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Modeling the Macroeconomic Consequences of Natural Disasters

Capital Stock, Recovery Dynamics, and Monetary Policy

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Abstract

Natural disasters can generate substantial damages to public and private sector infrastructure capital, generating macroeconomic losses through complex channels. To minimize the welfare impact of these disasters, these shocks need to be managed and accounted for in macro-fiscal and monetary policy. To support this process, we adapt the World Bank Macrostructural Model to capture key transmission channels of natural (geophysical or climate-related) disasters and their immediate aftermath. The macroeconomic model is extended on several fronts: (1) a distinction is made between infrastructure and non-infrastructure capital; (2) the production function is adjusted to account for short-term complementarity across capital assets; (3) the reconstruction process is modeled in a way that accounts for post-disaster constraints, with distinct processes for the reconstruction of public and private assets. Destroyed infrastructure capital makes the remaining non-infrastructure capital less productive, which means that disasters reduce the total stock of capital, but also its productivity. Applying the model to Türkiye data, the welfare impact of a disaster —proxied by the discounted consumption loss—is found to increase non-linearly with direct asset losses. Macroeconomic responses reduce the welfare impact of minor disasters but magnify it when direct asset losses exceed the economy's absorption capacity. The welfare impact also depends on the pre-existing economic situation, the ability of the economy to reallocate resources toward reconstruction, and the response of monetary policy. Appropriate macro-fiscal and monetary policies offer cost-effective opportunities to mitigate the welfare impact of major disasters.

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Modeling the Macroeconomic Consequences of Natural Disasters: Capital Stock, Recovery Dynamics, and Monetary Policy[*]

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1 Introduction

Natural disasters are a special type of macroeconomic risk because they impact economic growth and welfare in a persistent and nonlinear fashion (e.g., Aiyagari, 1994; Bewley, 1977; Krebs, 2003a,b). Natural disasters can be under-estimated in workhorse models, especially when it does not account for complex interactions. Indeed, although a wide range of macroeconomic frameworks have been used to inform policies aimed at increasing the resilience of economic systems to natural disasters, they have not been designed to capture specific impacts of disasters, such as the large share of damages affecting infrastructure and buildings (compared with other capital assets), or the practical constraints slowing down a reconstruction process (Hallegatte and Vogt-Schilb, 2019). This paper proposes a macroeconomic framework especially designed to capture the structure and dynamics of natural shocks to capital, and their link to macroeconomic losses and economic decision making.

A recent growing body of literature shows that natural disasters can affect the macroeconomic system in complex ways. For instance, the impact of disaster-related capital losses on output levels appears persistent (e.g., Akao and Sakamoto, 2018; Ikefuji and Horii, 2012; Müller-Fürstenberger and Schumacher, 2015), in contrast with what a simple Ramsey- or Solow-type model may suggest (e.g., Elliott et al., 2015; Hsiang and Jina, 2014; Raddatz, 2007; Strobl, 2011). And without extensive adjustments, most commonly used macroeconomic frameworks (i.e., real business cycle models or dynamic stochastic general equilibrium models) provide puzzling results when natural disaster strikes the economy as a negative shock to capital stock. For example, in Wright and Borda (2016), in part because of the high elasticity of substitution. Isore and Szczerbowicz (2017) shows that disaster risk may increase consumption if the intertemporal elasticity of substitution is larger than unity then interest rate risk increases, prompting agents to invest less and prefer current consumption over future consumption. Counter-intuitively, if the elasticity of substitution is below unity (an assumption used in many models), then an increase in risk leads to an increase in the discount factor, which results in an increase in savings and hence investment, which may then deliver an economic boom.[1] In Cantelmo et al. (2022), natural disaster generates an increase in total aggregate investment, because the loss in aggregate capital stock raises the marginal product of capital and consequently increases investment. But these models do not include complementarity across productive assets or real-world constraints on reconstruction.

To better represent disasters, we argue that aggregate models need to represent the complex interaction across sectors and firm in the network of supply chains (Baqaee and Farhi, 2020; Barrot and Sauvagnat, 2016; Boehm et al., 2019; Henriet et al., 2012; Inoue and Todo, 2019) and the effects through infrastructure systems, from transport systems to electricity grids (Colon et al., 2021; Rose and Liao, 2005; Rose and Wei, 2013). In particular, damages to infrastructure make the remaining non-infrastructure capital unproductive, magnifying output losses (Hallegatte and Vogt-Schilb, 2019). These effects are particularly important over the short run, when substitution opportunities are very limited (Barrot and Sauvagnat, 2016; Boehm et al., 2019) and capital assets cannot be reallocated

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[1] To solve this puzzle, Isore and Szczerbowicz (2017) use a time-varying discount rate, incorporating the role of preferences and uncertainty.

to their most productive uses (e.g., it takes time to reallocate some assets like undamaged buildings, and some assets like bridges and roads cannot be reallocated at all). Third, reconstruction after a disaster takes much more time than what a Ramsey- or Solow-type model would predict (e.g., Kates et al., 2006), because of a set of institutional, financial, and technical constraints. As a result, the impacts of natural disasters on GDP tend to be nonlinear (e.g., Felbermayr and Gröschl, 2014): doubling the direct damages does more than double the GDP impact, in part because it takes longer to recover from larger disasters (e.g., Hallegatte et al., 2008).

To replicate the key features of natural disasters in a macroeconomic framework, we build on previous efforts, notably Hallegatte et al. (2007); Hallegatte and Vogt-Schilb (2019). We use their production function that reproduces the stylized short-term impacts of disasters, taking into account the short time scales that prevent (1) substitution between factors of production like in the long-term, and (2) the immediate reallocation of undamaged assets to their most productive uses. In addition, we include constraints on reconstruction-related investments (e.g., institutional capacity, technological constraints, and imperfect access to finance) to ensure that the model is consistent with the observed consequences of disasters.[2] Furthermore, we draw from Marto et al. (2018) in distinguishing between public and private capital, allowing us to account for different decision-making processes, funding sources, and timing constraints for rebuilding these different types of assets. Finally, the aggregate capital stock is divided into infrastructure and non-infrastructure to better represent the effect of losses on output and the high vulnerability of infrastructure assets to many hazards. Differentiated impacts across capital types allows us to represent the fact that disasters reduce the stock of capital, but also lead to the misallocation of the remaining capital, thereby reducing overall productivity (as discussed in Hallegatte et al. (2007); Hallegatte and Vogt-Schilb (2019) and empirically measured by Bakkensen and Barrage (2021) and Dieppe et al. (2020)).

It should be noted that not all the channels of natural disasters are accounted for in this paper. While this paper introduces several extensions in the modeling of capital stock, we do not attempt to model the specificity of post-disaster labor supply and labor mobility decisions. With an aggregate model, we are also unable to account for important spatial and geographical effects, such as the effect of the spatial concentration of the losses. Another important aspect that we do not consider here is the effect of the risk — even in the absence of disater — investment and consumption choices. We leave these important dimensions for further work.

This paper uses the World Bank's macro-structural model, MFMOD (Burns et al., 2019; Burns and Jooste, 2019), which be adjusted to reproduce stylized dynamics of natural disaster consequences while keeping the core of the model unchanged. Furthermore, the short-term behavior of MFMOD allows the model to provide context-dependent disaster

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[2] Particularly important for the recovery process duration, and therefore total cumulative GDP or consumption losses, are the reconstruction investment choices that need to be modeled appropriately, taking into the account real-world constraints. The response of government expenditures to natural disasters may depend on initial fiscal positions (i.e., the ability to finance additional expenditures). The private sector investment channel will depend on the returns and costs of capital after damages, but also on access to financing and self-financing capacity. Households' consumption choices also matter. For instance, the constant coefficient of relative risk aversion implies that an increase in expected real rates will decrease consumption. Consumption may further deteriorate if the natural disaster causes permanent income losses.

impacts (Hallegatte and Ghil, 2008), exploring the difference between disasters affecting economies in different stages of the business cycle. We apply the model to the Republic of Türkiye, which has been recently affected by a major earthquake of magnitude 7.8 that lead to extensive human and economic losses.

After describing the methodology in Section 2, we apply the model to Türkiye data and discusses the model's behavior at the aftermath of a natural disaster in Section 3. Section 4 presents several policy implications, which highlight the main channels for policy and Section 5 concludes.

2 Methodology

The modeling builds on MFMod, a standard macroeconomic model used in international institutions, but the same modeling adjustments could also be applied to any DSGE or macrostructural econometric models. We extend MFMod along three lines. First, capital is divided into several dimensions and mapped to time series data. Second, the substitutability between infrastructure and non-infrastructure capital is estimated. This elasticity will therefore amplify or attenuate the damage, depending on the degree of substitution. Third, the modeling of post-disaster reconstruction takes into account the difference between private and public reconstruction. The key aggregate equations, long-run optimal behaviors, and accounting identities are unchanged and based on Burns et al. (2019) and summarized in Appendix A. In the main text of this paper, we focus on the adjustments made to represent natural disasters in the model.

In the initial model version, potential output (Y_t^*) combines aggregate capital and labor using a Cobb-Douglas production technology,[3]

$$Y_t^* = A_t K_{t-1}^{\alpha} N_t^{1-\alpha}. \tag{1}$$

The real costs of production equals the sum of labor costs and rental capital costs,

$$Y_t = \frac{W_t}{P_t} N_t + R_t K_{t-1}. \tag{2}$$

where Y_t is output, A_t is the total factor productivity (or TFP),[4], K_{t-1} is end of period capital stock, and N_t is structural employment. α is the output elasticity, R_t is the real rental rate of capital, and P_t and W_t are prices of output and labor.

Assuming cost-minimizing behavior, the (long-run) optimal aggregate capital to be rented equals its marginal productivity,

$$MPK_t = \frac{\partial Y_t^*}{\partial K_{t-1}} := R_t = \alpha \frac{Y_t^*}{K_{t-1}} \Rightarrow K_{t-1} = \alpha \frac{Y_t^*}{R_t}. \tag{3}$$

Note that at the long-term equilibrium, potential GDP and actual GDP are equal and $Y_t^* = Y_t$. The long-term is reached when the business cycle elements are zero, and when the economy reaches a steady state. Having defined the target (optimal) rental rate, we can derive the components of capital and solve for R_t.

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[3] Variable names are borrowed from Burns et al. (2019), all other notations will be described in the text. The functional form needs not be a Cobb-Douglas technology, but is used for ease of exposition.

[4] TFP is assumed to grow at a fixed rate.

2.1 Capital stocks

Starting from the aggregated capital stock of the initial model, we segment the capital stock into infrastructure and non-infrastructure capital, and within each asset class, between the private and public sectors. Total capital stock is the sum of infrastructure capital (denoted with subscript S) and non-infrastructure capital (denoted with subscript N). Infrastructure and non-infrastructure capitals include private capital (denoted with subscript P) and public capital (denoted with subscript G). The distinction between private and public capital is important. The private sector will invest in private sector infrastructure capital if it is profitable (based on first order conditions), while the public sector infrastructure provision is discretionary. As an example, if infrastructure capital is destroyed, the public sector may reconstruct damaged capital regardless of its economic return.

