

Macroeconomic Modeling of Managing Hurricane Damage in the Caribbean

The Case of Jamaica

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Abstract

This paper describes a modeling methodology that embeds climate damages from natural disasters and risk management strategies into a macroeconomic model for Jamaica. The modeled damages take the form of capital destruction, and the risk management strategies considered are (i) adaptation investment in hurricane resilient infrastructure, (ii) commercial disaster insurance for the government, (iii) the formation of a contingency fund, and (iv) lower debt

via higher future primary balances to create fiscal space for disaster recovery. Different risk management strategies are compared to a baseline of no risk management. The model behavior is estimated empirically on country-specific data. Hurricane damage and the model results are analyzed in deterministic and probabilistic settings, using the historical distribution of damages for Jamaica.

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Macroeconomic Modeling of Managing Hurricane Damage in the Caribbean: The Case of Jamaica

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1. Introduction

Damages due to hurricanes have a considerable impact on the economies of the Caribbean region. Among the 20 island economies in the Caribbean considered by Acevedo (2016), 15 experience annual damages that exceed 0.5% of GDP on average. Jamaica, the country chosen for this paper, experiences average annual losses of 0.1% of GDP according to Acevedo (2016), but 1.15% according to the broader definition in World Bank (2018). While the country is better off than the weighted regional average, hurricanes still cause substantial damage and disrupt economic activity. Hurricane Ivan for example caused damages of USD 360 million in 2004 (Acevedo, 2016). Historically, countries in the Caribbean have relied to a large extent on international disaster relief to deal with the damages caused by hurricanes.

This paper develops a structural model of the Jamaican economy with an explicit modeling of hurricane damages.

A single-country variant of the World Bank's macrostructural model, MFMod, (Burns, Campagne, Jooste, Stephan, & Bui, 2019) is adapted to account for hurricane damages to the capital stock and alternative disaster risk management strategies. The model incorporates 49 behavioral equations that determine the response of key economic variables (e.g. output, potential GDP, consumption, inflation, sovereign debt and external balances) to hurricane damage and the proposed policies to absorb the shocks. The adapted model allows both the long-run and short-run disequilibrium effects of hurricane-related damages to be quantified under each of the analyzed risk-management strategies. While the parameterization of some of the disaster-specific features of the model is challenging, a wide range of alternative parameter specifications are analyzed to better understand the sensitivity of outcomes to different modeling choices.

Four forms of risk management for hurricane damage are explored. The first is investment in hurricane-resilient infrastructure (adaptation). The other three are alternative mechanisms to ensure that funding is available to recover as rapidly as possible from the damage of a hurricane when it occurs. The funding mechanisms considered are commercial insurance taken out by the government, self-insurance via the accumulation of a hurricane-relief contingency fund, and the creation of fiscal space¹ through the anticipated lowering of government debt to permit an adequate response of the government to hurricane shocks. In all four scenarios, the authorities are assumed to use their own resources to deal with the economic disruption caused by hurricanes without relying on outside resources. Importantly, the paper analyzes the damage to physical capital, and not the ancillary disruption to economic activity that might accompany it.

The main objective of the risk management strategies is to reduce the amount of economic damage caused by hurricanes. For adaptation investment this is achieved by reducing the size of the damage, while the other three strategies are focused on accelerating recovery and therefore reducing the time period where the economy is running below capacity. The type of insurance examined is parametric insurance of physical capital losses. Notably, insurance aimed at defraying humanitarian aid or assuring short-term logistical support is not considered. The modeling also assumes that financing (in the amount planned) from all sources is readily available and reconstruction is not delayed while finance is arranged.

¹ Fiscal space is loosely defined as the reduction of debt below the debt rule ceiling equal to the amount of expected hurricane damages.

Relaxing these assumptions could yield different results. In this modeling exercise the results from different options are compared, but no effort is made to find an optimal combination of policies, principally because of the uncertainties surrounding the parameters.

The following Section (Section 2) discusses modeling of hurricane impacts. The risk management options are introduced in Section 3. Section 4 presents the modeling of government finances, a critical mechanism in determining economy-wide impacts of alternative strategies. Section 5 describes the calibration of the parameters. Section 6 presents the results, including graphical illustrations of economic performance. Section 7 provides general remarks, and Section 8 concludes. An appendix reports a short review of the literature on climate adaptation investments and additional results derived from various sensitivity analyses.

2. Modeling hurricane impacts

The gross damage of a hurricane, GD_t , is the amount of capital destruction that a hurricane causes to an economy with existing levels of adaptation measures in place.² With adaptation, the damage is reduced to residual damages, RD_t . How exactly a country can use adaptation to reduce the hurricane damage is described in Section 3.1. This section is concerned with the effect of the residual damage on the economy.

2.1. Marginal and average productivity of capital

Both residual and gross damages are given in terms of the reconstruction cost of the damaged capital. For example, if a hurricane destroys a bridge and the reconstruction cost of the bridge is USD 10 million, then the official damage caused by the destruction of the bridge is USD 10 million. However, the economic damage caused by the destruction of that bridge might be far higher than USD 10 million.³

In the production function approach to potential output employed in MFMod (Burns et al, 2019), simply subtracting the reconstruction cost of hurricane damage from the total capital stock implies that the productivity of the destroyed capital was equal to the marginal product of additional capital. In reality, hurricanes damage both infra-marginal and marginal capital. Importantly, the productivity of infra-marginal capital is higher than marginal capital and therefore the expected output loss would be higher. This is effectively an extension of the observation that in the face of decreasing marginal productivity, average productivity will always be higher than marginal productivity.

Assuming that damaged capital is evenly distributed across infra-marginal projects, the economic value of the destroyed capital is equal to the average productivity of capital.

2.2. Tracking unrepaired damages

Capital destroyed by a hurricane thus has approximately an average capital productivity, while newly constructed capital has a marginal productivity. To correctly estimate economic effects from hurricane damage it is necessary to keep track of unrepaired hurricane damage (DS_t) and calculate its economic

² Some level of adaptation investment has been undertaken in the past and is assumed to continue in the future. In the current modeling, the amount of that existing investment is unknown. If data were available, it could be incorporated into the modeling in the same way as the additional adaptation investment is accounted for in this paper.

³ Economic damages include the loss in asset value, but also the loss in economic value. In the case of the destroyed bridge, the additional loss is productivity loss of not being able to transport goods across that bridge.

effect separately from new incremental capital projects. The stock of unrepaired hurricane damage can be tracked with the following equation:

$$DS_t = DS_{t-1} + RD_t - I_t^R,$$

Where RD_t is residual damage (Gross damage net of the protection provided by adaptive investment) and I_t^R is investment into repairing damage in time t , where repairs are equal to a share (φ) of total investment or total destroyed capital, whichever is smaller.⁴

Given that the capital destroyed by hurricanes has an average capital productivity, it would be optimal to direct all investment to reconstruction. However, agency issues (not all investors will own damaged capital) and regional and sectoral capacity constraints will preclude this result from being observed. To reflect these considerations, it is assumed that reconstruction investment cannot exceed a share φ of total investment (with $\varphi = 0.5$ in this paper).

$$I_t^R = \min\{DS_t, \varphi I_t\}.$$

2.3. Adjusting the damage impact

To accommodate the idea that the economic impact of damaged capital exceeds that of marginal capital, the standard model of potential output in the MFMod system (a Cobb-Douglas function) is modified to explicitly account for the higher productivity of destroyed capital (see Hallegatte & Vogt-Schilb (2016) for an in-depth treatment). Thus

$$Y_t^{pot} = AL_t^\alpha K_t^{1-\alpha} - DS_t * \frac{Y}{K},$$

where the second term reflects the lost output from the (time variant) damaged capital, and K reflects the sum of undamaged capital and damaged capital. While damage is greater than zero it reduces output by the product of damaged capital times the average product of capital. When $DS_t = 0$ the equation reverts to the standard MFMod potential output equation. For the equations used in the model, see Appendix C.1.

2.4. Further considerations for modeling hurricane damage

Following the literature presented in Appendix B, hurricane damage is assumed to take the form of destroyed capital. This need not be the only economic impact of a hurricane, natural disasters may also negatively impact productivity, human capital (Hallegatte et al., 2016; Piontek et al., 2018), and even investment behavior (Hsiang & Jina, 2015). This paper abstracts from these possible effects and focuses on capital destruction.

Reconstruction occurs with a lag. While under normal economic circumstances it is reasonable to assume time to build of between one and two years (currently the case for MFMod), it is empirically hard to identify the time to rebuild after a natural disaster, especially if large resources are used imposing supply-side constraints or when it is difficult to mobilize finances. Hallegatte et al. (2016) argue

⁴ The probabilistic scenarios considered in Sections 8.4 and 8.5 show that a series of hurricanes can destroy the country's entire capital. For this reason, we assume that 10% of the capital stock is "indestructible" by setting $DS_t = \max\{DS_{t-1} + RD_t - I_t^R, 0.1 * \tilde{K}_t\}$.

that in many instances countries do not have ready-access to funds to replace destroyed capital. As a result, they do not fully repair the damaged capital resulting in permanent losses in output. In the current modeling, this effect is hysteretic effects. In MFMod this effect of the government not reconstructing important infrastructure due to an inability to raise funds is not reflected in instances of very large damages that exceed the funds available in the contingency fund or in available fiscal space in those two disaster mitigation scenarios (see below) and may thus underestimate the destructive effect of disasters.

3. Exploring alternative hurricane-damage risk management strategies

We consider four approaches of disaster risk management. One of these is adaptation. While adaptation investments reduce the physical impact of hurricanes, impacts can also be reduced by ensuring that the monetary resources to rebuild damaged infrastructure are readily available. Three separate financial strategies are examined. The first of these is a conventional insurance contract of the government with a commercial insurance company to cover the cost of hurricane recovery to the government. The second is a contingency fund, established specifically for funding hurricane recovery. The third type is self-insurance, that generates sufficient fiscal space so that the government can react quickly in response to the shock. We consider the four approaches separately, so that for all approaches except adaptation residual damages equal gross damages, $RD = GD$.

3.1. Adaptation

Modeling investments aimed at minimizing the damage from natural disasters (adaptation investment) involves considerable uncertainty, not least because adaptation strategies and the payoffs associated with them tend to be very sector and country specific (see Appendix B for a review of the literature). The treatment of adaptation in MFMod is based on an aggregate notion of capital stock.⁵ The linkages of adaptation and how it relates to economic variables are discussed below.

The formation of adaptation capital

MFMod distinguishes between productive capital (the type observed in the standard MFMod) and adaptation capital. Adaptation capital is investment that protects the economy from hurricane damage. The more adaptation capital an economy accumulates the less productive capital will be damaged by natural disasters such as a hurricane. Following (Bosello, Carraro, & De Cian, 2010) and (Millner & Dietz, 2015) adaptation capital is assumed to not have a productive use, see Appendix B. If a road is constructed in a resilient manner, the additional value over and above the standard infrastructure (i.e. the adaptation part) is not considered as productive and is treated in a separate accounting of capital which we refer to as adaptation capital.

The level of adaptation capital K_t^A accumulates in the same way as productive capital and is assumed to have the same rate of depreciation (δ) as productive capital.

$$K_t^A = (1 - \delta)K_{t-1}^A + I_t^A.$$

⁵ An aggregate capital stock is used because most countries do not produce time series of investment by sector, which would be necessary if the model were to track capital stock by sector.

The protection level

Define the amount of adaptation capital that would be obtained if the government invests the equivalent of the average hurricane damage into adaptation as K^{Amax} . If a constant share of GDP is invested in adaptation capital and GDP grows at a rate g , then in the long run adaptation capital will accumulate to a steady state share of GDP and grow at the same rate as GDP, giving the steady-state relation $K_t^A = (1 + g)K_{t-1}^A$. Inserting this in the equation for the accumulation of adaptation capital, gives $K_t^A = \frac{1-\delta}{1+g} K_t^A + I^A$. Solving for adaptation capital, generates $K_t^A = \frac{1+g}{g+\delta} I^A$. If the expected value of gross damages is invested into adaptation each year then $I^A = \overline{GD}$ and K^{Amax} is equal to

$$K^{Amax} = \frac{1 + g}{g + \delta} \overline{GD}.$$

Not all adaptation capital projects will offer the same level of protection per unit of adaptation capital. To account for this, the per unit effectiveness or amount of protection (P) derived from successive adaptation capital projects is assumed to decline with additional projects (Bosello et al., 2010; de Bruin, Dellink, & Tol, 2009; Millner & Dietz, 2015). The amount of protection (P) from a given level of adaptation capital K^A can then be expressed as a function of the ratio of actual investment K^A and the maximum adaptation capital stock,

$$P = \left(\gamma_1 \frac{K^A}{K^{Amax}} \right)^{\gamma_2},$$

where $0 < \gamma_2 < 1$ is a parameter that indicates the extent of diminishing returns to protection. $\gamma_2 = 1$ implies that the marginal protection from a one dollar of adaptation capital is constant and equal to γ_1 . γ_1 reflects the effectiveness of adaptive capital. If γ_1 equals one and $K^A = K^{Amax}$ protection would offset damages ($P = 1$) and equal to the expected value of damages. If $\gamma_1 < 1$ then average return to a dollar of investment is less than one and even if adaptation investments were equal to the expected damage from hurricanes, protection would be incomplete.

