIROAD and DCGE model. The implications for road extent are depicted in Tables 5 and 6. From Table 5, one can see that the basic conclusions with respect to adaptation pertain as in the standalone version of CLIROAD (see Table 4). Specifically, design standard evolution supplies benefits in all scenarios, however, the costs of broad-based flood investments outweigh the benefits.

Table 6 compares results between standalone and linked DCGE versions of CLIROAD. As noted earlier, the road infrastructure budget applied to CLIROAD in the BASE run of the standalone version is exactly the budget developed in the BASE scenario of the DCGE model. As a result, in the BASE scenario, CLIROAD produces exactly the same results in standalone and DCGE modes. As expected, the feedback effects derived from linking the models accentuate climate change impacts. The DCGE version produces lower final year total road infrastructure for all four climate change scenarios. The differential between the standalone version and the DCGE version is particularly strong in the CSIRO climate scenario, which produced the strongest climate impacts in standalone. The linked CLIROAD and DCGE model projects a final road extent in 2050 under the CSIRO climate that is only 85 percent of the BASE level.

The next sub-section considers the economy-wide impacts of the full set of climate impacts.

5.4 Results: economy-wide impacts of climate change

Table 7 illustrates the implications of climate change for the growth rate of real absorption (a good proxy for economy-wide welfare). These implications are uniformly negative across scenarios and appear to be potentially significant for Mozambique. The table illustrates baseline growth rates and then deviations from baseline by climate change scenario for the full simulation period (2003–50) and by decade. Climate change impacts and then adaptations are introduced sequentially and cumulatively. The first impact comes from yields and sea level rise. The second impact comes from transport (CLIROAD) and hydropower generation.[3] In the CSIRO (global dry) scenario, the annual growth rate of per capita absorption falls by about 0.11 percentage points as a result of climate change when all effects are accounted for (see the panel labeled 'transport & hydro') with the largest impact coming through the transport channel. Design evolution is able to recoup 14 percent of the growth rate losses in NCAR scenario (though this adaptation slightly worsens outcomes in the IPSL scenario). Broad-based flood investments worsen overall outcomes as in the standalone CLIROAD model. It is noteworthy that climate change impacts tend to worsen with time in all climate scenarios. Finally, transport effects are large in the CSIRO and NCAR scenarios but smaller in UKMO and IPSL. In the latter, yield effects tend to dominate.

Figure 4 illustrates the loss in real absorption over the period. In all scenarios, more substantial losses begin to accumulate around 2030. In the worst case scenario (CSIRO), the net present value (in 2003) of the losses over the period amount to around US$2.5 billion (in 2003 prices and discounted at 5 percent per year). The level of per capita absorption is about 5 percent below what it would otherwise be in 2050 the absence of climate change in the worst afflicted scenario (CSIRO) and about 1.4 percent below what it would otherwise be in the least afflicted scenario (IPSL).

6 Conclusions

Empirical evidence indicates that the quantity and quality of a country's road infrastructure is a key determinant of its rate of economic growth. As a corollary, a lack of adequate infrastructure can be a constraining factor to growth. The possibility that climate change may accelerate the depreciation of infrastructure and divert resources away from other development objectives is therefore of concern. Existing studies linking climate change to infrastructure, especially in Africa, have tended to be qualitative in nature and do not provide a precise estimate of economic damages. In this paper, we develop a detailed climate-infrastructure model (CLIROAD) that uses empirically calibrated stressor-response relationships to simulate the effects of climate change on road construction and maintenance costs and on road network length. We apply this model to Mozambique—a country whose road infrastructure is particularly exposed to climate change. The infrastructure model was also hard linked to a DCGE model. The full incorporation of CLIROAD into a dynamic CGE model represents a methodological improvement over previous analyses. The resulting DCGE model is able to estimate economy-wide costs and to compare road damages to other climate change impact channels, including crop yields, sea level rise, and hydropower generation. This integrated modeling framework was used to simulate four climate scenarios reflecting the full distribution of possible global and local climate change outcomes.

Simulation results conclude that construction and maintenance costs will increase as a result of climate change, and that, assuming a constrained public sector road budget, the total road

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[3] To 2050, the economic growth implications of climate change for sea level rise are small and for hydropower generation very small. Yields and transport infrastructure dominate the analysis.

network length will decline relative to a no climate change scenario. In the worst case scenario (CSIRO), damages from flooding are the primary cause of deteriorations in the road network. The economic model indicates that the economic costs of road damages may well exceed those of other climate change impact channels for Mozambique. Adaptation simulations that allow for evolutionary changes to road design standards (e.g., changing pavement mix designs) help to limit climate change damages. However, under the scenarios considered, the benefits of broad adaptation of investments designed to counter the increased threat of flooding do not exceed the costs.