Given the equations above, we can derive solutions for both infrastructure and non-infrastructure capital as well as a solution for the marginal product of capital that is consistent with aggregate capital.

We assume that capital is bundled together using a constant elasticity of substitution setting (CES), with several nests. This allows us to estimate the complementarity or substitutability of private and public capital in the provision of infrastructure and non-infrastructure capital. This addition makes an important contribution — infrastructure capital damages, as an example, may also make non-infrastructure capital inoperable (see examples discussed in Burns et al., 2020; Hallegatte and Vogt-Schilb, 2019).

We assume that the economy is endowed with the following nested CES technology for the aggregate capital, K_t, which is a weighted sum of infrastructure, $K_{S,t}$,[5] and non-infrastructure capital, $K_{N,t}$,

$$K_t = \left[\omega_1 K_{S,t}^{\rho_1} + \omega_2 K_{N,t}^{\rho_1}\right]^{\frac{1}{\rho_1}} , \tag{4}$$

the CES for infrastructure depends on private, $K_{S,t}^P$, and public sector provision, $K_{S,t}^G$,

$$K_{S,t} = \left[\omega_3 K_{S,t}^{P\ \rho_2} + \omega_4 K_{S,t}^{G\ \rho_2}\right]^{\frac{1}{\rho_2}} , \tag{5}$$

while non-infrastructure also depends private, $K_{N,t}^P$, public sector provision, $K_{N,t}^G$,

$$K_{N,t} = \left[\omega_5 K_{N,t}^{P\ \rho_3} + \omega_6 K_{N,t}^{G\ \rho_3}\right]^{\frac{1}{\rho_3}} . \tag{6}$$

The share parameters for each capital is denoted with ω_i and the elasticity of substitution $\sigma_i = \frac{1}{1-\rho_i}$ is either estimated or calibrated. This nesting allows for different levels of complementarity and substitution given that ρ_i will be different for each capital.

The final good producer minimizes its capital costs given the technology above, where aggregage capital costs are given as

$$R_t K_{t-1} = \underbrace{R_{S,t}^P K_{S,t-1}^P + R_{S,t}^G K_{S,t-1}^G}_{=R_{S,t}K_{S,t-1}} + \underbrace{R_{N,t}^P K_{N,t-1}^P + R_{N,t}^G K_{N,t-1}^G}_{=R_{N,t}K_{N,t-1}}, \tag{7}$$

where the definitions of rental rates, Rs, follow the same logic as for aggregate capital and hence imply the equilibrium rates. The final good producer solves the following optimization problems,

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[5] In this paper, infrastructure capital includes public and private buildings, including residential buildings.

$$\min_{K_{j,t-1}} \sum_j R_{j,t} K_{j,t-1} - \sum_j \lambda_t \left[\left[\omega_j K_{j,t-1}^{\rho_1}\right]^{\frac{1}{\rho_1}} - K_{t-1} \right], \tag{8}$$

$$\min_{K^i_{S,t-1}} \sum_i R^i_{S,t} K^i_{S,t-1} - \sum_i \lambda_{S,t} \left[\left[\omega^i_S {K^i_{S,t-1}}^{\rho_2}\right]^{\frac{1}{\rho_2}} - K_{S,t-1} \right], \tag{9}$$

$$\min_{K^i_{N,t-1}} \sum_i R^i_{N,t} K^i_{N,t-1} - \sum_i \lambda_{N,t} \left[\left[\omega^i_S {K^i_{N,t-1}}^{\rho_3}\right]^{\frac{1}{\rho_3}} - K_{N,t-1} \right], \tag{10}$$

where $\lambda_{j,i}$ is the respective Lagrange multiplier, or the shadow price for its respective capital, with $i \in \{P, G\}$ and $j \in \{N, S\}$.

The first CES yields the optimal demands for aggregate infrastructure and non-infrastructure respectively, while the second and third CES functions will yield the private and public optimal demands for infrastructure and non-infrastructure capital. Note that there are three elasticities of substitution $(\sigma)$and six share parameters (ω).

The first order conditions for infrastructure capital stock yield

$$R_{S,t} = \lambda_t \frac{1}{\rho_1} {K_{t-1}}^{1-\rho_1} \rho_1 \omega_1 K^{\rho_1 - 1}_{S,t-1}. \tag{11}$$

Simplifying, the rental rate for aggregate infrastructure becomes

$$R_{S,t} = \lambda_t {K_{t-1}}^{1-\rho_1} \omega_1 K^{\rho_1 - 1}_{S,t-1} = \lambda_t \omega_1 \left(\frac{K_{S,t-1}}{K_{t-1}} \right)^{\rho_1 - 1}. \tag{12}$$

Substituting the shadow cost value for marginal productivity of capital, i.e., $\lambda_t = R_t$, and solving for the optimal infrastructure capital stock $K_{S,t}$ yields,

$$K_{S,t-1} = \omega_1^{\sigma_1} \left(\frac{R_t}{R_{S,t}} \right)^{\sigma_1} K_{t-1}. \tag{13}$$

Similarly, we solve for non-infrastructure capital,

$$K_{N,t-1} = \omega_2^{\sigma_1} \left(\frac{R_t}{R_{N,t}} \right)^{\sigma_1} K_{t-1}. \tag{14}$$

Relative prices thus drive the decision to invest in either infrastructure or non-infrastructure capital. An increase in the price of infrastructure capital relative to the aggregate capital price will result in a reduction in capital demand. The value and sign of σ determines the degree of substitutability. In the same way we can write out the private and public optimal demands for both infrastructure and non-infrastructure capital.

$$K^i_{j,t-1} = \omega_i^{\sigma_i} \left(\frac{R_{j,t}}{R^i_{j,t}} \right)^{\sigma_i} K_{j,t-1}, \tag{15}$$

The CES aggregator yields the aggregate optimal rental rate indices for aggregate capital stock, infrastructure and non-infrastructure, respectively:

$$R_t = \left[\omega_1^{\sigma_1} {R_{N,t}}^{1-\sigma_1} + \omega_2^{\sigma_1} {R_{S,t}}^{1-\sigma_1} \right]^{\frac{1}{1-\sigma_1}}, \tag{16}$$

$$R_{S,t} = \left[\omega_3^{\sigma_2} {R_{S,t}^{P}}^{1-\sigma_2} + \omega_4^{\sigma_2} {R_{S,t}^{G}}^{1-\sigma_2}\right]^{\frac{1}{1-\sigma_2}}, \tag{17}$$

$$R_{N,t} = \left[\omega_5^{\sigma_3} {R_{N,t}^{P}}^{1-\sigma_3} + \omega_6^{\sigma_3} {R_{N,t}^{G}}^{1-\sigma_3}\right]^{\frac{1}{1-\sigma_3}}. \tag{18}$$

The investment decisions of the private sector depend on the relative returns of investment to costs. In equilibrium each capital rental rate should be equal to its own long-term replacement cost due to zero arbitrage. It is thus equally important to specify how the user cost calculation needs to be adjusted for different types of capital. As an example, a natural disaster that reduces supply may create inflation. Depending on the monetary policy reaction function and tax changes, the cost of capital can deviate from the marginal product of capital in the short run, rendering interesting investment dynamics. The replacement cost ($U_{j,t}^{i}$) is defined as (see Appendix A.10 for a detailed derivation):

$$U_{j,t}^{i} = \frac{P_t^I (r_t^b + \delta - \pi_t + prem_t)}{P_t(1-\tau_t^{CIT})} \times \frac{\partial K_{t-1}}{\partial K_{j,t-1}} \times \frac{\partial K_{j,t-1}}{\partial K_{j,t-1}^{i}}, \tag{19}$$

where δ is the capital depreciation rate, P_t^I is the investment price deflator and P_t is the domestic price deflator, r_t^b is the risk-free rate (in this case the average yield on government debt), $prem_t$ is the risk-premium, π_t is rate of inflation and τ_t^{CIT} is the corporate tax rate.

2.2 Disaster impacts

Following common practice, damages from disasters are expressed in terms of the cost of repairing or replacing the damaged capital. For example, if a disaster destroys a road and the cost of rebuilding the road is \$1 million, then the official damage caused by the destruction of the road is \$1 million minus the usual capital depreciation rate.[6]

Hallegatte and Vogt-Schilb's (2019) note that simply subtracting the cost of rebuilding damaged capital from the total capital stock in an unchanged macroeconomic framework implies that the destroyed capital has the lowest productivity (equal to the marginal product of the additional capital). For instance, if one road is damaged, the production declines like if the least productive road has been removed. In other words, undamaged capital can be reallocated instantly and without cost to its most productive use. In reality, climate damages include both infra-marginal and marginal capital, and capital reallocation is only partially possible (e.g, bridges cannot be moved), takes time and is costly. It is important to note that the productivity of infra-marginal capital is higher than that of marginal capital and therefore the expected output loss is magnified when infra-marginal damages are considered. Assuming that the damaged capital is evenly distributed across sub-marginal projects, the economic value of the destroyed capital is equal to the average productivity of capital. In that case, the capital destroyed by disasters has approximately the average capital productivity. And repairing damage capital also has a productivity equal to the average capital productivity, while investing in new capital has the marginal capital productivity.[7]

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[6] Note that the model ignores the responses of labor productivity and human capital to natural disasters, as well as impacts through the natural capital stock.

[7] The higher productivity of repairs, compared with investments in new capital, is consistent with the observation that repairs take priority over other investments in a post-disaster area.

To represent the reconstruction process, we keep track of unrepaired capital, DS_t, and calculate its impact on output. The stock of un-repaired capital from natural disasters can be tracked using the following equation (we provide equations for the private sector, P, only, the public sector follows the same rationale),

$$DS_t^P = (1-\delta)DS_{t-1}^P + RD_t^P - IR_t^P, \tag{20}$$

where RD_t^P is a amount of new disaster damage at time t, and IR_t^P is the reconstruction investment used in repairing damaged capital (past and present, indifferently) at time t, where repairs are equal to a constant share, ϕ, of the total investment or total capital destroyed, whichever is smaller (see equation 27 below).

During the reconstruction phase, substitution and reallocation of infrastructure assets are limited (Hallegatte and Vogt-Schilb, 2019) and we assume that the damaged capital alters potential real production as follows

$$Y_t^* = \left(\frac{KL_{t-1}}{K_{S,t-1}}\right) \underbrace{A_t N_t^{\alpha} K_{t-1}^{1-\alpha}}_{:=Y_t}, \tag{21}$$

where $KL_t := \left[\omega_3(K_{S,t}^P - DS_t^P)^{\rho_2} + \omega_4(K_{S,t}^G - DS_t^G)^{\rho_2}\right]^{\frac{1}{\rho_2}}$ is the aggregation of both public and private, with the same elasticity of substitution as the capital.[8] This expression keeps track of damaged infrastructure capital relative to total capital stock. If damaged capital increases relative to total available capital, the potential GDP will fall. This expression modifies the TFP (A_t) variable. Furthermore, this aggregation scheme is consistent with the CES specification in the previous section. This functional form is chosen so that the potential output is reduced proportionally to the loss in physical capital. This assumption of complementarity over the short term is consistent with anecdotal and empirical evidence, with substitution options very limited over the short term and increasing over time (Baqaee and Farhi, 2020; Barrot and Sauvagnat, 2016; Boehm et al., 2019).