Residual hurricane damage, RD , is determined by the product of gross damage (GD) and one less the level of protection,

$$RD = (1 - P)GD.$$

An economy without adaptation capital ($P = 0$) will be affected by the full force of the hurricanes. Any country that achieves a protection level of one would experience zero damages from a hurricane (assuming $\gamma_1 = 1$).

The amount of investments α is a policy choice of the government. If \overline{GD} is the average hurricane damage per year, then we can expect the government to set $\alpha Y \leq \overline{GD}$, otherwise the economy would expend more resources on adaptation investments than actual expected hurricane damage.

Accounting equations

The investment into adaptation capital needs to be considered in the calculation of GDP and government expenses. The standard GDP and government spending identities are modified to account for spending on adaptation capital as follows:

$$Y = C^P + C^G + I + I^A + \Delta Stock + X - M + Disc,$$

$$G^{tot} = G^{GN} + G^{Int} + G^K + G^{oth} + I^A,$$

where C^P is private consumption, C^G is government consumption, I is investment in productive capital, I^A is investment in adaptation capital, $\Delta Stock$ is the change in stock, X is export, M is import, $Disc$ is the statistical discrepancy, G^{tot} is total government spending, G^{GN} is government spending on goods and services, G^{Int} is government spending on interest, G^K is government capital expenditure and G^{oth} is other government expenditure.

3.2. Insurance purchased from an insurance company

An insurance contract is actuarially fair if the premia paid are equal to the expected value of the compensation received. Given the design of the hurricane shocks above, the actuarially fair premium is simply \overline{GD} . If the insurance company takes a mark-up μ^I on top to finance its operation and allows for partial insurance cover $\theta \in [0,1]$ the insurance premium A^I can be expressed as:

$$A^I = \theta(1 + \mu^I)\overline{GD}.$$

The insurance payout B^I is given by the insurance cover and the actual damage in that year,

$$B_t^I = \theta GD_t.$$

Historically, hurricane damage is zero in most years so that the insurance payout will also be zero in most cases.

Typically, the insurance premium μ^I depends on the variance of the insured events. Equation 4.2 in (Gray & Pitts, 2012) specifies a commonly used functional form

$$A^I = \theta * (\overline{D} + \beta * SD(GD)),$$

where \overline{GD} are expected damages, $SD(GD)$ is the standard deviation of damages and β is a parameter. From this, the markup can be derived as

$$\mu^I = \beta \frac{SD(GD)}{\overline{GD}}.$$

\overline{GD} and $SD(GD)$ are drawn from the empirical distribution of hurricane events of (World Bank, 2018) and the mark-up is an increasing function of the variance parameter β .

3.3. A contingency fund

A contingency fund is a separate account administered by the national government for the purpose of having funds available for immediate use after a hurricane disaster. The fund is assumed to receive regular payments from the government. If a share θ of hurricane damage is to be covered by the contingency fund, the regular payment must be

$$A^C = \theta(1 + \mu^C)\overline{GD}.$$

Since the government administers the fund itself, the administration cost μ^C should be lower than the markup paid to the insurer (although poor investment decisions or inappropriate use of the fund could increase the effective markup). Assuming that the contingency fund earns an interest rate of i^C , the fund volume V can be calculated recursively as

$$V_t = (1 + i^C)V_{t-1} + \theta \overline{GD} - B_{t-1}^C.$$

Distinct from an insurance scheme, the payout of the contingency fund in the case of a hurricane disaster is limited by the volume of the fund,

$$B_t^C = \min(V_t, \theta GD_t).$$

As a result, if a large disaster strikes shortly after the inception of the contingency fund (or two shocks that occur quickly after one another) the (second) event might not be fully covered. Over the long run, however, if the average of the damage was calculated correctly, the contingency fund should be sufficient to finance recovery from a disaster.

3.4. Creating additional fiscal space

A third option for ensuring that finance is available following a hurricane is to engage in an anticipated reduction of debt for example via a reduction in expenditures, to create sufficient fiscal space so that the authorities can rapidly issue additional fiscal debt to finance disaster recovery. A share θ of expected damages, would require an annual additional deficit reduction of

$$A^D = \theta \overline{GD}.$$

Creating fiscal space does not require any additional costs beyond the already existing cost of debt management. Our simulations do not consider creating fiscal space via higher future taxes. There are no specific administration costs as in the other forms of finance. There is no explicit insurance payout in this case, but the fiscal space created allows a share θ of damages to be paid rapidly through the emission of additional debt without increasing debt levels relative to what they would have been under one of the other financing schemes. Importantly, it is assumed with this financing scheme that additional debt can be immediately undertaken (or as quickly as with the other two payments schemes). It is important to note that we are not modeling immediate debt buy-back strategies. The cost of buying back debt may include a premium to compensate bond holders who wished to hold onto bonds until maturity.

A potentially important benefit from this approach arises if the interest rate paid on government debt is positively related to the debt/GDP ratio. In such instances, the additional fiscal space reduces debt levels in the period before hurricanes, lowering the debt to GDP ratio and reducing interest rates, which reduces debt financing costs allowing for additional debt reduction or the financing of other government priorities.

4. Modeling the government choices

Putting in place a hurricane risk management system, independent of which scheme, requires that the government allocate funds for its maintenance (to finance adaptive investment, pay insurance fees, feed the contingency fund or create fiscal space by paying down debt. Simply put, the government can either reduce program (consumption) spending, reduce transfers or subsidies, reduce capital expenditure (investment) or it can take on debt. Similarly, funds disbursed can be spent on capital restoration, goods and services or transfers. Macroeconomically, which approach is taken (including mixtures of them) matters.

4.1. The fiscal rule

In all five modeled scenarios (the business as usual baseline, adaptation investments, insurance, contingency fund, and enhanced fiscal space scenarios) the government is assumed to follow a fiscal rule, best summarized as Jamaica's long-term objective of reducing the debt-to-GDP ratio to 60% and stabilizing it at that level. In 2017 debt was 112% of GDP, and subsequently reduced below 100% of GDP in 2018/19 due to steep consolidation efforts. For Jamaica, this implicitly means that the financing of risk management strategies will have to come through reduced spending on transfers, or capital and consumption goods, as financing from debt would violate the fiscal rule.

The fiscal reaction function introduced here modifies the standard MFMod spending equations by setting

$$G_t^i = \varphi G_{t-1}^i + (1 - \varphi) * g_{2017}^i * (1 - d^*) * (Rev_t - (r_t * E_{t-1}) - B_t) - fin^i * A_t + exp^i * B_t^E,$$

where:

- G_t^i is government spending on category i ,
- $g_{2017}^i = \frac{G_{2017}^i}{G_{2017} - r_{2017} * E_{2016}}$ is the share of category i in total non-interest expenditure,
- d^* is the targeted government deficit,
- B_t is the payout from either insurance, the contingency fund or debt repayment,
- fin^i is the share of disaster risk management financing spent on category i ,
- A_t is the investment into disaster risk management,
- exp^i is the share of the disaster risk management payout going into spending on category i and
- B_t^E is the payout used for investment in the year t .

The government spending categories explicitly considered in the model are investment, consumption and "other" (which includes transfers). The first term in the fiscal rule φG_{t-1}^i is a lagged dependent variable where φ is the persistence parameter. $\varphi > 0$ implies that there is persistence in spending and that spending levels adjust slowly. The second term, $(1 - \varphi) * g_{2017}^i * (1 - d^*) * (Rev_t - (r_t * E_{t-1}) - B_t)$, is the core of the fiscal rule. It represents the recurring revenues after debt servicing ($r_t * E_{t-1}$) that are available for spending. B_t represents payouts from disaster finance schemes are excluded from recurring revenues as spending from this revenue sources are dealt with below.

The term $(1 - d^*)$ allows expenditure to exceed revenue by a small amount, defined by the targeted annual deficit.⁶ g_{2017}^i ensures that the spending composition of future budgets is roughly aligned to the historical composition. The third term, $fin^i * A_t$ represents the share of total disaster risk financing to be paid for by reduced spending on category i and is the opportunity cost of risk management schemes.

⁶ Note, if the government strictly adheres to a budget deficit of d^* , its debt will converge to a fixed debt-to-GDP ratio that may not be equal to the debt target of 60% of GDP, see Appendix C.2.

The fourth term, $exp^i * B_t^E$, is the share of disaster payouts spent in year t on category i . In this formulation, the total disaster risk payout need not be paid out in one year, thus $\sum_{t=0}^T B_t^E = B_t$ is the total payout equal to the sum of partial payments made over T years. Finally, the spending and finance shares must sum to one $\sum_i fin^i = 1$ and $\sum_i exp^i = 1$.

As modeled, the expenditure adjustment shares are set equal to the share of each observed in 2017. As a result, in the absence of risk management spending, in the steady state spending shares will be constant at those 2017 rates. The term $fin^i A_t$ determines from what categories of expenditure risk management strategies are paid and in what proportion. To the extent these shares differ from g_{2017}^i the steady state expenditure shares deviate from g_{2017}^i .

4.2. Risk premium in government debt

To reflect increased risk at higher interest rates, the interest paid on government debt is assumed to rise with the debt-to-GDP ratio in the previous year,

$$r_t^E = r^* + 0.02 * \left(\frac{Dbt_{t-1}}{Y_{t-1}} * 100 - 60 \right),$$

where r_t^E is the government interest rate, r^* is the estimated interest rate at a 60 percent Debt to GDP ratio, Dbt_t is the government debt and Y_t is GDP. r^* is estimated based on historical data for Jamaica.

Governments have debt contracts with contractually agreed interest rates. To approximate the yield curve, we calibrate the average interest rate on debt using a lag structure. The weights are roughly based on data on the actual debt maturity structure in Jamaica. Thus, the effective interest rate paid on all debt in a given year is calculated as a weighted average of the rates agreed in the previous four years,

$$\overline{r_t^{DBt}} = 0.1 * r_t^{DBt} + 0.1 * r_{t-1}^{DBt} + 0.15 * r_{t-2}^{DBt} + 0.2 * r_{t-3}^{DBt} + 0.45 * r_{t-4}^{DBt}.$$

4.3. Financing risk management

All four approaches to risk management require resources to be allocated by the government in advance of a hurricane, be it as adaptation investments, insurance premia, payments to the contingency fund or faster debt repayments. Each risk management strategy has its own strengths and weaknesses. Common to each of them, however, is the need to mobilize resources to make the *ex-ante* payments.

A first option for mobilizing additional resources is to raise additional debt. Appendix C.2 illustrates how this would affect the long run debt level. However, countries in the Caribbean are already at or near the limit of sustainable debt. Jamaica follows a fiscal rule that puts an upper limit on debt of 60% of GDP. Jamaica has made significant progress in reducing debt. Debt in 2013 equaled 135.9 percent of GDP and has been reduced to below 100 percent in 2019, the lowest level in nearly two decades. While good progress has been made, the country will require additional consolidation efforts to reduce debt below the 60 percent to GDP mark. In addition to the cost involved in increasing the interest rate on debt, many countries are unable to issue additional debt because financial markets are not willing to accept the debt. A second option is to increase government revenue, by increasing taxes. The final option, and the one pursued in this paper, is to reduce government spending. We acknowledge the challenges in reducing government expenditures given committed spending on social protection, education and health care. That choice is motivated by the already high debt levels faced by Jamaica, and the political

and practical challenges implied by raising taxes in a country where revenue mobilization is historically challenging (Small, 2016).

Government spending can be reallocated by decreasing either government investment or government consumption. Reducing government investment in order to finance adaptation or insurance is, however, a self-contradictory approach. The objective of adaptation and insurance is to avoid the loss of capital (or to rebuild it quickly) after a disaster. If the preparation for the disaster consists of accumulating less capital, the policy will not achieve a higher level of capital compared to the situation where the government takes no risk management measures at all. The government would only achieve an intertemporal shift of resources. Thus, the reduction of government consumption seems the only logical option in terms of reallocation of resources to finance adaptation or insurance. However, government consumption includes spending on education, public security, the military, the judiciary and other institutions as well as social security. It is thus not possible to reduce government consumption without a loss of welfare (to the extent that these items contribute to welfare) and GDP. Appendix D presents a possible approach to take into account the welfare loss of reduced government consumption – recognizing that there is no consensus on how to measure welfare (Fleurbay, 2009).

Most of the simulations assume that risk management strategies will be financed by a reduction in government investment (50%) and a reduction in government consumption (50%) given that a government might be constrained by the political economy or budgetary rigidities to reduce government consumption to finance risk management strategies. However, simulations are also run under the assumption of risk management strategies exclusively financed by a reduction in government investment to assess the impact of a scenario in which the government is unable to reduce consumption.