We conclude that climate change through 2050 is likely to place a drag on economic growth and development prospects. The economic implications of climate change appear to become more pronounced from about 2030. Nevertheless, the implications are not so strong as to drastically diminish development prospects. An adaptation policy of gradual evolution towards road designs that accommodate higher temperatures and follows rainfall trends (wetter or dryer) should be seriously considered. While a generalized policy of upgrading all roads does not appear to be merited, it appears likely that a focus on more vulnerable infrastructure, such as unpaved roads in flood prone zones, could provide positive net benefits in the face of a more extreme future climate.

The details of these policies will vary by country and should benefit from continued research related to stressor response functions and the economic benefits of alternative infrastructure types. The CLIROAD model coupled with the CGE model of Mozambique developed for this study is a first generation attempt to assist in assessing potential climate change impacts. A great deal remains to be done including: (1) compilations of additional cost data from local projects to reflect local construction practices, (2) the validation of the principal stressor-response relationships; and (3) enhanced understanding of flood impacts based on analysis of historical events.

References

Arndt, C., M.A. Hussain, E.S. Jones, V. Nhate, F. Tarp, and J. Thurlow, 'Explaining Poverty Evolution: The Case of Mozambique,' Working Paper 17, Helsinki: UNU-WIDER, 2011a.

Arndt, C., K. Strzepek, F. Tarp, J. Thurlow, C. Fant, and L. Wright, 'Adapting to Climate Change: An Integrated Biophysical and Economic Analysis for Mozambique,' *Sustainability Science* 6 (2011b):7–20.

AUSTROADS, *Impact of Climate Change on Road Infrastructure*, Austroads Publication AP–R243/04, Sydney; Austroads, 2004.

Calderón, C. and L. Serven, 'The Effects of Infrastructure Development on Growth and Income Distribution,' Policy Research Working Paper 3400, Washington, DC: World Bank, 2004.

Calderón, C. and L. Serven, 'Infrastructure and Economic Development in Sub-Saharan Africa,' Policy Research Working Paper 4712, Washington, DC: World Bank, 2008.

CCSP, *Effects of Climate Change on Energy Production and Use in the United States*, Washington, DC: US Climate Change Science Program, Department of Energy, 2006.

Chinowsky, P.S., C. Hayles, A. Schweikert, and N. Strzepek, 'Climate Change as Organizational Challenge: Comparative Impact on Developing and Developed Countries,' *Engineering Project Organization Journal*, 1 (2011).

COWI, *Making Transport Climate Resilient*, Report to the World Bank, Document P-70922A_02, Washington, DC: World Bank (2009).

Christie, F. and J. Hanlon, *Mozambique and the Great Flood of 2000*,Oxford: The International African Institute and James Currey, 2001.

Dervis, K., J. de Melo, and S. Robinson, *General Equilibrium Models for Development Policy*, New York: Cambridge University Press, 1982.

Dillon, A., M. Sharma, and X. Zhang, 'Estimating the Impact of Rural Investments in Nepal,' *Food Policy* 36 (2011):250–28.

Esfahani, H.S. and M.T. Ramirez, 'Institutions, Infrastructure, and Economic Growth,' *Journal of Development Economics* 70 (2003):443–77.

Fan, S. and C. Chan-Kang, 'Regional Road Development, Rural and Urban Poverty: Evidence from China,' *Transport Policy* 15 (2008):305–14.

Fan, S. and P. Hazell, 'Returns to Public Investments in the Less-Favored Areas of India and China,' *American Journal of Agricultural Economics* 83 (2001): 1217–22.

Fan, S., L. Zhang, and X. Zhang. 'Reforms, Investment, and Poverty in Rural China,' *Economic Development and Cultural Change* 52 (2004): 395–421.

Fan, S. and X. Zhang, ‘Public Expenditure, Growth and Poverty Reduction in Rural Uganda,’ *African Development Review* 20 (2008): 466–96.

FEMA, ‘Promoting the Adoption and Enforcement of Seismic Building Codes,’ Federal Emergency Management Agency, FEMA 313, September 1998.