When a natural disaster occurs, marginal productivities are affected, influencing investment choices.This framework is consistent with the conclusions of Hallegatte and Vogt-Schilb (2019) as reparation will always be preferred to building new capital (see Appendix B for the proof). Given that we have now defined real potential output, we are able to derive how damages enter the investment decisions of the private sector. Specifically, we write the marginal product of private sector infrastructure capital as

$$\frac{\partial Y_t^*}{\partial K_{S,t-1}^P} = \alpha \frac{Y_t^*}{K_{t-1}} \frac{\partial K_{t-1}}{\partial K_{S,t-1}} \frac{\partial K_{S,t-1}}{\partial K_{S,t-1}^P} + \omega_3 \frac{Y_t}{K_{S,t-1}} \left[\left(\frac{KL_{t-1}}{K_{S,t}^P - DS_t^P}\right)^{1-\rho_2} - \frac{Y_t^*}{Y_t}\left(\frac{K_{S,t-1}}{K_{S,t-1}^P}\right)^{1-\rho_2} \right]. \tag{22}$$

This result contrasts with traditional marginal productivity derivation as it shows larger increases in the marginal product of damaged capital through DS_{t-1} and Y_t^* on the right-hand side of the equality. As a comparison, the marginal productivity of non-infrastructure capital will take the form

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[8] A heat map is provided later in this section for a visual representation of the function with its calibration.

$$\frac{\partial Y_t^*}{\partial K_{N,t-1}^P} = \alpha \frac{Y_t^*}{K_{t-1}} \frac{\partial K_{t-1}}{\partial K_{N,t-1}} \frac{\partial K_{N,t-1}}{\partial K_{N,t-1}^P}. \tag{23}$$

2.3 Investment (and reconstruction) decisions

Private investment decisions in MFMod depends on (i) adjustment costs; (ii) expected returns and (iii) short-run returns vs. short-run costs. The framework is based on Tobin's Q, where the Q ratio is equal to the return to capital relative to the cost of capital (or market value of assets to its replacement value). In this model, Tobin's Q is defined as the ratio of the marginal product of capital to the cost of capital. The functional form for private sector decisions is derived in the Appendix (Section A.2). The standard empirical private investment equation is written as

$$\frac{I_{S,t}^P}{K_{S,t-1}^P} = \beta_2 \left(\frac{\partial Y_t^*}{\partial K_{S,t-1}^P} - U_{S,t}^P - \varepsilon \right) + (1-\beta_3)(\Delta y_t^* + \delta) + \beta_3 \frac{I_{S,t-1}^P}{K_{S,t-2}^P} + \varepsilon_t^{IPN} \tag{24}$$

where ε_t^{IPN} is an iid residual. This investment equation states that private investment increases if the return to capital exceeds the cost of capital. In the steady state, the private investment to capital stock ratio converges to long-run growth plus the rate of capital depreciation.

Given that the modeling approach ensures that the investment variables, among others, are on the same balanced growth path, and given that capital stocks are technologically bounded by the nested CES, it is easy to show that, in the long run, the following condition is satisfied $\forall j$

$$\lim_{t\to+\infty} R_{j,t}^i = \lim_{t\to+\infty} U_{j,t}^i + \varepsilon. \tag{25}$$

Therefore, in the long run,

$$\lim_{t\to+\infty} \alpha \frac{Y_t^*}{K_{t-1}} = \lim_{t\to+\infty} U_t \tag{26}$$

where U_t follows the same price aggregator as equation 16 using equation 19.

Private sector investment is then split between investment in new capital and reconstruction of damaged capital. Given that the capital destroyed by climate disasters has a productivity equal to the pre-disaster average capital productivity, typically higher than marginal productivity in the absence of disaster damages, the optimal response would be to direct all investment to reconstruction (and stop all other investments until all damages are repaired). However, agency problems (not all investors will own the damaged capital) and regional and sectoral capacity constraints means that only a fraction of investment flows can be dedicated to reconstruction. To reflect these considerations, it is assumed that rebuilding investment cannot exceed a share ϕ of total investment,

$$IR_t^P = \min\left((1-\delta)\, DS_{t-1}^P + RD_t^P, \phi I_{S,t}^P \right). \tag{27}$$

We assume that the ϕ is constant and equals 5%,[9] reflecting improved capacity to rebuild quickly whether from institutional, financial, or technical interventions.

The private sector capital is then driven by the following equation,

$$K_{S,t}^{P} = (1-\delta)K_{S,t-1}^{P} + I_{S,t}^{P} - IR_{t}^{P}. \tag{28}$$

Gross investments, $I_{S,t}^{P}$, are added to the existing capital stock net of depreciation, while reconstruction investments, IR_t^P, represent diverted investments to reconstruction. In the long-run, the investment to capital ratio equals the rate of capital depreciation plus long-term growth (Δy_t^*).

2.4 Data and estimation

The macroeconomic model is estimated and calibrated using the methodology presented in Burns and Jooste (2019). Appendix A summarizes the main equations of the model, while the main text focuses on the new features to the model. To calibrate the model, we use available capital data compiled by the World Bank[10] and the Penn World Tables (Feenstra et al., 2015). The Penn tables distinguish the capital stock in structures and non-structures, with their prices, which allows for an estimate of the elasticity of substitution across capital stocks. Note that model parameters are estimated using either OLS for single equations or FIML for systems (see Appendix C for key parameter estimates).[11]

Focusing on this paper's innovation, capital is aggregated using a CES function, with our main elasticity of interest being σ_1, which measures the substitution between infrastructure and non-infrastructure capital. This parameter is important for estimating the impact of disasters on the marginal product of capital. The productivity of non-infrastructure capital will rise or fall in line with an increase or decrease in infrastructure productivity if the two capital variables are complements.[12]

The data includes $n = 67$ countries from 1996 to 2017. We use a combination of pooled and fixed effects to estimate the elasticity of substitution. The dependent variable is the ratio of infrastructure capital to non-infrastructure capital, which is a function of the relative price of non-infrastructure capital to infrastructure capital, $\ln\left(\frac{K_{S,n,t}}{K_{N,n,t}}\right) \approx \alpha_n + \sigma^1 \ln\left(\frac{U_{N,n,t}}{U_{Sn,t}}\right)$. Table 1 includes four sets of estimates. Column 1 is the pooled estimate, column 2 controls for country fixed effects, column 3 controls for time fixed effects while column 4 controls for both time and country fixed effects. The sign of of the elasticity of substitution is positive but insignificant when we omit country fixed effects and has low explanatory power. Adding country fixed effects suggests that the equals $\sigma^1 = 0.57$ or $\sigma^1 = 0.45$ when controlling for time effects. This implies that infrastructure and non-infrastructure capital are complements.

Unfortunately, data availability does not allow us to estimate the elasticity of substitution between private and public infrastructure or between private and public capital outside

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[9] This is calibrated so that the model reproduces anecdotal evidence on reconstruction after large disasters. In practice, its value depends on multiple factors, including disaster preparedness (contingent planning and financing), the size of the economy, and the mobility of resources within the economy.

[10] `https://www.worldbank.org/en/publication/macro-poverty-outlook`

[11] Summary of all parameters is available upon request.

[12] The share parameter, ω_1, is calibrated using the standard cost-share approach.

Table 1: Estimate of the elasticity of substitution

	$K_{S,T}/K_{N,T}$			
σ^1	-0.74 (0.95)	0.57*** (0.17)	-0.99 (0.99)	0.45* (0.24)
FE: Country	No	Yes	No	Yes
FE: Time	No	No	Yes	Yes
Obs.	1,474	1,474	1,474	1,474
F-Stat	155.55	150.63	13.55	120.35
R^2	0.09	0.87	0.16	0.88

Note: Brackets represent cross-section clustered standard errors.

infrastructure. We assume that they are substitutes and set $\sigma^S(\rho_2) = \sigma^N(\rho_3) = 2$.[13] The model with all equations and identities are solved using iterative methods such as Newton solver.

Figure 1 plots a heatmap of the aggregate effective TFP (as definied from the aggregate production function of 1) after a natural disaster by any combination of private and public infrastructure capital destroyed using the article's calibration. This heatmap demonstrates the type of complementarity between the capital stocks resulting from the estimation process. For example, if 50% of private capital is destroyed and 10% of the public sector is destroyed, 70% of effective TFP remains in the economy (or a 30% decrease in total TFP).

3 Macroeconomic impact of a natural disaster: an application to Türkiye

We start by illustrating several properties of the model. For the simulations, we start by generating a model-determined baseline without shocks for 200 periods, i.e., 200 years, that we identify as the steady state.[14] We then introduce (in year three of the simulations) a single shock relative to the steady state baseline, in the form of destruction of the infrastructure stock. In all figures, results In other words, we explore below the impact of shocks affecting out-of-steady-state economies..

3.1 Economic response after a natural disaster

To illustrate the model's behaviour, we simulate disasters with damages ranging from one to ten percent of the total infrastructure stock. We also include a disaster of equivalent intensity to the 7.8 Richter scale earthquake that devastated northwest Türkiye on August 17, 1999, causing losses estimated around 4 percent of the infrastructure stock.

Precise estimates of the economic losses due to the recent earthquake that affected Türkiye and Syria in February 6, 2023, are not yet available, but early estimates suggest

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[13] For other estimates of aggregate capital substitution between the private and government sector, see An et al. (2019).

[14] See Figure 11 in Appendix D.