4.4. The government use of disaster-related finance

A similar government choice needs to be made for the use of the payouts received from an insurance or contingency fund. Payouts enter the government accounts immediately after a disaster. The standard equations in MFMod, including those for government expenditure, are calibrated and estimated using historical data. If the payout were simply added as a government revenue, this estimated use of revenue would determine the use of payouts as well. This is not likely to be a realistic model for the use of disaster payouts.

In principle, it would be possible to estimate the government reaction in terms of expenditure categories empirically from post-disaster data. However, there is insufficient historical data on hurricanes to allow an estimation of the reaction function. For the purposes of the simulations conducted here, the estimated government behavior is overridden for the treatment of payouts and a specific model reaction to an insurance payout is specified. As modeled, post-disaster payout is assumed to be spent only on rebuilding destroyed infrastructure – consistent with the financing assumption.

Since a payout from an insurance or contingency fund is likely to exceed the reconstruction capacity of a country after a large disaster, the rebuilding is assumed to take five years to complete. Alternative spending rules were examined to test the sensitivity of results to this assumption.

5. Calibration

With the basic structure of the model specified, model behavior will depend importantly on the values of certain key parameters. As with the standard MMod model the majority of parameters are estimated econometrically either on Jamaican data or in the cases where not enough data exists are imposed using results from the literature or cross-country regressions (Burns & Jooste, 2019). A similar approach is followed for this model, but with the added complication that many of the parameters are unobservable. Below is a brief description of the rationale for the default parameter values chosen. Results from sensitivity analyses for alternative choices are presented in Figure 5 and Figure 12.

5.1. Protection and adaptation capital

The actual effectiveness of adaptation capital is not well understood. Measuring it historically, would require knowing how much of a country's capital is dedicated to adaptation and by how much this reduced damages that would have occurred in the absence of adaptation. One estimate (Multihazard Mitigation Council, 2018) suggests that the benefit-cost rate of hurricane adaptation is 10:1 at existing levels of adaptation investment. Importantly, this would not translate into a $\gamma_1 = 10$ unless adaptation investments equaled the expected value of hurricane damages (which is unlikely to be the case).

The literature discussed in Appendix B is somewhat vague in describing its calibration methods. Nevertheless, this work follows De Bruin et al (2009) in setting the curvature parameter of the protection function, γ_2 , to 0.3 (close to the inverse of their parameter of 3.6). The effectiveness parameter is set to $\gamma_1 = 1$, implying that if an amount equal to the expected value of hurricane damages were invested each year in adaptation, the productive capital stock would be protected from hurricanes.

5.2. Insurance

Premia for natural disaster insurance can vary widely, with empirical estimates rising as high 700% percent (Froot, 2001). Disaster insurance markups tend to be higher than those in other insurance policies, because the rare and large payouts required for natural disasters are much more difficult to handle for insurance companies. Some authors have used mark-ups in the range of 50-100% (Lemoine de Forges, Bibas, & Hallegatte, 2011), while the markup for insurance assumed in World Bank (2017) was 50%.

This paper uses the insurance mark-up formula discussed earlier, calculating it on the discrete cumulative distribution function for climate damages in Jamaica (World Bank, 2018). This data implies a mean damage of $\bar{D} = 165$ million USD or 1.15% of GDP and a standard deviation of $SD(D) = 672$ million. Using this information in the markup equation and using an industry average weight for $\beta = 0.15$, gives an insurance markup $\mu^I = \beta \frac{SD(D)}{\bar{D}} = 0.61$, which is the value used in this paper.

5.3. Contingency fund

The mark up on the contingency fund is assumed to be zero ($\mu^C = 0$) and its return relatively low $i^C = 0.02$. This implies that a contingency fund would require only negligible administrative cost and that it would earn a 2% nominal interest rate on the fund volume (assuming that the fund would be invested in liquid investments, e.g. money market funds, that earn a lower rate of return). Note that the relative performance of the different policies depends critically on the assumptions on cost. With a markup of 0, the low 2% return can also be interpreted as the net return. If administrative costs were higher, say 1 or 2 percent, then the current assumptions would be equivalent to a 3 or 4 percent return on investments.

6. Simulations

In order to investigate the broader economic costs and benefits of alternative disaster relief strategies, five sets of scenarios were run. The first scenario represents a business as usual (BAU) scenario – where no additional risk management is done beyond what has been done historically. In the second scenario investments are made in adaptation capital. In the third scenario, insurance is purchased from a firm or consortium outside of Jamaica. In the fourth scenario, a contingency fund is established. In the fifth scenario, domestic savings are increased and used to reduce government debt and to create sufficient fiscal space to allow the government to react promptly to a hurricane – without need to use other measures.

To facilitate identification of transmission channels and impacts, each scenario was first run with a deterministic shock once every 10 years. The value of the shock was set to ten times the average annual hurricane damage. Scenarios were run with different levels of spending running from 20 percent of the expected value of damages to 100 percent. Finally, a probability distribution of outcomes was generated by running thousands of simulations for each set of scenarios, where the incidence of hurricanes in each year was drawn from the existing probability distribution.

6.1. Deterministic shocks in the adaptation scenario

Figure 1 illustrates the effect of adaptation, comparing results for some key economic variables for different levels of adaptation investment running from 0% of the expected value of damages (the BAU scenario) to 100% of the expected value of damages. Outcomes are presented for GDP, potential GDP, household consumption and the public debt to GDP ratio. In each case, outputs are expressed as a percent deviation from a baseline of a hypothetical version of the Jamaican economy that does not have hurricanes. The exception is the debt to GDP ratio, which is presented as a percentage point change in the ratio.

The 0% line in Figure 1 shows the economic outcomes that can be expected if no adaptation (and no other disaster relief) is enacted. Deviations from this line thus show the economic responses capital being destroyed once every ten years equivalent to 11.5% of GDP. In this scenario, GDP is 1.25% percent lower in 2030 than it would have been if the economy had endured no hurricanes. The 20, 40, 60, 80% lines illustrate the impact on the economy, when adaptation spending was set equal 20, 40, 60 and 80% of the annual expected damages from hurricanes (1.15% of GDP). GDP is still lower in all these scenarios when compared to the no hurricane scenario. GDP losses are smaller in the case of 20% adaptation than in the 0% scenario, are about equal in the 40% scenario. In the scenarios where spending on adaptation exceeds 40% of the expected hurricane damages, GDP losses are higher – although the path of all economic variables is smoother.

GDP outcomes decline as expenditure on adaptation rises for two reasons. Most importantly there is an opportunity cost associated with the investment. With the fiscal rule forcing the government deficit to remain unchanged, the government is forced to reduce spending on other items (productive investment, consumption and transfers – in this scenario all the reduction is imposed on productive investment) to pay for the investment in adaptation capital. To the extent that productive investment is crowded out, the potential output of the economy declines (Panel 2 of Figure 1). This negative effect is counter-balanced by reduced losses of physical capital from hurricanes, which is most easily observed in the attenuation of the post-hurricane economic cycles at higher levels of adaptation investment.

At low rates of adaptation investment, the benefits of adaptation investment outweigh the opportunity costs coming from reduced government productive investment and other spending. However, as spending levels rise, the average benefit from adaptation declines due to the concave protection function, which means that the return on investment in adaptation capital declines at higher levels of investment. The extent of the decline in efficacy depends on the calibration of the protection function. In the presented simulations at 20% of expected losses adaptation reduces GDP losses, while also reducing volatility. At 40 percent the GDP effect mainly disappears as the second 20% of investments in adaptation capital are much less protective than the first and the crowding out of productive investment becomes a dominant effect on GDP. For investment rates higher than 40% of expected losses the crowding effect dominates, and GDP effects are actually worse than in the no investment 0% scenario. Different assumptions regarding the curvature of the protection function and the efficacy of adaptation capital would yield different crossover points (see Appendix E). Whether these results are welfare reducing will depend on the importance consumers attach to the smoother profile of GDP in the high adaptation investment scenarios.

Comparison across different amounts of disaster management investment

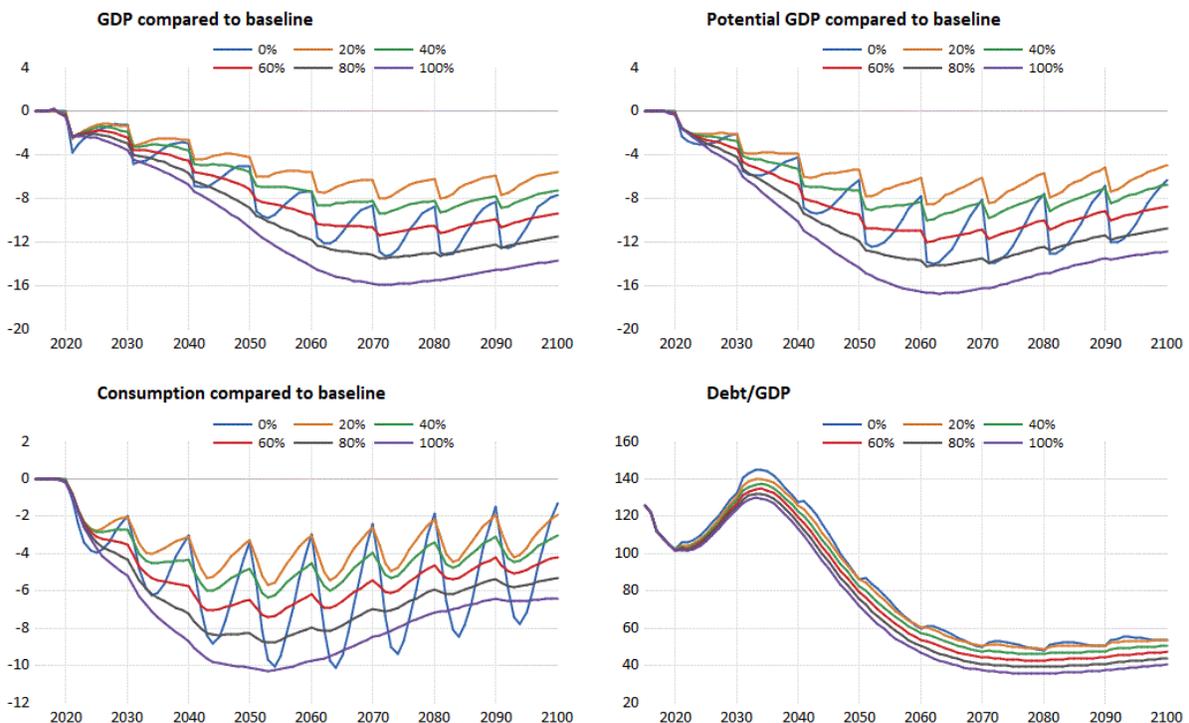


Figure 1: The effect of adaptation on key economic variables. Percentages are given relative to average hurricane damage

In all the above scenarios, the effectiveness of adaptation investment (the γ_1 parameter) is assumed to be one, implying that when spending equals the expected value of capital destruction a 1\$ expenditure on adaptation generates a 1\$ reduction in capital loss. Figure 12 in the Appendix E shows a variant of Figure 1 with $\gamma_1 = 0.5$. The reduced effectiveness of adaptation investment reduces the improvement

of a given level of adaptation investment, moving the cross-over point at which additional adaptation investment no longer reduces GDP losses as compared with no policy from above 40% of the expected value of hurricane losses to 60% because the level of protection is lower. In addition, the cycle damping effect is reduced.

6.2. Comparison of all options with deterministic shocks

Figure 2 compares results, setting spending on risk management strategies at 100% of expected damages in each of the five policies (BAU; adaptation investment, insurance, contingency fund and fiscal space creation) in turn. In Figure 2, the cost sharing is split between government consumption and investments equally.

The most important result is that all risk management strategies achieves a level of income and consumption which is permanently higher than the case without risk management. Without fiscal resilience instruments, the hurricane inflicts serious damages in terms of the short term but more importantly in the long term, pushing down the potential output. These results points to the importance of looking at the long-term benefits of fiscal resilience against the actual costs of natural disasters which are becoming more frequent and cyclical rather than comparing the cost of fiscal resilience against a baseline with no shocks.

The contingency fund and insurance scenarios show a similar pattern. This reflects the very similar mathematics of the two options, with the only difference being that the administrative costs of the contingency fund are lower than the markup of the insurance scheme. The fiscal-space-creation scheme generates better results because lower debt levels reduce the interest rate paid on debt, and therefore reduces the debt level in the periods between hurricanes. The lower debt level reduces debt payments and the amount by which productive investment must be reduced to pay for the increased fiscal space. In addition, lower debt payments reduce the interest rate further, reducing interest payments on the debt and the opportunity cost associated with the policy. Over time these lower interest payments mean the opportunity cost of the program (lower government spending and investment) is also reduced. These risk management strategies do also achieve a smoother path of consumption, with adaptation achieving the best results in this regard.