Fernald, J.G, ‘Roads to Prosperity? Assessing the Link between Public Capital and Productivity,’ *The American Economic Review* 89 (1999): 619–38.

Foster, V. and C. Briceño-Garmendia, *Africa’s Infrastructure: A Time for Transformation*, Washington, DC: Africa Development Forum, World Bank, 2010.

Galbraith, R.M., D.J Price, and L. Shackman, *Scottish Road Network Climate Change Study*, Edinburgh: Scottish Government, 2005.

Gwilliam, K., V. Foster, R. Archondo-Callao, C. Briceño-Garmendia, A. Nogales, and S. Kavita, *Africa Infrastructure Country Diagnostic: Roads in Sub-Saharan Africa*, Summary of Background Paper 14, Washington, DC: World Bank, 2008.

Industrial Economics, *Costing Climate Impacts and Adaptation: A Canadian Study on Public Infrastructure*, Report to the National Round Table on the Environment and the Economy, Canada, 2010.

IPCC, *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds), Cambridge: Cambridge University Press, 2007.

IRF, *World Road Statistics 2009*, Geneva: International Road Federation, 2009.

Jackson, N. and J. Puccinelli, ‘Long-Term Pavement Performance (LTPP) Data Analysis Support: Effects of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost,’FHWA-HRT-06-121, 2006.

Jacoby, H.G., ‘Access to Markets and the Benefits of Rural Roads,’ *The Economic Journal* 110 (2000):713–37.

Lea International, L.D., *Modelling Road Deterioration And Maintenance Effects In HDM-4, RETA 5549-Reg Highway Development And Management Research*, Final Report, Prepared For Asian Development Bank, 1995.

McCool, C., J. Thurlow, and C. Arndt, ‘Documentation of Social Accounting Matrix (SAM) Development,’ in C. Arndt and F. Tarp (eds) *Taxation in a Low-Income Economy: the Case of Mozambique*, New York: Routledge, 2009.

Mills, B. and J. Andrey, ‘Climate Change and Transportation: Potential Interactions and Impacts,’ in *The Potential Impacts of Climate Change on Transportation: Workshop Summary*, U.S. Dept. of Transportation, Workshop, 1–2 October, 2002. Available at: http://climate.volpe.dot.gov/workshop1002/

Miradi, M.,’Artificial Neural Network (ANN) Models for Prediction and Analysis of Ravelling Severity and Material Composition Properties,’ in M. Mohammadian (ed.), Gold Coast: CIMCA, 2004: 892–903.

Ndulu, B.J., ‘Infrastructure, Regional Integration and Growth in Sub-Saharan Africa: Dealing with the Disadvantages of Geography and Sovereign Fragmentation,’ *Journal of African Economies* 15 (2006):212–44.

NOAA, Heating and Cooling Degree Day Data. NOAA Satellite and Image Information Service, (2009). Available at: http://www.ncdc.noaa.gov/oa/documentlibrary/hcs/hcs.html#51overview

Ramos-Scharron, C.E. and L.H. MacDonald, ‘Runoff and Suspended Sediment Yields from an Unpaved Road Segment, St. John, U.S. Virgin Islands’, *Hydrological Processes*, 21 (2007):35–50.

Roodman, D., ‘A Note on the Theme of Too Many Instruments,’ *Oxford Bulletin of Economics and Statistics* 71 (2009): 135–58.

Stratus Consulting, *Climate Change Impacts on Transportation Infrastructure*, Prepared for U.S. Environmental Protection Agency, 2010.

Strzepek, K., C. Arndt, P. Chinowsky, A. Kuriakose, J. Neumann, R. Nicholls, J. Thurlow, and L. Wright. *Economics of Adaptation to Climate Change: Mozambique*, Washington DC: World Bank, 2010.

Tarp, F., C. Arndt, H.T. Jensen, S.R. Robinson, and R. Heltberg. *Facing the Development Challenge in Mozambique: A General Equilibrium Perspective*, Research Report 126,Washington DC: International Food Policy Research Institute, 2002.

TRB, *Potential Impacts of Climate Change on U.S. Transportation*, TRB Special Report 290, Washington, DC: Transportation Research Board, 2008.