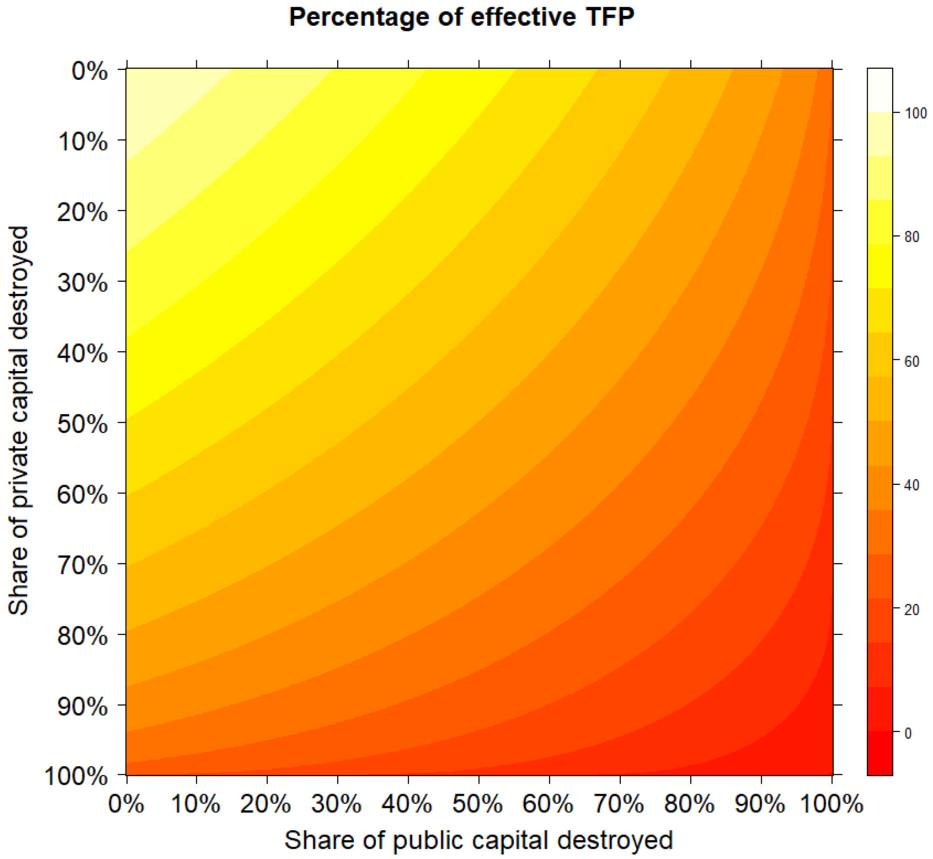

Figure 1: Heatmap of effective aggregate TFP after a natural disaster by any combination of private and public infrastructure capital destroyed using the paper's calibration

damages of similar or even higher magnitude than the 1999 event. World Bank's estimate suggest damages around $34 billion, or 3.6% of GDP, with 53% affecting residential buildings, 28% for non-residential buildings (e.g., health facilities, schools, government buildings, and private sector buildings), and 19% for other infrastructure (e.g., roads, power, water supply).[15] Since these damages are only for the infrastructure sector as defined in our model (which includes residential and non-residential sector), these damages would represent around 7% of the infrastructure stock.

Results of the simulations are shown in figure 2.[16] They highlight the importance of the macroeconomic dynamics, and the difference between GDP and potential GDP. While supply (i.e., potential GDP) reacts strongly to large shocks, economic mechanisms and dynamics smooth and delay the economic response. For instance, the model estimates that the 1999 Marmara earthquake resulted in a loss of 1.5 percent of GDP in the year of the event, which is much lower than the 4 percent decline in potential GDP. The earthquake occurred during an economic recession that makes it difficult to quantify empirically the GDP losses and compare historical data series with the model result (which starts from the

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[15] https://www.worldbank.org/en/news/press-release/2023/02/27/earthquake-damage-in-turkiye-estimated-to-exceed-34-billion-world-bank-disaster-assessment-report

[16] Appendices E and F provide a simulation using global earthquake modeling and flood impact input to calibrate shocks and discuss macroeconomic impact results.

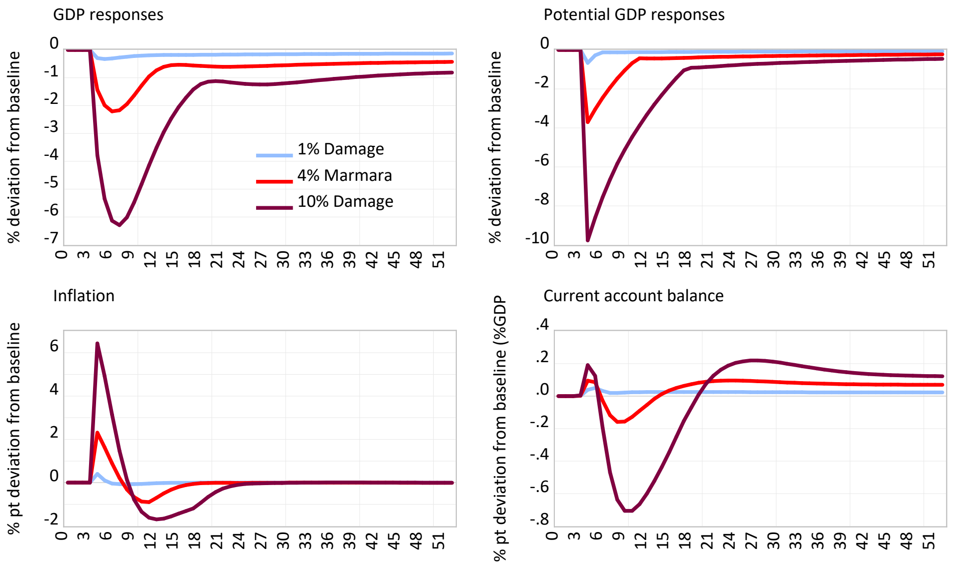

Figure 2: Sensitivity of economic response (GDP and inflation) to capital losses of different intensity, including a loss illustrating the 1999 Marmara earthquake.

steady state). For comparison, a model-based simulation done after the event (World Bank, 1999) suggested immediate losses amounting to 0.6 to 1 percent of GDP.

The V-shaped response of potential GDP reflects the reconstruction process. It takes the economy about three years to repair damages from a 1% loss in the capital stock, but the reconstruction period increases to six and fourteen years respectively for a Marmara-sized shock and a 10% shock.

The model also suggests a spike in inflation following the disaster. This result can be compared with empirical findings, but the latter remain mixed and inconclusive. For instance, Parker (2018) finds that inflation increases after climate shocks and that earthquakes increase the price of energy, clothing and footwear (while food prices seem decline in the first few quarters after the shock). More recently, using a simultaneous equation model with global data, Klomp (2020) finds a positive response of inflation after the occurrence of an earthquake. However, Cavallo et al. (2014) studies the impacts of the 2010 Chilean and the 2011 Japanese earthquakes and show that shortages after these events did not translate into higher prices. And Doyle and Noy (2015) showed that the Canterbury earthquake in 2010 generated a (insignificant) fall in aggregate demand that decreased prices.

To better illustrate investment responses we also simulate a very large shock with damages reaching 20% of total infrastructure capital. In this scenario, reconstruction occurs over a 20-year period. Figures 3 shows that GDP falls by about 14%. The marginal product of capital increases by just over 5%, which induces some positive response of infrastructure investments (in addition to reconstruction investments - Figure 4). This large-scale destruction generates a surge of inflation, which has an impact on household consumption through real income. While the debt-to-GDP ratio initially declines, mainly because the denominator is dominated by prices, it then increases when the fiscal rule kicks in and inflation returns to its baseline.

The fiscal rule in the model captures actual spending behavior of the government,[17] but also include a long-term debt sustainability anchor: when debt exceeds a threshold of 60%, expenditures decline and the market premium increases, diverting more resources to debt service. Monetary policy is modeled as a Taylor rule (Appendix A.10), and the nominal interest rate rises in response to inflation. While both exports and imports fall following the shock, exports fall by more. Imports fall in response to a decline in domestic demand, which is slightly offset by the real currency appreciations. Exports fall because of a loss in real competitiveness. Trade balance worsens after the disaster, and the real exchange rate appreciates due to both inflation and higher nominal interest rates (See Appendix A.11). Note that the initial increase in the current account balance reflects the short run elasticity of imports to a reduction in final demand - i.e., final demand falls immediately following the natural disaster causing imports to fall, reflecting a temporary current account balance gain.

One important response in the model is the drop in aggregate private investment after a major disaster, which is driven by the drop in GDP. The bottom panel of figure 4 shows the reconstruction spending after a large disaster (20% of capital). By far the most important response is from the private sector, which accounts for the largest share of total capital stock in Türkiye. The top panel shows the deviation of non-reconstruction investment from the baseline. While total investments decline, the *share* of infrastructure investment in GDP, before accounting for reconstruction, initially increases and then deteriorates, while non-infrastructure investment increases. Note that total investment is still declining relative to baseline, but less than GDP, and hence the top panel shows as an increase in percent of GDP.

The dynamics of private sector investment are determined by three factors: the persistence of investment decisions, the level of capital stock, and the net return on capital (see equation 24) (which is in turns influenced by the complementarity across capital types). .

Figure 5, bottom left panel, shows that the net return on capital is volatile in the short-term, responding to real and monetary factors. However, this volatility has little influence on capital stock (upper left panel). In the short term, the response of investment dynamics after the shock is mainly driven by the strong variation in potential output growth, which dominates the impact of the volatility of net returns.

The reduction in medium- to long-term infrastructure investments is primarily determined by the reduction in the amount of infrastructure capital relative to the baseline. To understand these medium- and long-run supply-side responses, we focus the interpretation on the denominator of the investment equations (see equation 24). The top panel of Figure 5 shows that both infrastructure and non-infrastructure capital decline following the shock. Since reconstruction investments are financed by reducing other investments in these simulations, resources are diverted away from productive capital investments that would have been made in the absence of shocks. The net effect of the shock on capital is negative.

The dynamics of the positive response of non-infrastructure investment relative to GDP is explained by the inertia of this type of investment while GDP, the denominator, deteriorates. We note that the signs of the variations between infrastructure and non-infrastructure are similar throughout the simulation, which is the consequence of the complementary be-

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[17] The infrastructure investment reaction function has an R^2 of 0.94, while for non-infrastructure it is 0.84.