Comparison of different types of disaster management investments

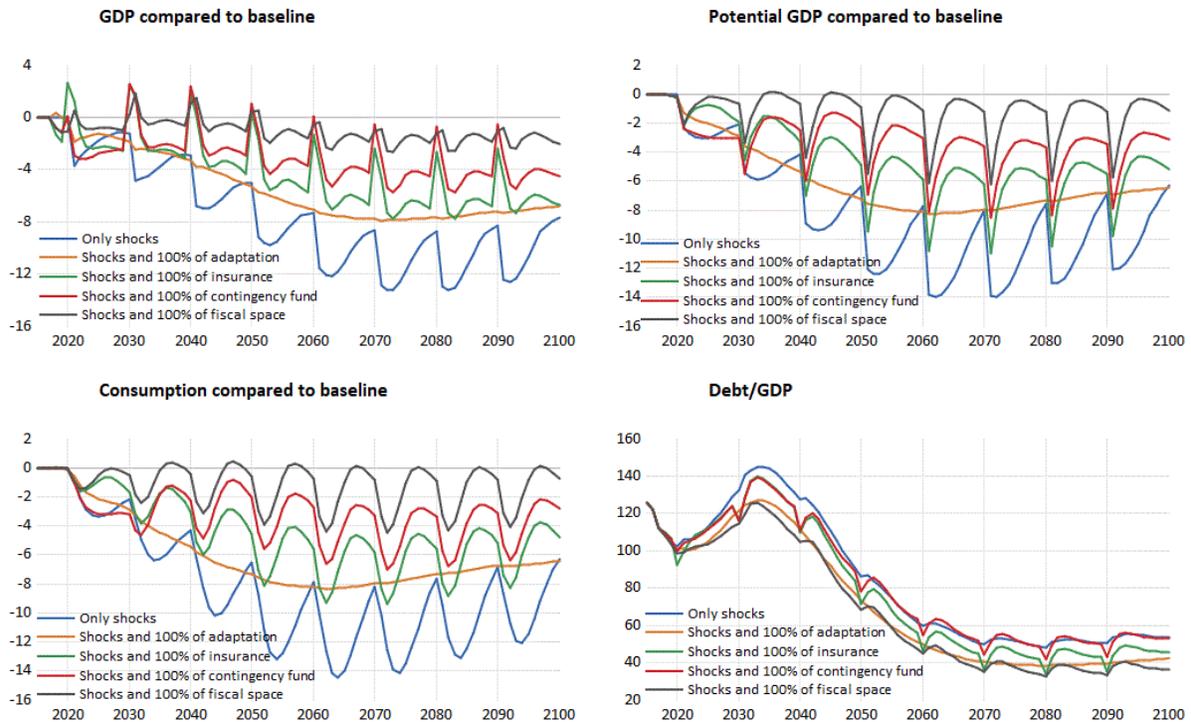


Figure 2: Comparison of adaptation, insurance, a contingency fund and fiscal consolidation to the case without any form of hurricane risk management. Financed by a reduction in government investment (50%) and a reduction in government consumption (50%).

Figure 3 illustrates the effect of reducing government consumption within the model. The figure shows the sum of private and government consumption compared to the baseline. Initially the impact on total consumption is larger than in Figure 5 when all the cost of risk mitigation is paid by investment. However, over time total consumption rises (impacts become less negative) because of the GDP boosting effect of higher productive investment in these scenarios vs. those of Figure 5. Appendix D discusses a more sophisticated approach to aggregate private and government consumption.

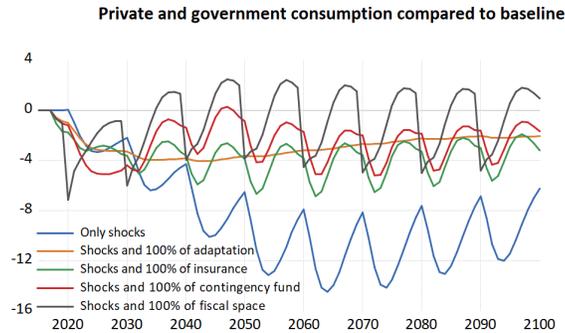


Figure 3: The sum of private and government consumption compared to the baseline

Figure 4 reports results from the scenarios as in Figure 2, except in this instance the government reaction function concerning the financing of risk reduction is changed. In this scenario, all of the costs of financing for disaster relief were paid for by reduced government investment in productive capital $fin^{invest} = 1$. This results in a higher real GDP effect, because the crowding out of productive investment is more intense, but government consumption is higher than in the scenarios reported in Figure 2— and to the extent that government programs contribute to household utility, it too will be higher.

The most important result is that none of the risk management strategies achieves a level of income and consumption which is clearly permanently higher than the case without risk management. While the hurricane inflicts serious damages, the economy can however recover quickly, because it is not burdened by the regular payments for adaptation or insurance. This points out to the importance on how to finance fiscal resilience and simply switching from traditional investments to adaptation investments will not provide long term payoffs.

Comparison of different types of disaster management investments

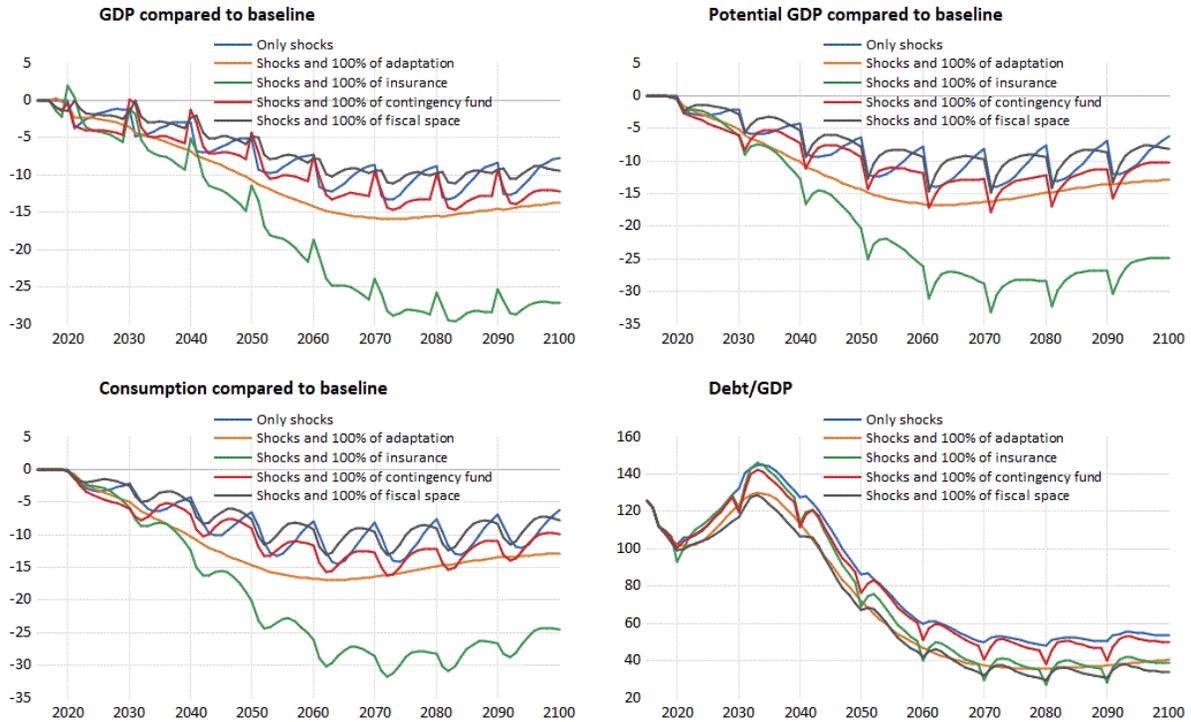


Figure 4: Comparison of adaptation, insurance, a contingency fund and debt repayment to the case without any form of hurricane risk management. Financed by a reduction in government investment.

Table 1 reports summary results from running deterministic scenarios on all four risk management strategies at different levels of spending. For spending levels less than 40 percent of expected losses adaptation investment generates lower GDP losses and reduced volatility. While at higher expenditure levels, the various financing schemes do better. According to this metric, the negative GDP effects for all schemes derive from the same mechanism (crowding out of productive investment). In the long run the more expensive schemes (insurance and the contingency fund) fare worse than both fiscal space creation and adaptation investment at low levels of spending. At higher levels of spending adaptation investment is less competitive and fiscal space creation generates the best output performance. Because of the linear sensitivity of output to financing schemes (as opposed to the non-linear effect of additional adaptation investment), the ranking of the financing schemes across spending scenarios at different periods of time is broadly the same. Over time, the relative benefits of the fiscal reduction scheme tend to increase because of the lower interest rate effect discussed above.

Table 1: Comparison of GDP losses (compared to the no-hurricane baseline) in different scenarios

Year	2035				2055				
	Coverage	20%	40%	60%	100%	20%	40%	60%	100%
BAU		-3.77	-3.77	-3.77	-3.77	-9.00	-9.00	-9.00	-9.00

Adaptation	-2.49	-3.05	-3.73	-5.25	-5.58	-6.95	-8.68	-12.65
Insurance	-4.42	-5.07	-5.75	-7.35	-10.39	-11.86	-13.44	-18.55
Contingency	-3.91	-4.05	-4.20	-4.84	-9.22	-9.45	-9.68	-10.09
Fiscal space	-3.55	-3.35	-3.16	-2.83	-8.59	-8.23	-7.90	-7.37

At spending levels of 20 and 40 percent of expected damages, the adaptation expenditure strategy yields the smallest GDP and consumption losses, while also reducing the variability of incomes, which would translate into a further welfare gain if consumers value certainty. At levels of spending above 40 percent the financing strategies do better. The fiscal-space creation strategy tends to do better than the insurance or contingency fund strategies.

The better performance of the fiscal consolidation strategy derives from two main factors, the fact that the funds made available are not subject to a markup or administrative cost like the funds made available through the insurance or contingency fund, and because of the fall in the interest rate on debt frees up additional funds for productive investment, lifting potential output as compared with the other scenarios.

Importantly, at levels of spending in excess of 40% of the expected value of damages, all output and consumption in all risk management strategies is lower than in the no risk management scenario. The risk management strategies do achieve a smoother path of consumption, because of the availability of finance for repair or protection from investments in adaptation. The consumption smoothing can be expected to have positive implications for welfare.

6.3. Parameter sensitivity of the adaptation function

As mentioned in Section 5.1, the value of $\gamma_2 = 0.3$ is based on similar numbers in the literature, but ones that lack strong empirical foundation. Figure 5 shows a variant of Figure 1 with $\gamma_2 = 0.15$ conducted as a robustness check. With this parameter, the speed with which returns to adaptation investment decline is reduced. For a given average effectiveness, the relative effectiveness of low levels of adaptation spending is reduced but the effectiveness of higher levels is increased. As a result, the cross-over point where adaptation no longer produces better results than the financing issue moves from 40 percent of expected losses to 60% of expected losses. A higher level for γ_2 (0.5 for example) would imply much more bang for the buck from initial adaptation investments and a lower level of spending for the crossover point.

Comparison across different amounts of disaster management investment

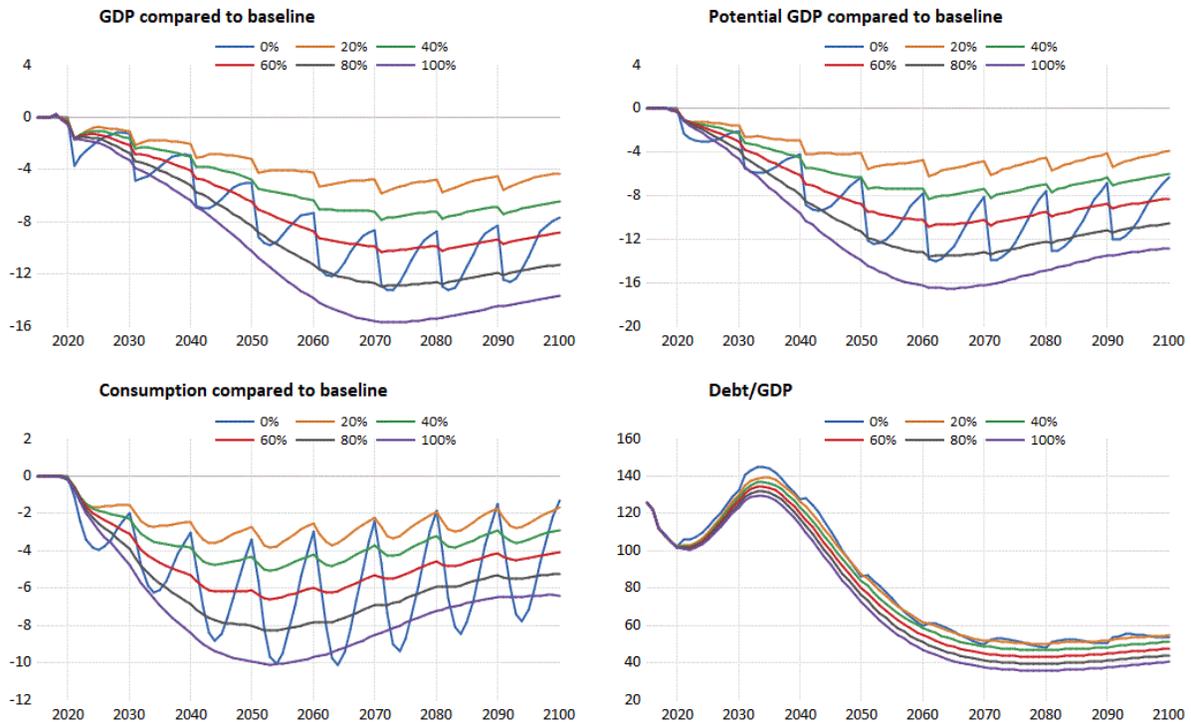


Figure 5: Comparison of different adaptation levels with a value of $\gamma_2 = 0.15$ in the protection function

6.4. Probabilistic shocks

The preceding section outlines model results under an artificial set of assumptions where hurricanes occur at regular intervals. This helps visualize the effects of different interventions and to identify major transmission channels that shape those results. However, the simulations are fundamentally unrealistic. Hurricanes do not arrive on a regular schedule. They can and do arrive irregularly, sometimes one right after another. If damages from an earlier hurricane have not been fully repaired, a second hurricane in quick succession can increase the damage more than linearly.