Table 1: Climate changes in Mozambique by 2050

	Global dry CSIRO	Global wet NCAR	Moz. dry UKMO	Moz. wet IPSL
Temperature change (ºC)				
North region	1.23	1.89	1.37	1.47
Center region	1.40	1.81	1.78	1.49
South region	1.51	1.58	1.66	1.36
Precipitation change (%)				
North region	3.5	1.94	-22.46	18.23
Center region	-6.96	-2.12	-27.19	6.36
South region	-11.87	1.50	-21.74	15.60

Source: Own calculations using GCM results (CSIRO, NCAR, UKMO, and IPSL).

Table 2: Flood and adaptation costs in US$

		Flood cost/km	Share of new road cost	Adaptation cost/km
Primary	Unpaved	77,000	0.51	28,000
	Paved	247,500	0.50	55,000
Secondary	Unpaved	61,600	0.62	18,000
	Paved	96,800	0.48	16,500
Tertiary	Unpaved	27,500	0.39	7,000
	Paved	55,000	0.55	7,700

Source: Authors’ calculations.

Table 3: Discounted simulated road maintenance costs over 2003–50 (US$million or %)

	North	Center	South	Urban	Primary	Secondary	Tertiary	Paved	Unpaved	Totals
	Without Adaptation									
BASE	$1,352	$1,992	$1,060	$715	$2,818	$888	$1,414	$2,408	$2,711	$5,119
CSIRO	16.6%	13.5%	7.9%	8.9%	9.8%	13.3%	17.4%	7.4%	17.1%	12.5%
NCAR	16.1%	6.1%	7.6%	7.2%	6.9%	8.0%	14.6%	4.7%	13.3%	9.2%
UKMO	-5.1%	-5.7%	22.7%	8.0%	2.4%	1.2%	2.8%	1.7%	2.8%	2.3%
IPSL	-1.4%	-3.9%	4.0%	0.7%	-0.5%	-1.8%	-1.5%	-0.4%	-1.5%	-1.0%
	With Design Standard Evolution									
BASE	-0.2%	0.2%	0.4%	0.2%	0.1%	0.2%	0.1%	0.1%	0.2%	0.1%
CSIRO	15.9%	12.9%	6.6%	7.8%	9.2%	12.4%	16.0%	7.1%	15.7%	11.6%
NCAR	12.9%	4.3%	7.4%	5.8%	5.7%	6.4%	11.4%	4.0%	10.4%	7.4%
UKMO	-4.4%	-5.7%	20.7%	7.0%	2.0%	0.8%	2.2%	1.4%	2.2%	1.9%
IPSL	-1.0%	-3.8%	4.0%	0.9%	-0.3%	-1.7%	-1.2%	-0.3%	-1.2%	-0.8%
	With Design Standard Evolution and Flood Investments									
BASE	6.3%	6.0%	7.6%	8.5%	9.7%	3.6%	2.8%	9.7%	4.1%	6.7%
CSIRO	17.6%	15.6%	12.2%	14.2%	16.5%	12.7%	14.4%	14.9%	15.6%	15.2%
NCAR	18.5%	9.3%	12.1%	13.0%	14.4%	8.5%	12.3%	12.9%	12.7%	12.8%
UKMO	3.4%	2.0%	22.4%	13.6%	11.3%	4.3%	4.6%	10.8%	5.9%	8.2%
IPSL	5.5%	3.1%	9.5%	8.6%	9.2%	2.0%	1.4%	9.3%	2.7%	5.8%

Source: Simulation results from the CLIROAD model.

Table 4: Deviation in road network length in 2050 from baseline (%) using CLIROAD