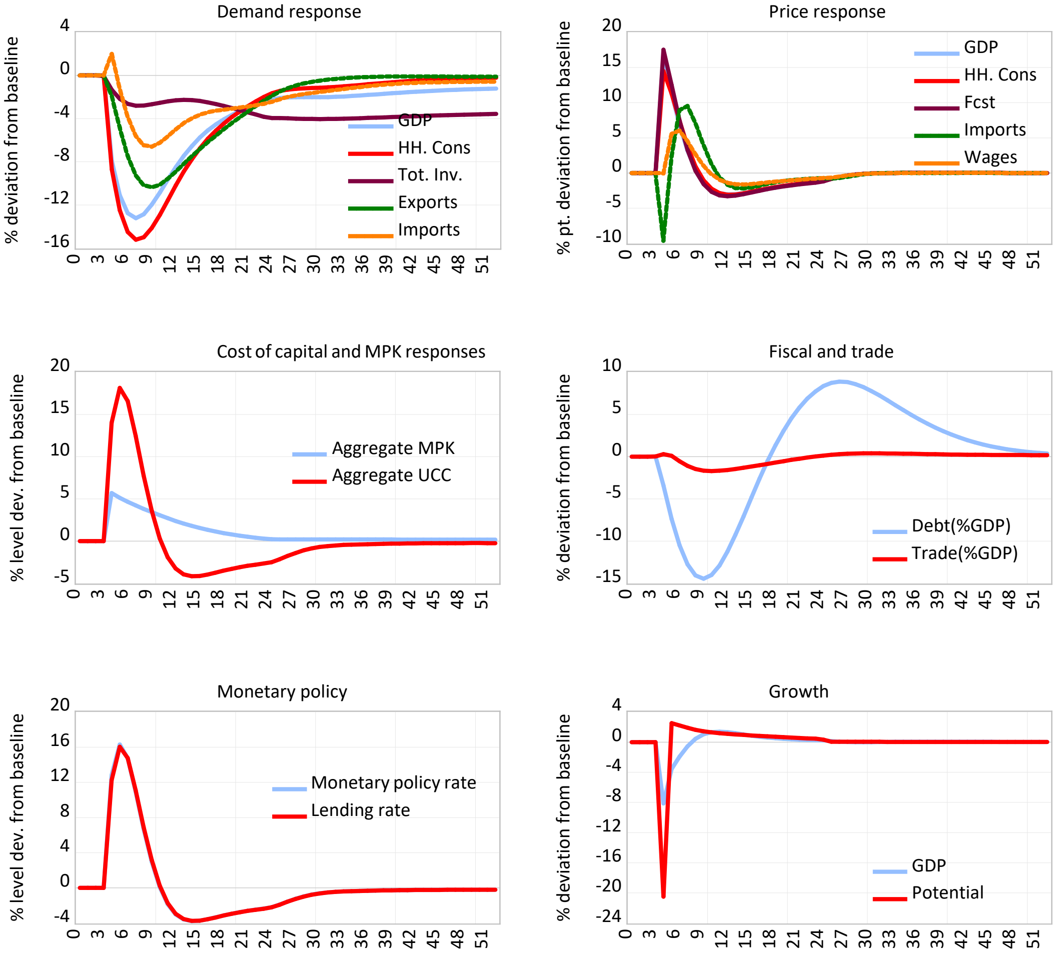

Figure 3: Economic impacts of large-scale disaster with damages equal to 20% of the infrastructure stock

Note: HH. Cons refers to household consumption; Tot. Inv refers to total investment; Fcst refers to factor cost GDP; MPK refers to the marginal product of capital; UCC is the user cost of capital.

tween these two types of capital.

3.2 Main differences with standard framework

We now compare the model's responses to the original version of the model with a single capital stock, as is standard in most macroeconomic models. Figure 6 summarizes the contribution of this paper. A standard framework with a unique capital stock tends to minimize the short-term shock compared to the modeling framework proposed in this paper. At least two factors account for this difference. First, the standard framework assumes that the remaining capital remains as productive as it was before the shock, while the augmented model takes into consideration the the complementarity between infrastructure and non-infrastructure capital. Second, a lower level of capital after a shock significantly increases the marginal productivity of capital in the standard framework, which increases investment

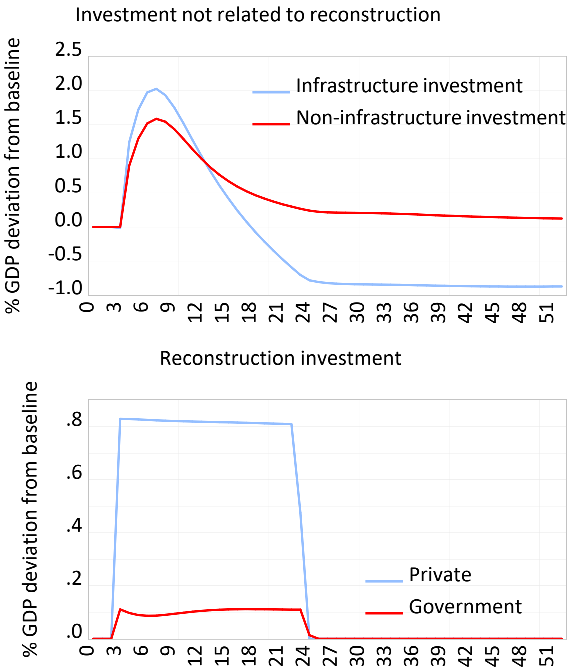

Figure 4: Share of GDP dedicated to investment in reconstruction and other investment.

that partially offsets the loss of capital after the shock. Together, these two factors lead to significantly lower estimates of the economic consequences of major disasters.

The influence of the substitutability across capital types is also estimated by running the model with different values of ρ_1, ρ_2, and ρ_3, ranging from an almost-Leontief assumption of perfect complementarity ($\rho_i = -9$) to an almost-Cobb-Douglas ($\rho_i = 0.09$) to an almost-linear assumption of perfect substitution ($\rho_i = 0.93$). A higher degree of substitution reduces the impact on potential GDP. In the most optimistic case (almost perfect substitutability), the potential GDP is even above the baseline after a few years. Specifications ranging from Cobb-Douglas to Leontief show a negative path and a relatively narrow range, which shows the robustness of the results discussed in this section to potential calibration errors.

This result shows the potential bias of simply adding different types of capital in the presence of strong complementarity . Macroeconomic models with damages (be from natural or climate disasters) need to account for he effect of aggregation, as the policy response may be inadequate when different types of capital stocks are not substitutable.

4 Policy implications in terms of welfare, business cycles, and monetary policy

We explore next the importance of macroeconomic and monetary policies in determining the total impact on welfare after natural disaster shocks. The section begins by discussing the relationship between asset losses and consumption (and welfare) losses. It then looks at the role of economic conditions (boom or bust) at the time of the disaster, and finally

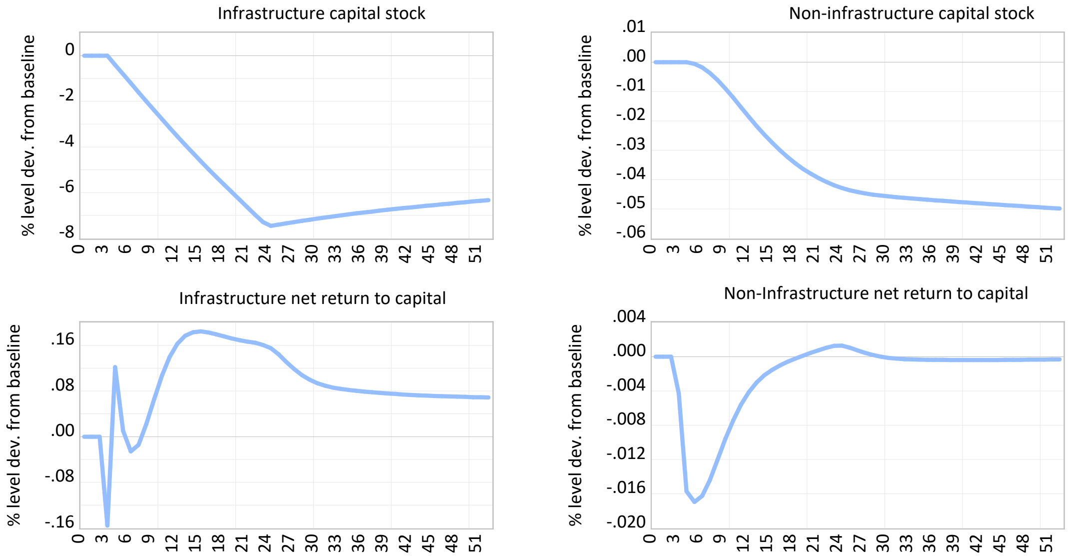

Figure 5: Capital stocks and their net returns in response to a large shock

explores the role of monetary policy.

4.1 The role of recovery and reconstruction finance and preparedness

Figure 7 summarizes the consumption losses in net present value (NPV) for different magnitudes of the natural disaster damages, assuming a 6% discount rate. The x-axis shows the damages on capital (in terms of GDP), and both are expressed in percent of GDP after a disaster shock.

Figure 7 shows that total consumption losses (discounted) increase nonlinearly with the amount of damage. For large disasters, total consumption losses exceed the value of the physical damages. In our simulations, consumption losses exceed direct asset losses when the latter are bigger than around 6% of GDP. For smaller shocks, these simulations suggest that the economy can absorb the shock, building on its ability to borrow and reallocate resources, so that the final consumption losses are below or equal to the replacement cost of the lost capital. For larger shocks, the longer duration of the reconstruction period and the propagation of impacts (with a reduction in the production of the non-affected capital) magnify consumption losses. Qualitatively, these results are consistent with empirical results (e.g., Felbermayr and Gröschl, 2014) and previous modeling exercises (e.g., Hallegatte and Ghil, 2008), but realized within a more sophisticated macroeconomic framework.

In the case of Türkiye, our model suggests that the threshold level (i.e., when curves are above the 45-degree line in light dotted grey) at which consumption losses exceed asset losses is high, and the nonlinearity is low. This result should be viewed with caution, however, as this threshold will depend on a few parameters that are difficult to estimate, such as the economy's ability to mobilize resources for reconstruction.

Figure 7 also illustrates the potential benefits from preparedness: by increasing the capacity to mobilize (or divert) resources for reconstruction, changing the parameter ϕ in eq. 27 from 5% to 20%, the threshold increases from 6% to 21%. The faster the economy

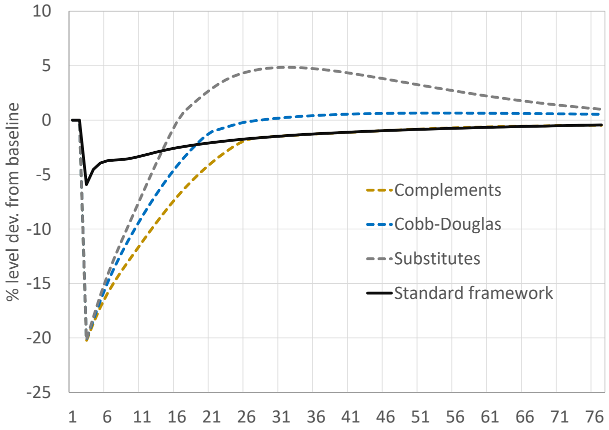

Figure 6: Changes in potential GDP in response of a 20% shock on capital for the original model (single capital stock), and three assumptions regarding the complementarity across capital types

is able to rebuild, the less welfare is lost. This can be achieved. This can be achieved through institutional interventions (e.g., streamlining procurement and permitting for reconstruction), financial interventions (e.g., reserve funds, contingent credit lines or insurance products), and technical interventions (e.g., measures to increase production capacity in the sectors involved in reconstruction, such as special work permits for foreign workers).

4.2 The importance of the economic situation before the shock

The previous simulations were performed on a steady state growth path, but disasters affect economies at specific phases of their business cycle. For example, the Marmara earthquake affected Türkiye during a recession. The economic response to a shock is likely to depend on the phase of the business cycle: in particular, the increase in demand created by reconstruction is less likely to displace workers and production capacity during a recession than during an expansion. In addition, the demand created by reconstruction can act as a stimulus, boosting aggregate demand and accelerating the macroeconomic recovery and reconstruction process. For example, the 1992 Hurricane Andrew hit Florida when half of the construction workers in the state were unemployed, while the 2004 hurricane season affected Florida when resources in the construction sector were already fully employed to meet a large demand.