To investigate the implications that a more realistic modeling of the timing (and strength) of hurricanes, a series of stochastic simulations were performed by drawing damage values for each year from an empirical distribution based on the history of damages in Jamaica. The reported scenarios assume annual risk management expenditures equal to 100% of the expected value of damages (the same 1.15% of GDP as used in the deterministic scenarios), financed from reducing government productive investments. In order to get a sense of the underlying probability distribution, each scenario was run 999 times drawing randomly from an empirical distribution of hurricane damages.

Figure 6 reports the cumulative distribution function of annual hurricane capital damages for Jamaica (World Bank, 2018) with damages expressed as a percent of GDP. The raw data is shown in blue, and a function fitted to the data is shown in grey. The figure indicates that there is a 43% probability every

year that damages will be zero and a 97% probability that damages will be below 10% of GDP. The isolated point at the top indicates that there is a 0.0003% probability that damages will be 91% of GDP or higher. The hurricane damages used in the simulations were drawn from the grey fitted line, because a functional relationship is much more computationally efficient than drawing damage events from the discrete data.

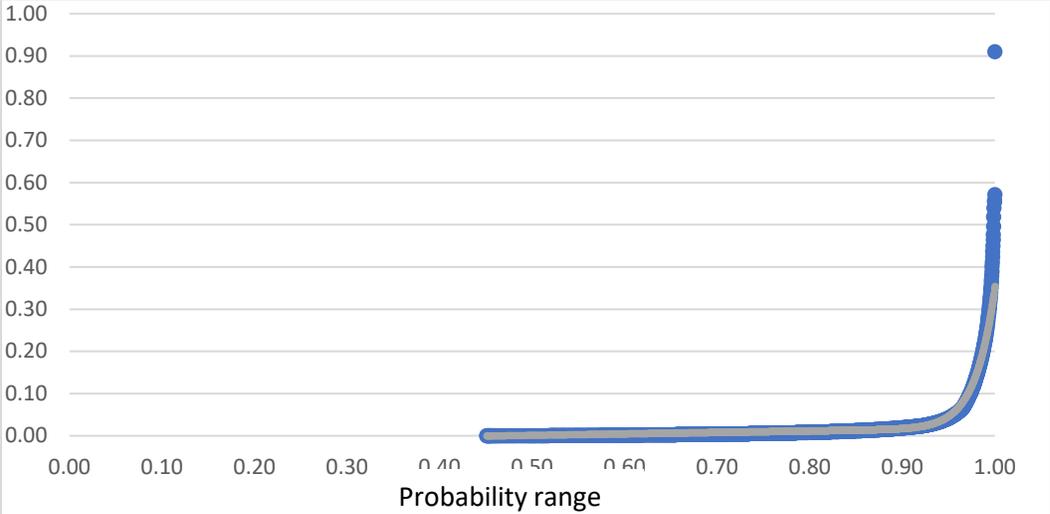


Figure 6: Probability of hurricane damage in Jamaica: actual data (blue dots) and fitted equation (grey line). Source: (World Bank, 2018).

Figure 7 presents the outcomes of these stochastic simulations under probabilistic hurricane shocks with insurance as the disaster risk financing strategy. The dark blue line represents the median result, and the 25th to 75th percentiles boundaries are the edge of the dark blue area, while the 10th to 90th percentiles boundaries are shown by the edge of the light blue area.

As with the deterministic scenarios, Figure 7 illustrates that GDP, potential GDP and consumption would be lower under a scenario with hurricanes than under a scenario without. While individual hurricane shocks are softened by insurance payouts, the opportunity cost of foregone productive investment required to pay insurance premia reduces potential output and, with it, GDP and consumption. Importantly, the GDP impacts are larger than the consumption impacts, reflecting the use of lower productive investment to pay for hurricane financing. Note also that GDP impacts are skewed to the high side, while consumption effects are skewed to the downside. In both cases the bulk of scenario outturns fall within a relatively narrow range.

Fans charts of probabilistic hurricane events

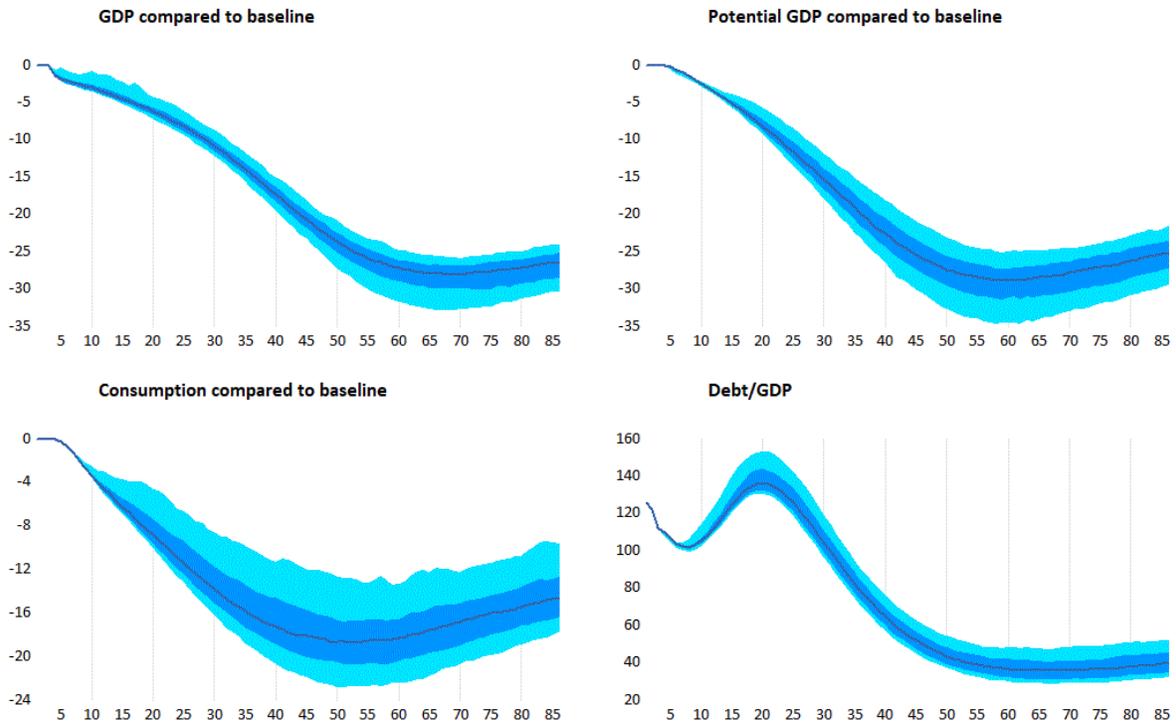


Figure 7: Median value and percentile ranges for model runs with probabilistic shocks for the case of insurance. The risk management is financed by a reduction in government investment in this graph.

Figure 8 illustrates the fan chart results for GDP outcomes for the same five scenarios illustrated in the first panel of Figure 7. As is the case with the deterministic scenarios the biggest GDP losses are associated with the insurance scenario, and the smallest losses with the fiscal space creation strategy. Under adaptation, the dispersion in GDP is much narrower because the damage from hurricanes is reduced by the protection.

The model is calibrated such that investing 100% of average hurricane damage into adaptation provides a 100% protection level against hurricanes. At first it appears surprising that there should be any dispersion in the adaptation case at all. However, 100% protection is reached only in steady state. In the first years the protection level has to be built up first, so that the protection level is initially below 100%. The capital destruction causes further disturbance. Even in the long run, economic growth means that adaptation capital is always a step behind full protection.

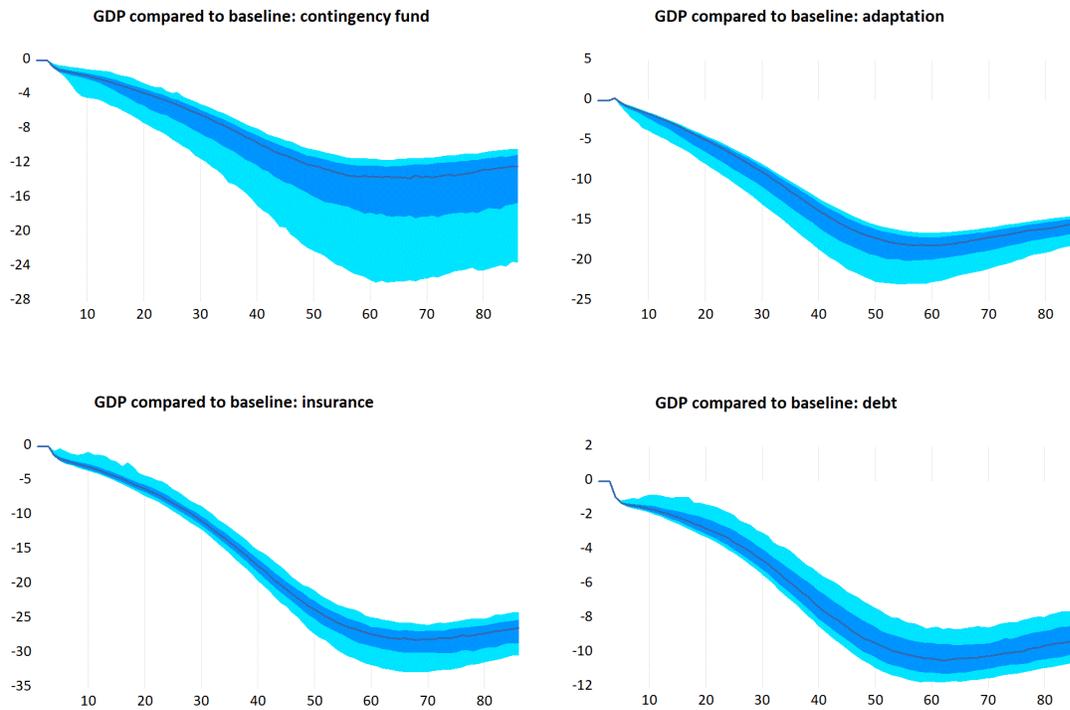


Figure 8: Comparison of fan charts of GDP losses for all four risk management options, for 100% coverage

Outcomes under the contingency fund show the widest variation. Indeed, the worst outcomes under the contingency fund are worse than the worst in the adaptation scenario. This reflects the possibility in the contingency scenario of a binding finance constraint. While once it has reached maturity, the average accumulated funds in the contingency fund should equal the average size of hurricane damages, if hurricanes follow quickly one after another or are unusually large, the fund could be exhausted. In such circumstances, delays in the replacement of damaged capital would extend the economic losses over a longer period allowing them to accumulate and potentially resulting in a much worse outcome. Under the insurance option, outcomes are lower, but the certainty of repayment means the dispersion is lower as well.

6.5. Comparison of probabilistic medians

The above discussion focused on the full distribution of results for the insurance scenario. Figure 9 below reports just the median results for a range of scenarios. Each of the medians appearing in Figure 9 was calculated from the results of 999 simulations reflecting independent draws from the hurricane damage distribution as described earlier.

The median results echo the results from the deterministic scenarios examined earlier. First, for low investment in adaptation of less than 40% of expected damages, the adaptation investment strategy is dominant. Second, at higher spending rates the fiscal space scenario tends to generate the smallest net declines. Third, the principal factor distinguishing the results from the insurance, contingency fund and fiscal space scenarios is the cost of the program (mark up or administrative costs). In the case of the fiscal space scenarios, the cost can be negative due to falling interest rates.