	North	Center	South	Urban	Primary	Secondary	Tertiary	Paved	Unpaved	Totals
	Without Adaptation									
BASE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CSIRO	-12.4%	-11.8%	-10.0%	-9.3%	-10.7%	-12.1%	-11.0%	-11.1%	-11.4%	-11.3%
NCAR	-6.5%	-5.7%	-8.2%	-5.0%	-6.7%	-8.8%	-4.5%	-8.8%	-5.2%	-6.7%
UKMO	-1.7%	-1.3%	-3.5%	-1.3%	-2.3%	-3.5%	-0.5%	-3.7%	-1.0%	-2.1%
IPSL	-4.7%	-4.5%	-4.8%	-3.7%	-4.5%	-5.5%	-3.9%	-5.3%	-4.2%	-4.6%
	With Design Standard Evolution									
BASE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CSIRO	-10.8%	-10.2%	-8.3%	-8.0%	-9.1%	-10.2%	-9.6%	-9.3%	-10.0%	-9.7%
NCAR	-3.9%	-3.2%	-5.4%	-2.9%	-4.2%	-5.6%	-2.4%	-5.8%	-2.9%	-4.1%
UKMO	-0.5%	-0.2%	-2.2%	-0.4%	-1.1%	-2.1%	0.5%	-2.3%	0.1%	-0.9%
IPSL	-4.1%	-4.0%	-4.2%	-3.2%	-3.9%	-4.7%	-3.4%	-4.6%	-3.7%	-4.0%
	With Design Standard Evolution and Flood Investments									
BASE	-5.4%	-4.9%	-7.4%	-3.8%	-6.6%	-8.7%	-2.2%	-6.0%	-5.6%	-5.7%
CSIRO	-10.6%	-9.6%	-11.5%	-7.8%	-11.0%	-13.2%	-7.1%	-10.4%	-10.3%	-10.4%
NCAR	-8.0%	-6.9%	-9.6%	-5.6%	-8.8%	-11.1%	-4.4%	-8.3%	-7.8%	-8.0%
UKMO	-6.1%	-5.6%	-8.3%	-4.4%	-7.4%	-9.6%	-2.8%	-6.9%	-6.2%	-6.5%
IPSL	-7.2%	-6.7%	-9.4%	-5.2%	-8.4%	-10.8%	-3.8%	-8.2%	-7.2%	-7.6%

Source: Simulation results from the CLIROAD model.

Table 5: Deviation in road network length in 2050 frombaseline (%) using CLIROAD linked to the DCGE

	North	Center	South	Urban	Primary	Secondary	Tertiary	Paved	Unpaved	Totals
	Without Adaptation									
BASE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CSIRO	-16.0%	-15.2%	-13.6%	-12.1%	-14.1%	-16.2%	-13.9%	-15.1%	-14.6%	-14.8%
NCAR	-8.3%	-7.4%	-10.1%	-6.4%	-8.4%	-10.9%	-5.9%	-10.9%	-6.8%	-8.4%
UKMO	-4.7%	-4.3%	-6.7%	-3.7%	-5.2%	-7.1%	-3.0%	-7.2%	-3.7%	-5.1%
IPSL	-5.2%	-5.0%	-5.3%	-4.0%	-4.9%	-6.0%	-4.4%	-5.7%	-4.7%	-5.1%
	With Design Standard Evolution									
CSIRO	-14.3%	-13.6%	-11.9%	-10.8%	-12.5%	-14.2%	-12.6%	-13.2%	-13.1%	-13.1%
NCAR	-5.5%	-4.7%	-7.2%	-4.2%	-5.8%	-7.6%	-3.7%	-7.6%	-4.3%	-5.7%
UKMO	-3.5%	-3.1%	-5.4%	-2.7%	-4.1%	-5.7%	-2.0%	-5.8%	-2.6%	-3.9%
IPSL	-4.7%	-4.5%	-4.7%	-3.6%	-4.4%	-5.3%	-3.9%	-5.1%	-4.2%	-4.6%
	With Design Standard Evolution and Flood Investments									
CSIRO	-14.0%	-12.9%	-15.1%	-10.5%	-14.2%	-17.2%	-10.0%	-14.4%	-13.3%	-13.7%
NCAR	-9.9%	-8.9%	-11.8%	-7.2%	-10.7%	-13.4%	-6.0%	-10.7%	-9.5%	-10.0%
UKMO	-9.5%	-8.8%	-11.8%	-7.0%	-10.6%	-13.5%	-5.6%	-10.9%	-9.1%	-9.8%
IPSL	-8.1%	-7.6%	-10.2%	-6.0%	-9.2%	-11.8%	-4.6%	-9.1%	-8.0%	-8.5%

Source: Simulation results from the CLIROAD model linked to the DCGE model.