To explore the importance of pre-existing economic conditions, we simulate the same disasters affecting the same economy (i.e., a 20% reduction in output), but during an expansion or recession phase of its business cycle. We generate business cycle movements (i.e., booms and recessions) by altering TFP and then adding the natural disaster shock. Figure 8 shows,as expected, the drop in GDP is smaller and the recovery faster if the economy is in recession before the shock. These results confirm previous theoretical and empirical findings from Ginn (2021); Hallegatte and Ghil (2008) that economies in recession are

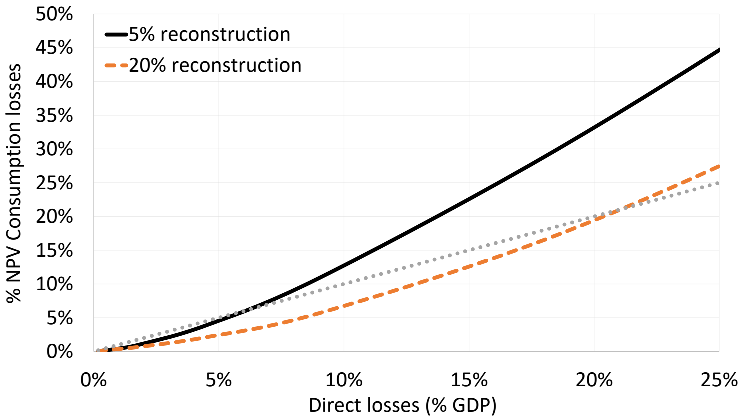

Figure 7: Direct versus the net present value consumption losses: Reconstruction — the light dotted grey line is the 45 degree line lags

more resilient to natural disasters, as the reconstruction process can mobilize idle resources without crowding out other investments.

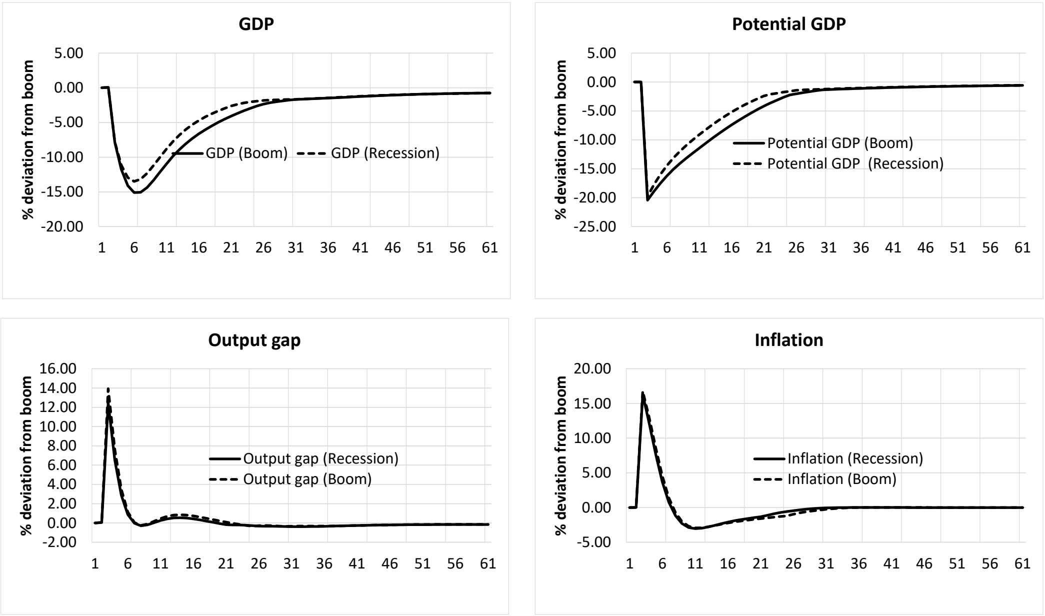

Figure 8: Model responses after a large natural disaster that occurs during economic recessions and booms

4.3 The importance of monetary policy

The role of monetary policy and the degree of price stickiness are also important factors that determine the total economic cost during disaster shocks. In the model, inflation is anchored by inflation expectations (modeled explicitly through the Taylor rule), while the dynamics of inflation depend on the degree of price stickiness when marginal costs change. While Türkiye currently has high inflation rates (at the time of writing this paper), it is assumed in this paper that it will return to target inflation via changes in interest rates.

Results in the previous section illustrate the classical monetary policy dilemma: how to accommodate the supply-side real shock without magnifying economic costs or destabilizing inflation expectations? We conduct a monetary policy experiment to shed light on possible policy actions. In practice, we compare the model's responses in cases with rigid and flexible prices, under an active monetary policy or a *delayed* monetary policy response that does not react immediately to the disaster-related response in inflation. This strategy somewhat mimics the optimal monetary policy during temporary supply contractions presented in Caballero and Simsek (2022) for a similar macro-framework.

Figure 9 shows that active monetary policy does not significantly reduce inflation after the shock, because the initial supply-side shock outweighs the impact of monetary policy. Note that the inflation responses are determined by the cost of capital and hence an increase in the marginal cost and producer prices as shown in Figure 3. Furthermore, active monetary policy reduces further consumption, investment, and thus output (see right panel), which in effect amplifies the recessionary effects after natural disasters. In a flexible price system, inflation returns to equilibrium faster, but results in a larger cumulative loss of output.

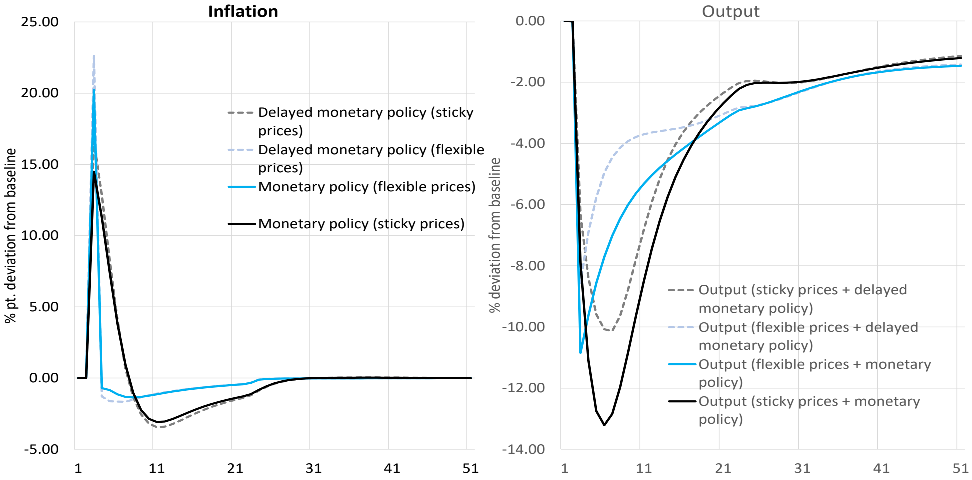

Figure 9: Model responses conditional on monetary policy strategies with and without delays after a large shock

Delayed monetary policy response assumes a lag (roughly 4 years) in the reaction function during the period of cost-push pressure immediately after the shock, supposing that the inflation created by the sudden supply-side shock should not trigger monetary tightening. This simulation would be equivalent to a catastrophe *escape clause* in the application of the Taylor rule. Figure 9 shows that the suspension in monetary policy response can mitigate the output and consumption impact significantly, without generating large trade-off with long-term inflation. These findings are aligned with past monetary policy practices reported in Klomp (2020) in the context of earthquakes. This paper shows that the policy interest rate drops in the first year after an earthquake, meaning that monetary authorities prioritized recovery over price stability.

To illustrate the potential benefit from such a delayed monetary policy response, figure 10 shows the consumption losses in net present value (NPV) for different magnitudes of the natural disaster damages, but this time with the two monetary policy responses. If the monetary policy response is suspended for a short period after the shock (so that it responds only to second-round inflationary effects), the welfare impact of the disasters is reduced. In particular, threshold beyond which consumption losses exceed asset losses increases from 6% to roughly 11% (see orange curve), making the economic system significantly more resilient to the shock.

These results call for more research on the design of monetary policy in post-disaster and crisis situations, a topic with considerable uncertainty. As an example, Ehrmann and Smets (2003) explore the economic consequences when monetary policy reacts to incorrect information, and show that a more conservative approach (i.e., reducing the weight on the output gap in the interest rate reaction function) reduces the welfare loss from supply-side shocks. And Ferrero et al. (2019) show that the uncertainty on the inflation response to the output gap should lead to a monetary policy response that is more aggressive for transient shocks and more cautious for permanent shocks. Alternative monetary policy reaction functions, such as nominal GDP or price-level targeting, can also be considered in this modeling framework. With these rules, interest rates would fall only in cases where output would fall by more than the increase in the price level.

Natural disasters are exogenous, short, and transitory shocks. They are therefore less likely to destabilize inflation expectations. In this particular case, our model suggests that a temporary suspension in monetary policy (i.e., not increasing rates immediately following a natural disaster) helps the economy cope with the transient supply-side shock. However, in the context of climate change, when particular shocks become increasingly frequent, they may affect inflation expectations and a similar strategy may have unintended adverse effects (Batten et al., 2016; Rudebusch et al., 2019). In the current Turkish context, it should be recognized that inflation is historically high and that inflation expectations may not be anchored and therefore sensitive to shocks under a loose monetary policy regime.

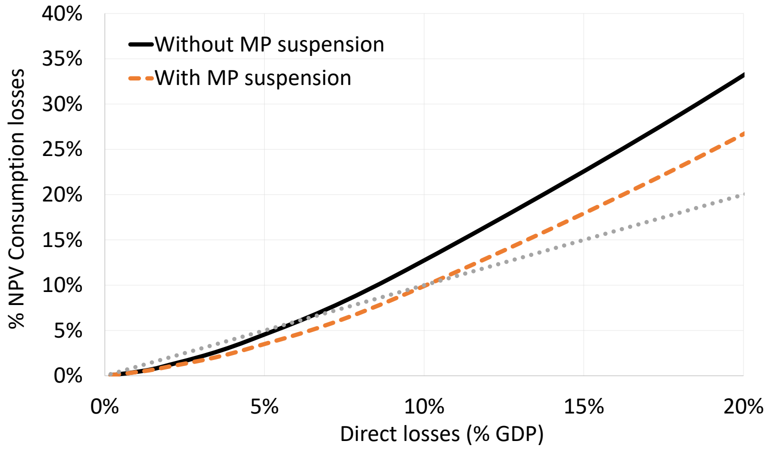

Figure 10: Direct versus the net present value consumption losses, with and without monetary policy suspension — the light dotted grey line is the 45 degree line

5 Concluding remarks

This paper presents an extension of a macroeconomic model to capture the impacts of natural disasters. It includes several changes that are essential to analyze the impact of natural disasters on economic activity, taking into account the specific of disaster-caused capital damages: (1) The capital stock is disaggregated into infrastructure and non-infrastructure capital. (2) Private and public sector investment decisions into reconstruction are separated and explicitly modeled. (3) The impact of the shock on the productivity of non-affected capital is explicitly introduced. (4) Realistic constraints on the pace of reconstruction are taken into account.