**Comparison of different types of disaster management investments
(100% coverage, policy financed 50% by investment, 50% by consumption)**

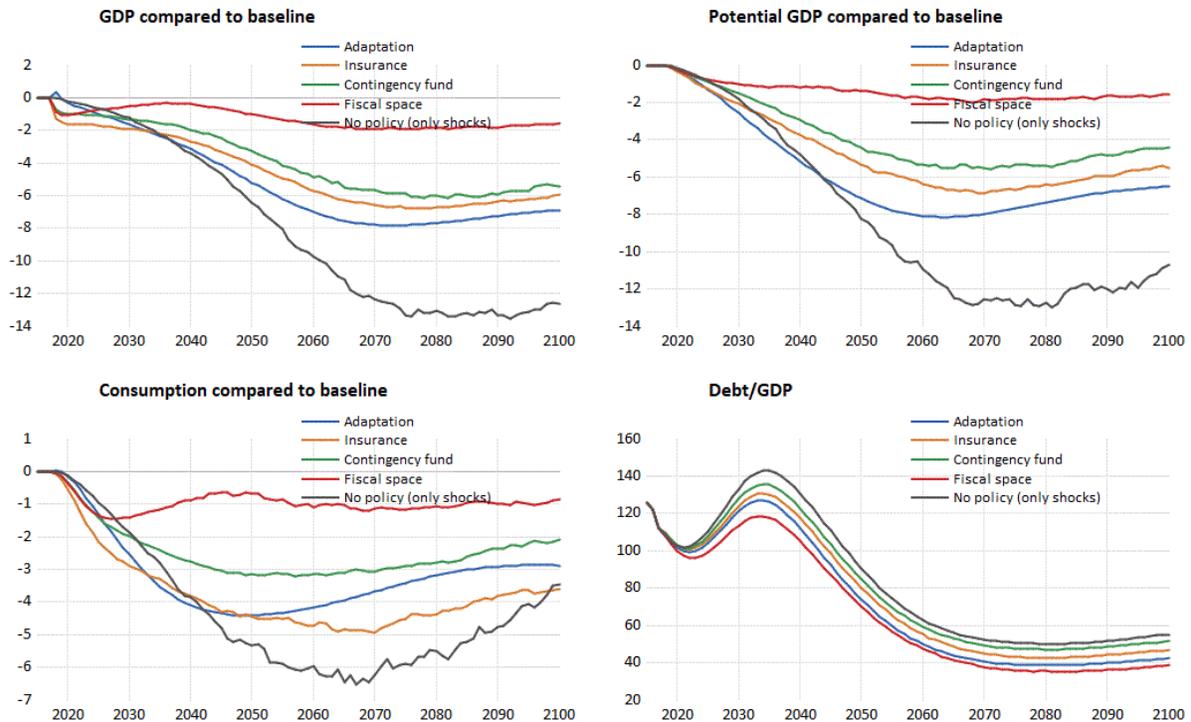


Figure 9: Comparison of the median values from different risk management scenarios. The risk management in this scenario is financed both by reducing government investment (50%) and government consumption (50%).

The median results echo the results from the deterministic scenarios examined earlier. First, for low investment in adaptation of less than 40% of expected damages, the adaptation investment strategy is dominant, see Figure 13. Second, at higher spending rates the fiscal space scenario tends to generate the smallest net declines. Third, the principal factor distinguishing the results from the insurance, contingency fund and fiscal space scenarios is the cost of the program (mark up or administrative costs). In the case of the fiscal space scenarios, the cost can be negative due to falling interest rates.

As in the case of the deterministic scenarios, the reduction of productive investments to finance risk management matters for the relative performance of the scenarios. Figure 9 shows the comparison of medians in the case where the government reduces both investment and consumption. In that scenario, GDP declines are smaller because less of the opportunity cost of the risk management strategy is borne by productive investment. However, better GDP cannot be interpreted as a higher welfare— especially if consumers garner some utility from government spending.

**Comparison of different types of disaster management investments
(100% coverage, policy financed 100% from investment)**

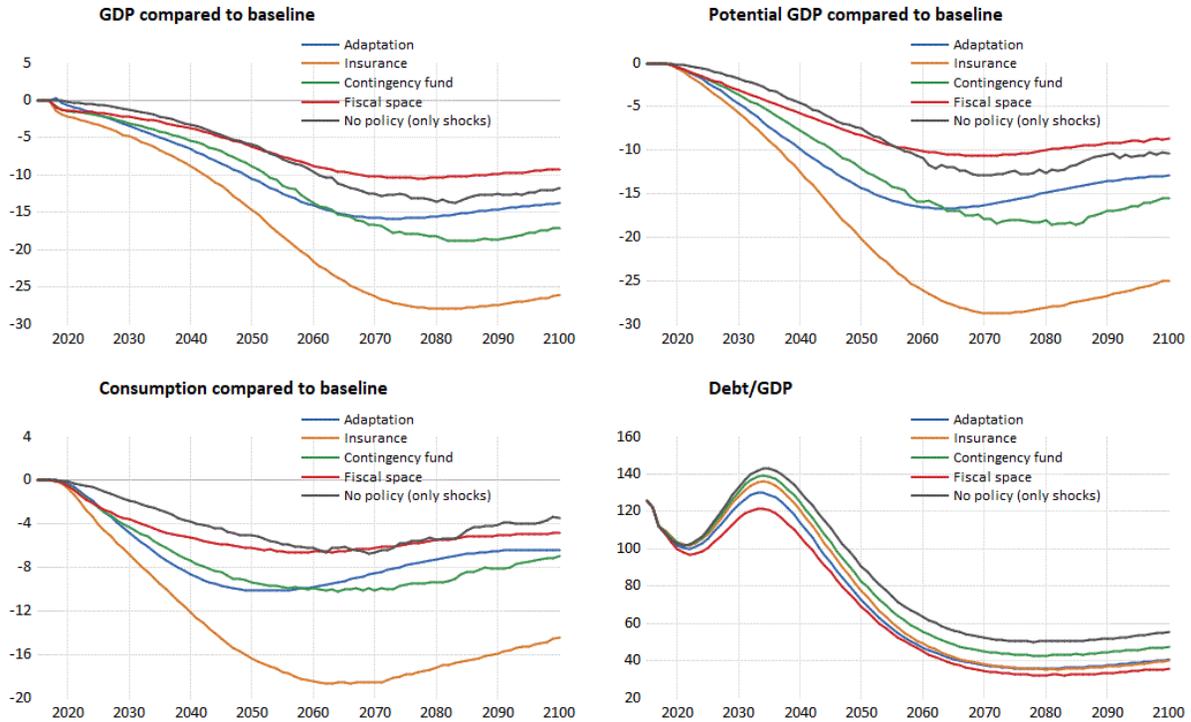


Figure 10: Comparison of the median values from different risk management scenarios. The risk management is financed by a reduction in government investment in this graph.

As discussed in the context of Figure 3, reducing consumption at the expense of investment reduces welfare in the near future and increases it in the more distant future. Consumption levels in the future may thus be higher when government consumption is reduced in favor of government investment.

6.6. The relative merits of the three forms of insurance

Each of the three forms of insurance has its merits, see Table 2. Which type is best for a given country (or what combination of them and investment in adaptation capital) depends on country specific economic variables or on country preferences.

The advantage of the contingency fund compared to the commercial insurance fund is that it likely has a lower service fee ($\mu^C < \mu^I$). A disadvantage is that the contingency fund may not be able to fully fund a disaster recovery during its ramp-up phase, because an early hurricane could exceed the fund volume. The long-run advantage of insurance as opposed compared with a contingency fund when several large shocks exhaust the contingency fund is potentially an important result favoring insurance in cases of high uncertainty. This favorable result is dependent in the modeling on the markup on insurance being held constant, whereas historically mark-ups have tended to rise following large payouts as insurance companies seek to restore their financial assets. The creation of additional fiscal space has the advantage over both other types of insurance that it reduces the interest rate payments on all

government debt, because of a lower sovereign risk premium. The principal advantage of the insurance scheme (assuming payments are made) is its ability to deal with multiple or very large events.

As modeled, the median results of the fiscal space scenario are always superior to the other financial approaches. However, that dominance depends heavily on the assumption that the government does lower its debt-to-GDP ratio, and that it can obtain needed finance as quickly as it can get an insurance payout. In reality, it may take a long time for a government to obtain money through issuing debt, while the payout from a commercial insurance or a contingency fund can be expected to be faster. As concerns the contingency fund, its lower cost advantage might disappear if the likelihood of mismanagement of the fund were considered as a cost.

Table 2: Comparing the modeled benefits and costs of different insurance schemes

Schemes	Benefits	Costs	Unmodeled considerations
Insurance	Immediate payout triggered by natural disaster	Endogenous insurance markup	May be particularly useful for immediate post-hurricane humanitarian and logistic efforts
Contingency fund	Immediate payout triggered by climate event; interest earned on unspent resources	Monitoring costs, insufficient payout when not enough capital is accrued	Risk of misappropriation of funds or poor investments not included in costs – could eliminate cost advantage
Debt reduction	Fiscal space to react to climate shock; reduced present value interest expenses imply more spending on other categories or even greater debt reduction		Given fungibility of money, there is a real hazard that the fiscal space is not created or that it is used to deal with “political” disasters that leave the space unavailable when hurricane strikes.

7. General remarks

Three main results flow from the preceding analysis. First, at low levels of spending (expressed as a share of expected damages), adaptation investment is the dominant approach – generating smaller GDP losses from hurricanes and less volatility than the other risk management strategies examined. At higher spending levels this advantage dissipates, with the cross-over effect depending importantly on the largely unknown curvature of the protection curve.

Second, the contingency fund and the fiscal space strategies cost less than disaster insurance. However, their payouts are bound by the size of the contingency fund or the fiscal space accumulated. As a result, under stochastic simulation in those cases where shocks are very large or fall in quick succession, available funds are not sufficient to promptly repair hurricane damages. As a result, economic losses accumulate, and the variance of outcomes is unusually large and skewed to the downside. The way that disaster management costs are financed, via reduced productive investment versus reduced government spending on goods and services or transfers matters. Financing from productive investment results in larger GDP losses, but cutting consumer transfers or government spending on consumption goods results in larger decline in total consumption – generally considered a better proxy for consumer welfare than GDP.

Finally, all four risk management mechanisms are faced with real-world hazards that may reduce their effectiveness. A policy focused on adaptation investment will only be effective if the investments are additional to what would have happened anyway and if they really improve adaptation. The fungibility of funds allocated for such efforts runs the real risk that investments are only nominally for adaptation or that they are not additional. Contingency funds are only of use if they are sufficiently fungible and liquid so that money can be quickly extracted. Almost by definition that means they need to be held out of the country, as a fund invested in domestic firms or assets of a small country are likely to lose value and become less liquid following the onset of a hurricane.

There is also a risk that funds get misallocated or misappropriated. A fiscal space strategy will work only if the space really is created, and if the space is available when disaster strikes. For insurance there is always the risk that insurance will not be paid out, either because multiple events prevent the insurer from meeting their obligations, or because the realization of an event causes an insurer to withdraw future coverage (for Jamaica, this risk is mitigated by the Caribbean Catastrophic Risk Insurance Facility). Moreover, if the mark-up rises following several large payouts, the benefits of insurance over a contingency fund that gets exhausted would be less obvious.

Some important aspects of hurricane disaster preparation have not been considered in the model but are important for the evaluation of risk management options. Implicit in the preceding discussion is the speed at which funds can be accessed and effectively disbursed. In the analysis the speed of access and disbursement was held constant across mechanisms. In reality, private insurance may pay more quickly after a disaster than the government can raise the funds for disaster relief and recovery.

The preceding discussion speaks to economic volatility but does not evaluate it in a rigorous way. Economic theory clearly suggests that stability is valued, but the tradeoff at a national level between the average level of GDP and its volatility is not integrated into this work.

The impact that disasters have on productivity and their dependence on the depth and duration of a shock is not treated. Natural disasters have been shown to affect human capital investments (Rosales-Rueda, 2018) and health (Lloyd et al., 2019), in such a context efforts that succeeded in minimizing both over time and in amplitude the economic disruption of a disaster could yield additional benefits.

Finally, the modeling work depends on several parameters and estimates that for the moment are not well determined. Further work will be needed to identify both the average effectiveness of adaptation investment (γ_1) and the curvature of the protection function (γ_2). Similarly, information on the cost of insurance, and contingency funds is limited. Historically, there has been great volatility in insurance premia and that volatility has tended to be correlated with earlier losses, suggesting that the strength of the insurance mechanism in the face of large or successive events may be overstated. Finally, the current exercise was modeled on the assumption that the incidence of damages going forward would be the same as in the past, whereas there is a fair body of research suggesting that the intensity of storms is increasing as the planet warms and that therefore the distribution of future damages is likely to be skewed toward more frequent large scale events.

8. Conclusion

Models can generate insights, not otherwise evident, into how climate systems interact with the macroeconomy. This paper illustrates a specific feature of modeling climate disasters and adaptation in

the context of financing options. Jamaica is used as a case study given the frequent climate shocks and financial pressure they apply to the government.