Table 6: Comparison of CLIROAD results when run standalone and linked to the DCGE

	Kilometers		Ratio to Base		DCGE/
	Standalone	DCGE	Standalone	DCGE	Standalone
BASE	124,010	124,010	1.00	1.00	1.00
CSIRO	109,993	105,653	0.89	0.85	0.96
NCAR	115,748	113,581	0.93	0.92	0.98
UKMO	121,433	117,680	0.98	0.95	0.97
IPSL	118,267	117,680	0.95	0.95	1.00
With Design Standard Evolution					
CSIRO	111,997	107,704	0.90	0.87	0.96
NCAR	118,978	117,000	0.96	0.94	0.98
UKMO	122,910	119,179	0.99	0.96	0.97
IPSL	119,002	118,367	0.96	0.95	0.99
With Design Standard Evolution and Flood Investments					
CSIRO	111,143	106,960	0.90	0.86	0.96
NCAR	114,103	111,657	0.92	0.90	0.98
UKMO	115,949	111,831	0.93	0.90	0.96
IPSL	114,618	113,528	0.92	0.92	0.99

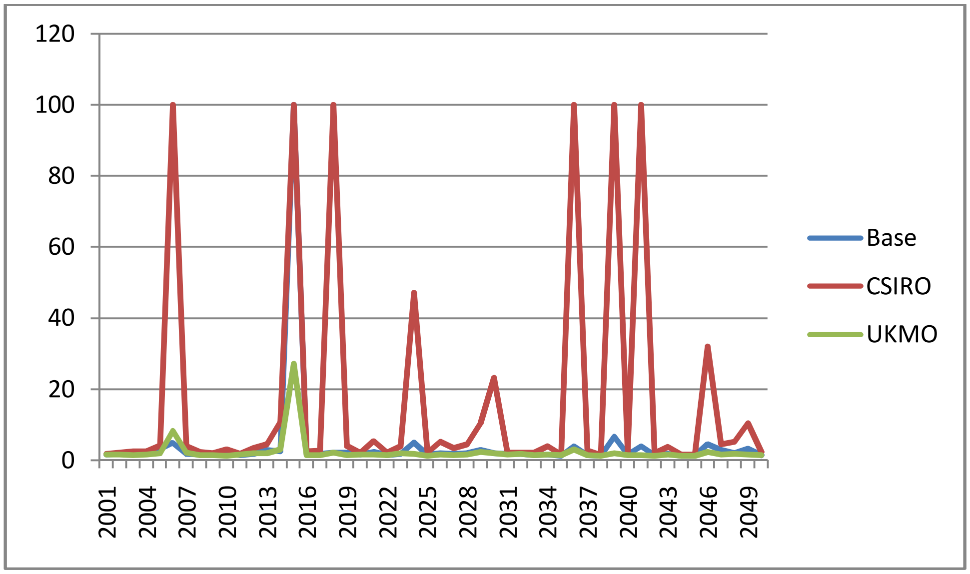
Source: Simulation results from the CLIROAD model in standalone and linked to DCGE modes.

Table 7: Difference in growth rate of real absorption from BASE

		2003-50	2010s	2020s	2030s	2040s
Baseline	BASE	2.117	1.567	1.912	2.524	2.934
+Yields & SLR	CSIRO	-0.048	-0.042	-0.079	-0.065	-0.001
	NCAR	-0.030	-0.026	-0.080	-0.080	-0.010
	UKMO	-0.059	-0.006	0.004	-0.065	-0.040
	IPSL	-0.026	0.004	-0.050	0.071	-0.026
+Transport & hydro	CSIRO	-0.110	-0.082	-0.129	-0.139	-0.118
	NCAR	-0.060	-0.038	-0.105	-0.123	-0.063
	UKMO	-0.074	-0.005	-0.004	-0.089	-0.076
	IPSL	-0.031	0.008	-0.046	0.059	-0.045
+Design evolution	CSIRO	-0.106	-0.082	-0.127	-0.132	-0.105
	NCAR	-0.051	-0.038	-0.101	-0.110	-0.041
	UKMO	-0.072	-0.005	-0.003	-0.086	-0.068
	IPSL	-0.032	0.008	-0.048	0.056	-0.045
+Flood investment	CSIRO	-0.110	-0.084	-0.123	-0.139	-0.113
	NCAR	-0.073	-0.053	-0.110	-0.134	-0.087
	UKMO	-0.095	-0.021	-0.016	-0.112	-0.117
	IPSL	-0.049	-0.001	-0.054	0.037	-0.083