The marginal product of capital plays an important role in investment allocation decisions. The productivity of infrastructure capital increases significantly after a natural disaster, while the implications for non-infrastructure capital depend crucially on the elasticity of substitution between types of capital. Empirical estimates suggest that the two capital stocks are complements. Thus, if a natural disaster destroys infrastructure capital, then non-infrastructure capital also becomes unproductive, which magnifies the impact of the disaster on GDP and affect incentives to invest. In a simpler model where the capital stock is represented with a unique variable K, this effect would be equivalent to a loss in capital and a loss of total factor productivity (which is consistent with empirical observations). Models where only a single capital stock variable exists will thus under-estimate the impact of natural disasters, unless an impact of the disaster through capital productivity is also included.

In the model, disasters generate total (discounted) consumption losses that respond non-linearly to (and may exceed) direct physical damage. This result is also consistent with empirical evidence. For small disasters, the economic system can absorb the impact thanks to resource reallocation, imports, and borrowing, such that the total welfare cost is similar to or even lower than the direct physical damages.[18] For larger disasters, the economy reaches the limits of its ability to reallocate resources, the reconstruction period extends over several years, and direct physical impacts are magnified. The absorptive capacity of the economy is controlled by a few parameters, including the ability of the economy to reallocate resources toward reconstruction and to implement the appropriate monetary policy response.

The destruction of capital (and the increase in the marginal product of capital) generates inflation, which can be more or less persistent depending on price stickiness. If monetary policy reacts immediately to the supply shock by increasing interest rates, economic losses are magnified. Monetary policy tightening increases the cost of borrowing for both the government and the private sector and reduces consumption. A delayed response (usually when second round effects materialize due to changes in demand) can mitigate the negative economic effects of disasters. However, in the context of climate change or in countries with high inflation, increasingly frequent shocks may unanchor inflation expectations and reverse this result.

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[18] This is ignoring the direct human impact of disasters, which is not included in the model in spite of its scale and importance, especially after strong earthquakes.

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Appendices

A Main modeling equations of MFMod

This annex details the main equations used for the simulations.

Output, Y_t, in the economy is produced using capital, K_t, and labor, N_t, as inputs. The efficiency of labor and capital as well as technological change in captured in the total factor productivity term, A_t, and is assumed to be Hicks-neutral.

$$Y_t^* = A_t K_{t-1}^{1-\alpha} N_t^{*\alpha}$$

where capital is installed at the end of period and α is the output elasticity of labor.

In this economy private and public capital are substitutes or compliments (as described in the main text).

Structural employment (i.e., that part of employment consistent with the equilibrium unemployment rate, U_t^*, and when the economy is operating at potential) is derived from a natural wage rate of unemployment derivation (i.e., a function of product and wage markups, tax wedges and minimum wage):

$$N_t^* = (1 - U_t^*) \underbrace{PR_t WPOP_t}_{\text{Labor Force}}.$$

Note that the labor force is simply the participation rate, PR_t, multiplied by the working age population, $WPOP_t$.

GDP

We measure GDP from the three standard approaches: (i) expenditure, (ii) production and (iii) income accounts.

GDP from the expenditure side (also called market price GDP) is the sum of private household consumption, C_t, government consumption, C_t^G, private and public investment, $I_t^P + I_t^G$, the change in inventories, II_t, exports, X_t less imports, M_t and a statistical discrepancy, $Stat_t$:

$$Y_{MKTP,t} = C_t + C_t^G + I_t^P + I_t^G + X_t - M_t + II_t + Stat_t.$$

GDP from the production (GDP at factor prices) side is the sum of all value added activities (in this model it is agriculture, industry and services):

$$Y_{FCST,t} = Y_{AGR,t} + Y_{IND,t} + Y_{SRV,t}$$

Finally GDP from the income side is the sum of the wage bill, $W_t N_t$, plus gross operating surplus, $R_t K_t$:

$$Y_{INC,t} = \underbrace{W_t N_t}_{\text{Wage bill}} + \underbrace{R_t K_t}_{\text{GOS}}.$$

How do these equations relate to each other? We know that value-added is the sum of the wage bill and gross operating surplus. As an example, agricultural value-added is

$Y_{AGR,t} = (W_{AGR,t}N_{AGR,t} + R_{AGR,t}K_{AGR,t})$. Economy-wide GDP is thus just the sum over all sectors:

$$Y_{FCST,t} = Y_{INC,t} \Rightarrow \sum_{i=1}^{K}(W_{i,t}N_{i,t} + R_{i,t}K_{i,t})$$

Mapping factor cost and income GDP to market price GDP is easy at the aggregate level. One simply adds net indirect taxes less subsidies, $T_{NITS,t}$:

$$Y_{MKTP,t} = Y_{FCST,t} + T_{NITS,t} = Y_{INC,t} + T_{NITS,t}.$$

The mapping at a sectoral level is only slightly more complicated. The following equations create a map from input output tables value-added. As an example, agriculture value-added, Y_{AGR}, can be written as:

$$\mathrm{Y}_{AGR,t} + INTD_{AGR,t} + M_{AGR,t} + T_{NITSt} = C_{AGR,t} + C^G_{AGR,t} + I^P_{AGR,t} + I^G_{AGR,t} + II_{AGR,t} + X_{AGR,t} + INTS_{AGR,t},$$

where $INTD_{AGR,t}$ is the intermediate demand by agriculture and $INTS_{AGR,t}$ is the intermediate supply. A slight reorganization yields:

$$Y_{AGR,t} = \frac{(1+\beta_{AGR})(C_{AGR,t} + C^G_{AGR,t} + I^P_{AGR,t} + I^G_{AGR,t} + II_{AGR,t} + X_{AGR,t}) - M_{AGR,t} - T_{NITSt}}{1+\gamma_{AGR}}.$$

Note that $\beta_{AGR} = \frac{INTS_{AGR,t}}{C_{AGR,t}+C^G_{AGR,t}+I^P_{AGR,t}+I^G_{AGR,t}+II_{AGR,t}+X_{AGR,t}}$ and $\gamma_{AGR} = \frac{INTD_{AGR,t}}{Y_{AGR,t}}$.

We can simplify the expression once more by writing each of the agricultural demands as a fraction of total:

$$\mathrm{Y}_{AGR,t} = \frac{(1+\beta_{AGR})(\alpha^C_{AGR}C_t+\alpha^{C^G}_{AGR}C^G_t+\alpha^{I^P}_{AGR}I^P_t+\alpha^{I^G}_{AGR}I^G_t+\alpha^{II}_{AGR}II_t+\alpha^X_{AGR}X_t)-\alpha^M_{AGR}M_t-\alpha^T_{AGR}T_{NITS,t}}{1+\gamma_{AGR}},$$

where it is important that the sum of each parameter for demand type j over the sectors equal 1: $\sum_{i=1}^{K}\alpha_i^j = 1$

Our main set of equations for activities can be represented as

$$Y_{j,t} = \frac{(1+\beta_j)(\alpha^C_j C_t + \alpha^{C^G}_j C^G_t + \alpha^{I^P}_j I^P_t + \alpha^{I^G}_j I^G_t + \alpha^{II}_j II_t + \alpha^X_j X_t) - \alpha^M_j M_t - \alpha^T_j T_{NITS,t}}{1+\gamma_j}$$

$$Y_{FCST,t} = \sum_{j=1}^{K} Y_{j,t}$$

A.1 Market price GDP components

In the following sections we derive the main aggregate demand components.

Household consumption

Lifetime utility (U) is given as:

$$U = u(C_1) + \beta u(C_2),$$

where $u^{'} > 0, u^{''} < 0$ and $\beta = 1/(1+\rho)$ which is the rate of time preference.

The consumer's budget constraint includes real income for labor net of taxes, $W_tN_t(1-\tau_t^N)$, and inherited wealth/debt, V_1. The wealth that the consumer will be left with in period 1 will depend on the real interest rate and can be written as:

$$V_2 = (1+r)[V_1 + W_1N_1(1-\tau_1^N) - C_1].$$

Period 2 budget constraint is given by:

$$C_2 = V_2 + W_2N_2(1-\tau_2^N).$$

Substituting wealth into the constraint above and reordering

$$C_1 + C_2/(1+r) = V_1 + W_1N_1(1-\tau_1^N) + (W_2N_2(1-\tau_2^N))/(1+r).$$

This equation is the household's intertemporal budget constraint. The household will choose the time-path of consumption to maximize its utility function subject to the intertemporal budget constraint. Insert the budget constraint into the utility function to eliminate C_2:

$$U = u(C_1) + \beta u((1+r)[V_1 + W_1N_1(1-\tau_1^N) - C_1] + W_2N_2(1-\tau_2^N)).$$

The first order condition can be written as:

$$\frac{\partial U}{\partial C_1} = u^{'}(C_1) - \beta(1+r)u^{'}(\underbrace{(1+r)[V_1 + W_1N_1(1\tau_1^N) - C_1] + W_2N_2(1-\tau_2^N)}_{C_2}) = 0,$$

$$u^{'}(C_1) = \frac{1+r}{1+\rho}u^{'}(C_2).$$

If we assume the following constant elasticity of substitution utility function:

$$u(C_t) = \frac{C_t^{1-\sigma}}{1-\sigma},$$

then we can write the marginal rate of substitution as:

$$\frac{u^{'}(C_1)(1+\rho)}{u^{'}(C_2)} = (1+r) \Rightarrow \left(\frac{C_2(1+\rho)}{C_1}\right)^{\frac{1}{\sigma}} \Rightarrow C_2 = \left(\frac{1+r}{1+\rho}\right)^{\sigma} C_1.$$

Finally, if we substitute the solution above into our budget constraint $C_1 + C_2/(1+r) = V_1 + W_1N_1(1-\tau_1^N) + (W_2N_2(1-\tau_2^N))/(1+r)$, we obtain an equation similar to a standard Keynesian consumption function (with some differences):

$$C_1 = \frac{\left[V_1 + W_1N_1(1-\tau_t^N) + \frac{W_2N_2(1-\tau_2^N)}{1+r}\right]}{1 + (1+r)^{\sigma-1}(1+\rho)^{-\sigma}},$$

$$C_1 = \zeta(V_1 + H_1).$$

We may write our consumption function as:

$$C_1 = \hat{\zeta} W_1 N_1 (1 - \tau_1^N),$$

$$\hat{\zeta} = \zeta \left(1 + \frac{\kappa}{(1+r)} + v_1\right),$$

$$\kappa = \frac{(W_2 N_2 (1 - \tau_2^N))}{(W_1 N_1 (1 - \tau_t^N))}; v_1 = \frac{V_1}{(W_1 N_1 (1 - \tau_t^N))}.$$

If $W_2 N_2 (1 - \tau_2^N) = (1 + \Delta y^*) W_1 N_1 (1 - \tau_t^N)$ then $\hat{\zeta}$ can be written as:

$$\hat{\zeta} = \zeta \left(1 + \frac{1 + \Delta y^*}{1 + r} + v_1\right).$$

This equation says that consumption is positive in expected income and wealth, while negative in the real interest rate. Note that Δy^* is the steady state growth of the economy.