The modeling considers and compares four management strategies for hurricanes damages. Adaptation investment to strengthen capital stock is compared to purchasing insurance from the private sector, setting up and managing a contingency fund and reducing debt via a reduction in expenditures to create fiscal space in anticipation of responding to climate shocks. Each requires a set of assumptions on financing these strategies, such as a reprioritization in terms of the expenditure composition.

The economic impacts of each strategy depend on initial conditions (i.e. the size of the contingency fund, existing fiscal space, current levels of adaptation and insurance premiums). In general, reducing debt and running an efficient contingency fund costs less than taking out private insurance. This assumes that there are no leakages with operating a contingency fund and that the reduction in debt service costs decreases opportunity costs. However, for very large and frequent climate shocks, a contingency fund might be limited in terms of the cover it can provide – under these circumstances a private insurance strategy can pay off. Finally, the economic gains of adaptation depend on the parametrization of the protection function. The modeling results show that adaptation smooths consumption and GDP for small shocks. The level of protection dissipates for large shocks.

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Appendix A: Disaster data

Table 3: Absolute damages in Caribbean economies

Source: EM-DAT: The Emergency Events Database - Universite catholique de Louvain (UCL) - CRED, D. Guha-Sapir - www.emdat.be, Brussels, Belgium

	LCA Total damage (current US\$) LCAHURDAMCD	BRB Total damage (current US\$) BRBHURDAMCD	JAM Total damage (current US\$) LCAHURDAMCD
1980	87,990,000	1,500,000	64,000,000
1981	0	0	0
1982	0	0	0
1983	0	0	0
1984	0	0	5,200,000
1985	0	0	0
1986	0	0	0
1987	0	100,000,000	0
1988	2,500,000	0	1,000,000,000
1989	0	0	0
1990	0	0	0
1991	0	0	0
1992	0	0	0
1993	0	0	0
1994	0	0	0
1995	0	0	0
1996	0	0	3,000,000
1997	0	0	0
1998	0	0	0
1999	0	0	0
2000	0	0	0
2001	0	0	55,487,000
2002	0	200,000	1,030,000
2003	0	0	0
2004	500,000	5,000,000	895,000,000
2005	0	0	34,500,000
2006	0	0	0
2007	40,000,000	0	300,000,000
2008	0	0	66,198,000
2009	0	0	0
2010	500,000	0	150,000,000
2011	0	0	0
2012	0	0	16,542,000
2013	0	0	0
2014	0	0	0
2015	0	0	0

2016	0	0	0
2017	0	0	0

Appendix B: Climate adaptation in the literature

For the modeling of climate adaptation, we made a modeling choice which requires some justification. We followed a “standard approach” identified in previous research articles. To make this choice transparent, we present the formulations in the literature.

It can be expected that a country which adapts to regular disasters like hurricanes implements the most effective measures first. As a consequence, there will be decreasing returns to scale as the amount of protection obtained from further adaptation reduces. There is no general agreement on how this should be modeled and calibrated, however. This section presents the approaches used in published academic articles.

The paper (Dumas & Ha-Duong, 2013) takes a unique approach by using temperature-specific capital stocks. The papers (Lecocq & Shalizi, 2007), (de Bruin et al., 2009), (Bosello et al., 2010) and (Millner & Dietz, 2015) have in common that adaptation has decreasing returns to scale and that adaptation capital does not have a productive use, but instead works only to reduce damages. (de Bruin et al., 2009) and (Millner & Dietz, 2015) further have in common that adaptation takes the form of a capital stock. (Bosello et al., 2010), by contrast, use a flow variable for adaptation albeit in a model framework where a period is 10 years long.

Concerning the structure for how adaptation works on damages, we follow the approach of (de Bruin et al., 2009). The reason is that protection will have to be proportional to GDP, a concept that the other approaches do not have. Further, we assume that adaptation is accumulated as a capital stock as in (Bosello et al., 2010) and (Millner & Dietz, 2015), because adaptation often takes the form of infrastructure, which is best represented as a capital stock.

(Lecocq & Shalizi, 2007)

This paper is a theoretical model, using abstract functional forms. It assumes that protection P reduces damages, $\frac{\partial D}{\partial P} < 0$, but with diminishing returns, $\frac{\partial^2 D}{\partial P^2} < 0$.

(de Bruin et al., 2009), (De Cian, Hof, Marangoni, Tavoni, & van Vuuren, 2016)

This paper considers a level P of protection which reduces gross damages, GD , to residual damages,

$$RD_t = GD_t \times (1 - P_t),$$

where $0 \leq P_t \leq 1$. Protection is purchased in the form of protection cost PC ,

$$\frac{PC_t}{Y_t} = \gamma_1 P_t^{\gamma_2},$$

where $\gamma_1 > 0$ and $\gamma_2 > 1$. The model used is DICE, the Integrated Assessment Model developed by William Nordhaus. It uses periods of 10 years. This period length may explain why the level of protection is a flow variable in this model, not a stock variable.

Basing their calibration on earlier literature, the paper obtains the following values: $\gamma_1 = 0.115$ and $\gamma_2 = 3.6$.

(Bosello et al., 2010)

In this paper, adaptation activities, *ADAPT*, reduce climate change damages, *CCD*, to climate change damages with adaptation, *CCDA*,

$$CCDA_{n,t} = \frac{1}{1 + ADAPT_{n,t}} CCD'_{n,t}.$$

Adaptation is a combination of proactive, *SAD*, and reactive, *FRAD*, adaptation,

$$ADAPT_{n,t} = A_{ADA} (\alpha_{1,n} SAD_{n,t}^{\rho_{ADA}} + \alpha_{2,n} FRAD_{n,t}^{\rho_{ADA}})^{\frac{1}{\rho_{ADA}}}.$$

Proactive adaptation is a capital stock, which follows standard capital accumulation,

$$SAD_{n,t} = (1 - \delta)SAD_{n,t-1} + IA_{n,t}.$$

The calibration is in an appendix, which is “available on request”.

(Dumas & Ha-Duong, 2013)

In this paper, there are different types of capital K_j and each is designed for a certain temperature θ^j . The efficiency of capital is given by $g(\theta_t - \theta^j)$, where θ_t is the realized temperature. $g(x) = 1$ for $|x| \leq \frac{w}{2}$ and zero otherwise. Total efficient capital is given by

$$\tilde{K} = \sum_j g(\theta_t - \theta^j) K_j$$

And each type of capital follows standard capital accumulation,

$$K_{t+1}^j = (1 - \delta)K_t^j + I_t^j.$$

In this mode, adaptation thus takes the form of investments into types of capital, which is designed for a future climate.

(Millner & Dietz, 2015)

In this paper, total output is multiplied with a damage multiplier D ,

$$D(K_A, X) = \frac{1 + g(K_A)}{1 + g(K_A) + f(X)},$$

where K_A is adaptation capital and X is global temperature. Further, we have

$$f(X) = \alpha_1 X + \alpha_2 X^2,$$

$$g(K_A) = \beta_1 K_A^{\beta_2}$$

with $\beta_1 > 0$ and $\beta_2 \in [0,1]$. Adaptation capital follows standard capital accumulation,

$$K_A = I - \delta_A K_A.$$

The calibration is based on (Agrawala et al., 2010), which compares different models with adaptation and includes $\beta_1 = 0.0032$ and $\beta_2 = 0.17$.

Appendix C: Theoretical derivations

In the modeling of disaster risk management, we are making use of theoretical derivations. In order to make these derivations transparent, we discuss them here. In the first part, we derive the long run relationship between the current government deficit and government debt.

C.1: Adjusting the damage impact

In order to model the destruction of capital in a detailed way, Hallegatte & Vogt-Schilb (2016) argue that different types, or “layers” of capital need to be modeled. As an alternative, they suggest taking the randomness of capital destruction into account by calculating output as $Y(\tilde{K}, DS) = \left(1 - \frac{DS}{\tilde{K}}\right) F(L, \tilde{K})$.⁷

This exact equation cannot be included in MFMod, because it would create discrepancies in the GDP accounting. We thus need to assign the damage to capital. MFMod uses a Cobb-Douglas production function, $Y_t = A_t L_t^\alpha K_t^{1-\alpha}$. We can thus rewrite $Y(\tilde{K}, DS) = \left(1 - \frac{DS}{\tilde{K}}\right) F(L, \tilde{K}) = \left(1 - \frac{DS}{\tilde{K}}\right) A_t L_t^\alpha \tilde{K}^{1-\alpha} = A_t L_t^\alpha \left(1 - \frac{DS}{\tilde{K}}\right)^{\frac{1}{1-\alpha}} \tilde{K}^{1-\alpha} = A_t L_t^\alpha K^{1-\alpha}$, where

$$K = \left(1 - \frac{DS}{\tilde{K}}\right)^{\frac{1}{1-\alpha}} \tilde{K}$$

and where

$$\tilde{K}_t = (1 - \delta)\tilde{K}_{t-1} + (I_t - I_t^R).$$

C.2: Debt and deficit

In this section we calculate the link between the budget deficit and the debt/GDP ratio in long run equilibrium. Let E_t be government debt and let x be government budget deficit as a share of GDP. Then the growth of debt can be written as

$$E_t - E_{t-1} = xY_t.$$

In the long run government debt will grow at the same rate as GDP,

$$\frac{E_t}{E_{t-1}} = \frac{Y_t}{Y_{t-1}} = (1 + g).$$

Inserting this we obtain

$$gE_{t-1} = (1 + g)E_{t-1} - E_{t-1} = xY_t = x(1 + g)Y_{t-1}.$$

With this, we obtain for the debt/GDP ratio:

$$\frac{E_t}{Y_t} = x \frac{1 + g}{g}.$$

⁷ See equation (4) in Hallegatte & Vogt-Schilb (2016).

C.3: Partial equilibrium optimization of adaptation

In order to get an idea of the trade-off involved in the model setup in Section 3, we can use the equations to calculate the optimal amount of adaptation in a partial equilibrium setting. For this, we assume that the economy outside this set of equations does not react to changes in the adaptation investments and that the government is minimizing the expected sum of residual damages and adaptation spending,

$$\min_{I_t^A} E(RD_t + I_t^A).$$

Due to the concave nature of the protection function, the first units of adaptation are very beneficial and should be done in any case. Very high levels of adaptation cannot be optimal as the cost of adaptation is lower than the additional protection obtained. There is thus an intermediate level of investments, which is optimal. Formally, we obtain the following result.

Proposition: *The cost minimizing investment into adaptation capital is $I_t^A = \gamma_2^{\frac{1}{1-\gamma_2}} \left(\gamma_1 \frac{g+\delta}{1+g} \right)^{\frac{\gamma_2}{1-\gamma_2}} \overline{GD}$.*

Proof: We have $E(RD_t + I_t^A) = E((1 - P_t)GD_t) + I_t^A = (1 - P_t)E(GD_t) + I_t^A = \left(1 - \left(\gamma_1 \frac{K^A}{K^{Amax}} \right)^{\gamma_2} \right) \overline{GD} + I_t^A = \left(1 - \left(\gamma_1 \frac{I_t^A}{\overline{GD}} \right)^{\gamma_2} \right) \overline{GD} + I_t^A$. With this, we have $\frac{d}{dI_t^A} E(RD_t + AI_t) = -\gamma_2 \left(\gamma_1 \frac{g+\delta}{1+g} \right)^{\gamma_2} \left(\frac{I_t^A}{\overline{GD}} \right)^{\gamma_2-1} + 1 = 0 \Leftrightarrow I_t^A = \gamma_2^{\frac{1}{1-\gamma_2}} \left(\gamma_1 \frac{g+\delta}{1+g} \right)^{\frac{\gamma_2}{1-\gamma_2}} \overline{GD}$.

The result shows that optimal adaptation investment is proportional to GDP. This reflects that both damages and the need for protection are proportional to GDP. It further shows that the optimal adaptation investment increases in γ_1 , because a higher γ_1 makes adaptation investment more beneficial.

Appendix D: Aggregate consumption

In this discussion, we introduce an approach to take the welfare losses of lower government consumption into account. Section D.1 introduces the approach, Section D.2 puts it into the context of the literature.

D.1 Aggregating private and government consumption

GDP and consumption are standard variables of national accounting, and both are an integral part of MFMod. Neither is an adequate measure of welfare, see (Fleurbaey, 2009) for example. MFMod does not provide a welfare analysis, because 1) there is no unique or agreed-on definition of welfare (see (Fleurbaey, 2009)) and 2) a welfare function would need to be defined and calibrated by a government. The comparison of scenarios below is not a direct measure of welfare. The results should be analyzed with caution from a welfare perspective. For example, households may prefer a smooth consumption path to a more volatile one, even if it is lower on average, because of risk aversion. In MFMod, the standard household maximizing utility function yields a Euler consumption equation. The model is linearized and hence uncertainty (typically requiring a second order approximation around a steady state) is not fully captured. Climate damages are uncertain by nature, and households may react differently as a consequence of this uncertainty.