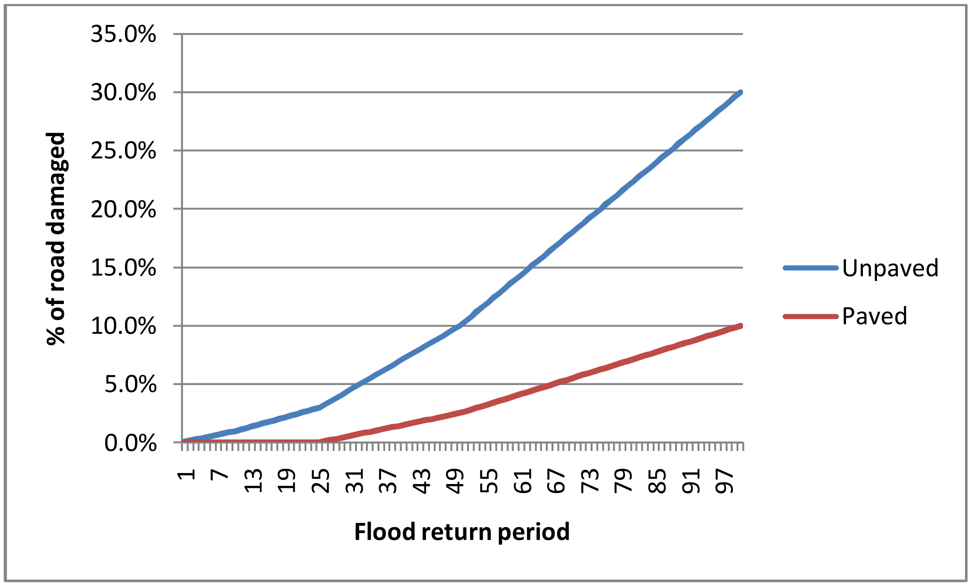
Source: DCGE model.

Figure 1: Simulated flood event return periods for northern Mozambique



Source: Strzepek et al (2010).

Figure 2: Estimated road damage functions by flood return period



Source: Authors' calculations.

Figure 3: Integrated modeling framework

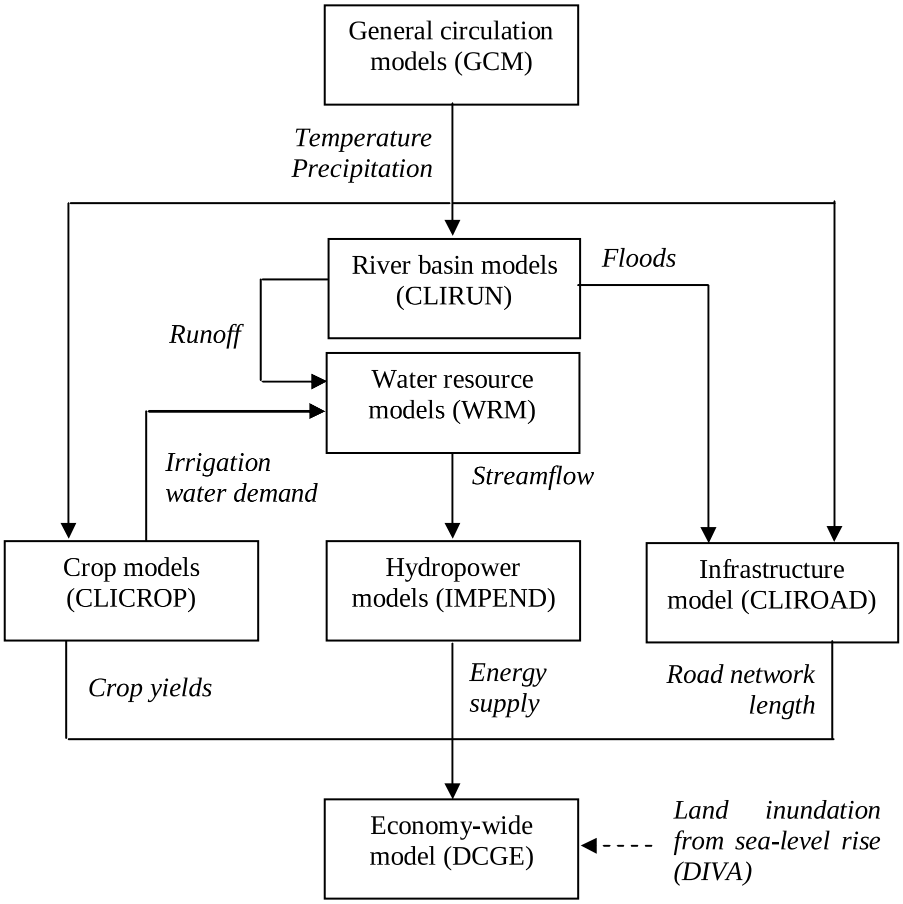


Figure 4: Reduction in real absorption relative to BASE, 2003–50