The government may choose to reduce government consumption (instead of government investment) in order to finance disaster risk management. This is not reflected in private consumption, but it will affect household welfare, since the level of public services will be reduced. It could thus be useful to compare *aggregate* consumption instead of private consumption. The literature has used different functional forms for aggregating private and government consumption, some of these are presented in the following subsection.

As the constant elasticity of substitution (CES) function is a generalization of the Cobb-Douglas function, we follow the use of the CES function of (Marattin & Palestini, 2014) and define aggregate consumption as a combination of private consumption C and government consumption C^G ,

$$C^{agg} = \left(\theta C^{\frac{v-1}{v}} + (1 - \theta)(C^G)^{\frac{v-1}{v}} \right)^{\frac{v}{v-1}}.$$

While the model does compute aggregate consumption, the results below will display private consumption, since the aggregation of consumption cannot be done in an unambiguous way.

Figure 1 shows a variant of Figure 3, where private consumption is replaced with aggregate consumption. This figure shows that aggregate consumption reduces even less than private consumption, indicating that a more detailed understanding of the welfare effects of reductions in government consumption requires further finetuning.

Comparison of different types of disaster management investments

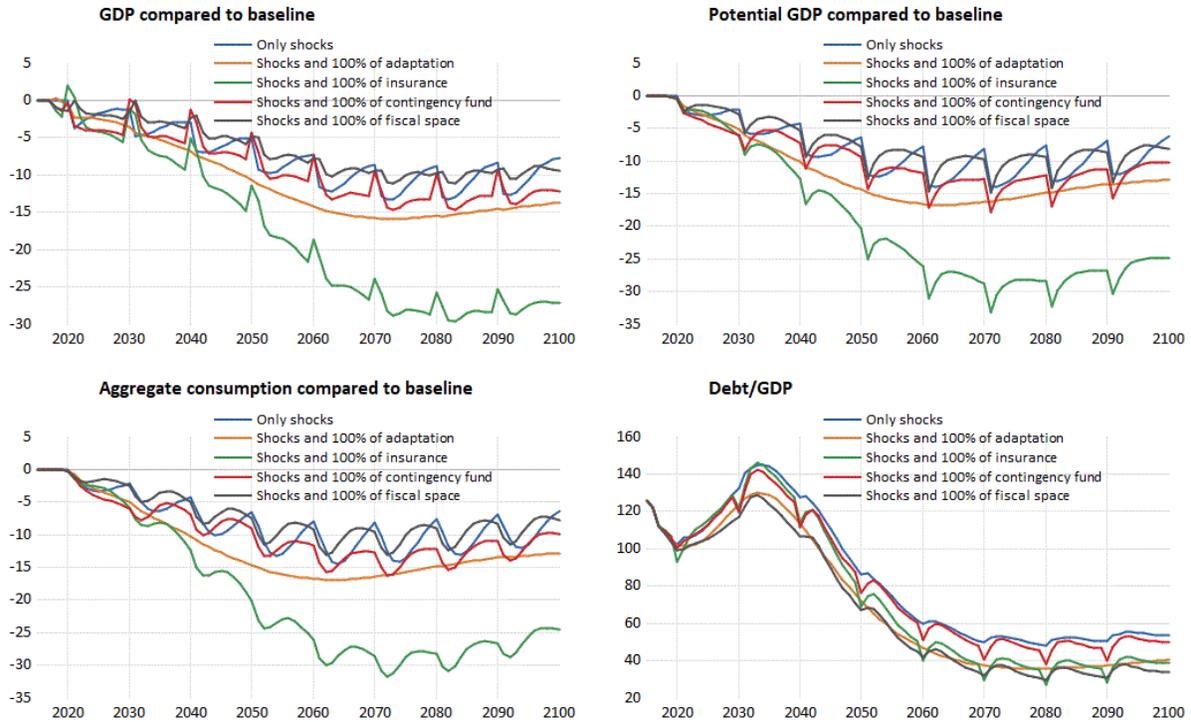


Figure 11: Comparison of risk mitigation scenarios with aggregate consumption

D.2 Literature on aggregating consumption

In this subsection, we present different options to model the aggregation of private and government consumption so that the approach we have chosen in the previous subsection can be compared to similar efforts in the literature.

One of the first models to consider the use of government consumption explicitly is (Barro, 1990). The paper proposes to write utility as a combination of private consumption c and government consumption services h as

$$u(c, h) = \frac{(c^{1-\beta} h^\beta)^{1-\sigma} - 1}{1 - \sigma}.$$

(Turnovsky, 1996) proposes a similar approach, where private consumption C and government services G_s are combined as

$$U(C, G_s) = \frac{1}{\gamma} (C G_s^\beta)^\gamma.$$

The paper further specifies that government services are a combination of the absolute amount of government expenditure G and of government expenditure relative to GDP, so that $G_s = G^\delta \left(\frac{G}{Y}\right)^1 - \delta = GY^{\delta-1}$.

(Shieh, Chen, & Lai, 2006) argue that the stock of government services should be considered in the utility function instead of the flow, because “public goods, such as public libraries, national defense, national parks, hospitals, highways and transportation programs, which have been presented in recent neoclassical growth frameworks, are stock variables by nature”. They use a general functional form $U(c, G)$, where c is private consumption and G is the stock of government services. The stock evolves according to a standard capital accumulation function $\dot{g} = g + \delta_G G$, where g are investments in government services and δ_G is the specific depreciation rate.

(Ganelli & Tervala, 2010) also use the Cobb-Douglas function, but use the formulation in logarithms,

$$u(C_s, \dots, G_s^C) = (\log C_s + \dots + \varphi \log G_s^C).$$

Private consumption at time s is given as C_s and public consumption is given by G_s^C . The omitted part contains real balances and disutility from labor.

(Christiano, Eichenbaum, & Rebelo, 2011) take a simplified approach to including government consumption in the utility function by making it additively separable,

$$u(C_t, N_t, G_t) = \frac{[C_t^\gamma (1 - N_t)^{1-\gamma}]^{1-\sigma} - 1}{1 - \sigma} + v(G_t).$$

Here, C_t is consumption, N_t is hours worked, G_t is government consumption and v is a concave function.

(Marattin & Palestini, 2014) consider two explicit functional forms for government consumption in the utility function. One is that of (Ganelli & Tervala, 2010), the other a generalization of the utility functions seen above to a CES function,

$$u(C, G) = \frac{1}{1 - \gamma} \left[\left(\theta C^{\frac{\gamma-1}{\gamma}} + (1 - \theta) G^{\frac{\gamma-1}{\gamma}} \right)^{\frac{\gamma}{\gamma-1}} \right]^{1-\gamma}.$$

(d’Agostino, Dunne, & Pieroni, 2016) present a different modeling approach by including total public spending, disaggregated into military spending, government investment and government consumption, into the production function,

$$y = Ak^{1-\alpha-\beta-\delta} m^\alpha i^\beta c_p^\delta.$$

Further, articles like (Glomm & Ravikumar, 1997) and (Blankenau, Simpson, & Tomljanovich, 2007) model government investments into human capital.

Appendix E: Additional graphs

Comparison across different amounts of disaster management investment

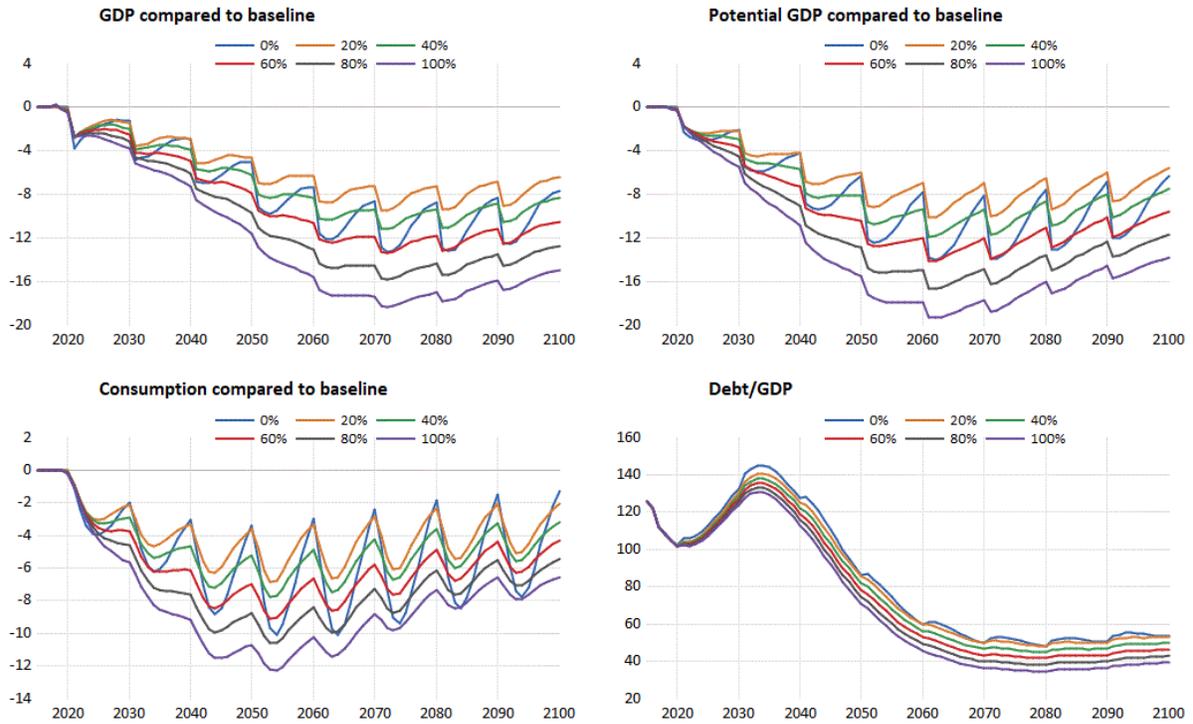


Figure 12: Comparison of different investment levels in adaptation with $\gamma_1 = 0.5$

**Comparison of different types of disaster management investments
(20% coverage, policy financed 100% from investment)**

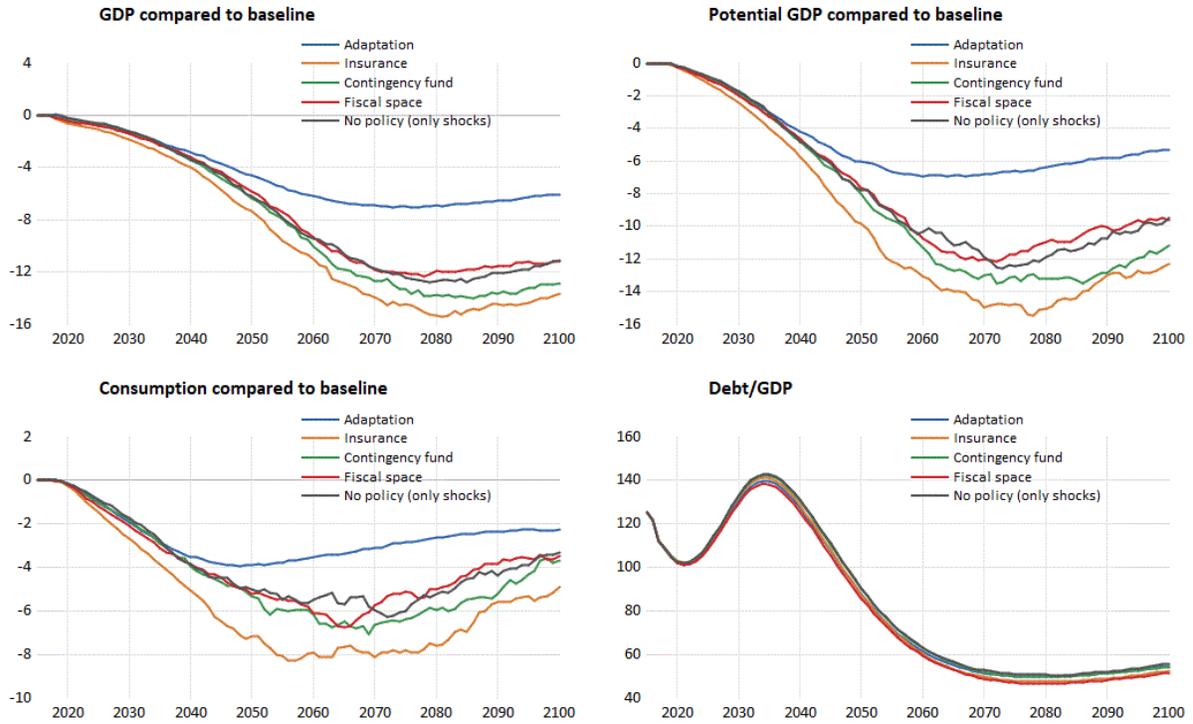


Figure 13: Comparison of medians with 20% coverage rate