Taking logs and writing the equation in dynamic form:

$$\Delta c_t = \omega + \theta[c_{t-1} - c_{t-1}^*] + \sum_{j=1}^{k} \lambda_j \Delta c_{t-j}^* + \varepsilon_t^c,$$

$$c_t^* = ln(W_t N_t (1 - \tau_t^N) + V_t) e^{\Delta y^*} - \mu(r_t^{CR} - \pi_t).$$

This equation is a dynamic equation and represents an error-correction setup. θ is the error correction parameter, while c^* is the log of the long-run part of consumption. The dynamic short run elasticities are captured by λ_j while ε_t^c is an iid disturbance term.

In the long-run, the balanced growth path of consumption will be (drop time subscripts, $\varepsilon_t^c = 0$, and denote $\Delta c = g^c, \Omega = [c - c^*]$):

$$g^c = g^{C^*},$$

$$\Rightarrow g^{C^*}(1 - \lambda) = \omega + \theta\Omega,$$

$$\Rightarrow \Omega = \frac{g^{C^*}(1 - \lambda) - \omega}{\theta},$$

$$\Rightarrow c = c^* + \frac{g^{C^*}(1 - \lambda) - \omega}{\theta},$$

$$\Rightarrow c = ln(WN(1 - \tau^N) + V) + \frac{g^{C^*}(1 - \lambda) - \omega}{\theta}$$

$$\Rightarrow c = ln(\Theta Y) + \frac{\Delta y^*(1 - \lambda) - \omega}{\theta},$$

where $\Theta = \frac{(WN(1-\tau^N)+V)}{Y}$.

Household consumption is equal to a fixed share to GDP in the long-run due to the fixed relationship of the wage bill to GDP, and it should grow that the same rate as GDP in the long-run.

We approximate the some of the variables. Wealth is the difference between accumulated capital and foreign capital,

$$V_t = (K_t - KF_t).$$

Foreign capital stock is the difference between the current account balance and capital flows adjusted for the exchange rate and local prices,

$$KF_t = KF_{t-1} + (CAB_t - KFLOW_t).\frac{FX}{P_t^C}.$$

The real interest rate that the household faces is the nominal rate on credit less inflation,

$$r_t = (r_t^{CR} - \pi_t).$$

While long run growth is pinned down by population growth (Δpop_t) and TFP growth ($\frac{\Delta a_t}{\alpha}$):

$$\Delta y_t^* = \Delta pop_t + \frac{\Delta a_t}{\alpha}$$

Our main set of consumption equations are then

$$\Delta c_t = \omega + \theta[c_{t-1} - c_{t-1}^*] + \sum_{j=1}^{k} \lambda_j \Delta c_{t-j}^* + \varepsilon_t^c \tag{29}$$

$$c_t^* = ln(W_t N_t (1 - \tau_t^N) + V_t) e^{\Delta y^*} - \mu(r_t^{CR} - \pi_t) \tag{30}$$

A.2 Private Investment

Private investment decisions for firms depend on (i) adjustment costs; (ii) long-run returns and (iii) short-run returns vs. short-run costs. The framework is based on Tobin's Q, where the Q ratio is the solution to the return to capital and the cost of capital (or market value of assets of its replacement value.

The required rate of return, RR, must equal the expected rate of return, ER:

- RR = value of assets invested into bonds, r^b, plus a risk premium in order to invest in stock market
- RR = value of assets invested into bonds, r^b, plus a risk premium in order to invest in stock market
- ER = dividend plus expected capital gain, $(r^b + \epsilon)V_t = D_t^e + (V_{t+1})^e - V_t)$
- The real market value or share price can then be written as $V_t = \frac{(D_t^e + V_{t+1}^e)}{(1+r^b+\epsilon)}$
- The fundamental share price is then: $V_t = \frac{(D_t^e)}{(1+r^b+\epsilon)} + \frac{(D_{t+1}^e)}{(1+r^b+\epsilon)^2} + ... + \frac{(D_{t+n}^e}{(1+r^b+\epsilon)^n}$
- Note that in the limit: $\lim_{n\to\infty} \frac{V_{t+n}^e}{(1+r^b+\epsilon)^n} = 0$

Firms want to maximize their market value by choosing the level of investment taking as given the required rate of return. The relationship between the market value and replacement value as of firm's capital stock is

$$V_t = q_t K_t.$$

where $q_t = 1$ if the market and replacement values are equal.

It is assumed that current investment is financed via retained capital and that there are quadratic adjustment costs related to investment ($c(I) = \frac{a}{2}I^2$). The expected dividends are then equal to expected profits (Π_t^e) less retained earnings to finance expenditures,

$$D_t^e = \Pi_t^e - I_t^{KN^P} - c(I_t).$$

Noting that capital stock tomorrow is equal to capital in the previous period net of depreciation plus new investment ($K_{t+1} = (1-\delta)K_t + I_t^{KN^P}$), the value of the firm can then be written as:

$$V_t = \frac{(D_t^e + V_{t+1}^e)}{(1 + r^b + \epsilon)} = \frac{\overbrace{\Pi_t^e - I_t^{KN^P} - c(I_t)}^{D_t^e} + \overbrace{q_t((1-\delta)K_t + I_t^{KN^P})}^{V_{t+1}^e}}{1 + r^b + \epsilon}.$$

The optimal level of investment is

$$\frac{\partial V_t}{\partial I_t} = \underbrace{q_t}_{\text{expected capital gain}} = \underbrace{1 + \overbrace{\frac{\partial c}{\partial I_t}}^{aI_t}}_{\text{forgone dividend}} .$$

Thus, investment that maximizes firm value

$$I_t^{KN^P} = \frac{q_t - 1}{a}.$$

Note that we can rewrite the Tobin's q as: $q_t = \frac{\left(\frac{D_t^e}{K_t}\right)}{(r_t+\epsilon)}$ which relates the marginal product of capital to the cost of capital.

Furthermore, firm profits or dividend payouts equal the gross operating surplus: $D_t^e = (1-\alpha)Y_t$ for a competitive firm.

The discussion above describes the short-run behavior. The long-run is expressed by dividing the perpetual inventory calculation by capital stock in the current period,

$$\frac{K_{t+1}}{K_t} - 1 + \delta = \frac{I_t^{KN^P}}{K_t} \Rightarrow \frac{I_t^{KN^P}}{K_t} = \Delta y_t^* + \delta.$$

In the long-run, the stock of capital should grow at the rate of potential GDP (defined below) and the rate of depreciation. The investment equation is thus written taking both the long-run and short-run behavior into account and can be expressed as:

Our main equation that describes private investment is

$$\frac{I_t^{KN^P}}{K_{t-1}} = \beta_1 + \beta_2 ln\left(\frac{\frac{D_t^e}{K_t}}{r_t + \epsilon}\right) + (1-\beta_3)(\Delta y_t^* + \delta) + \beta_3 \frac{I_{t-1}^{KN^P}}{K_{t-2}} + \varepsilon_t^{IP} \tag{31}$$

In the long-run Tobin's Q equals 1 (and hence drops out of the equation) and solves to $(\Delta y_t^* + \delta)$ with a lag (β_3 is a parameter that measures the degree of investment persistence)

A.3 Imports and Exports

The rest of the world (ROW) uses imports, M, and local production, Y^D, to produce goods, Y^T. Imports and local production are substitutes:

$$Y_t^T = \left[\omega_1^{\frac{1}{\epsilon_1}} (M_t)^{\frac{\epsilon_1 - 1}{\epsilon_1}} + \omega_2^{\frac{1}{\epsilon_1}} (Y_t^D)^{\frac{\epsilon_1 - 1}{\epsilon_1}}\right]^{\frac{\epsilon_1}{\epsilon_1 - 1}},$$

where ϵ_1 is the elasticity of substitution, and ω_i is the share parameter.

Total cost of inputs can be represented as

$$P_t^T Y_t^T = (1 + \tau_t^M) P_t^M M_t^D + (1 + \tau_t^C) P_t^D Y_t^D.$$

where P_t^T is the aggregate output deflator, τ_t^M is an import duty, P_t^M is the import price deflator and P_t^D is the domestic price deflator.

The objective is to minimize costs subject to the assembly function. The first order condition for imports from our trading partner is:

$$M_t = \omega \left(\frac{(1 + \tau_t^M) P_t^M}{\lambda}\right)^{-\epsilon_1} Y_t^T.$$

Note that λ is the shadow price, which will be equal to weighted average of import prices and local production prices. The optimal import demand equation is thus a negative function of the relative price of imports over local production prices, and positive in domestic demand (in this case the sum of consumption and investment).

Note that we are dealing with a small open economy. Türkiye is thus a price taker. We proxy the gross import price as a function of a weighted commodity price index $P_t^{M,Key}$ (multiplied by the exchange rate to express prices in local currency) and domestic prices.

In the long run import and domestic prices are assumed to equalize (law of one-price), but equalization does not occur instantaneously. Import prices in every period adjusts so that in the long-run import price inflation, π_t^M, should equilibrate to inflation expectations, $E_{t-1}\pi_t^e$. We capture the degree of indexation, Φ_t^M, as

$$\Phi_t^M = (\pi_{t-1}^M)^{\omega_m} (E_{t-1}\pi_t^e)^{1-\omega_m}.$$

The speed with which import price inflation converges to inflation expectations is governed by an estimated parameter $\omega_m \in (0, 1)$.

The law of motion for imported goods prices is expressed via a CES aggregator

$$P_t^M = [\theta_M (\Phi_t^M P_{t-1}^M)^{1-\epsilon_m} + (1 - \theta_M) P_t^{M^* \, 1-\epsilon_m}]^{\frac{1}{1-\epsilon_m}}.$$

θ_M is the probability of adjusting prices according to an indexation rule, while $(1 - \theta_M)$ is the probability of choosing optimal prices. From a purely econometric perspective, θ_M captures the relative weight of current prices to past prices and an optimal price. Note that the equation above only stipulates the rule for price setting behavior, but does not define the optimal price, $P_t^{M^*}$. Given our assumption of Cobb-Douglas technology which imposes a long run elasticity of substitution of 1, $\epsilon_m \to 1$, the optimal price function simplifies to

$$P_t^M = (\Phi_t^M P_{t-1}^M)^{\theta_m} P_t^{M^* \, 1-\theta_m}.$$

Taking logs, we obtain an expression for the long-run component of import prices

$$p_t^M = \theta_m \ln(\Phi_t^M) + \theta_m p_{t-1}^M + (1 - \theta_m) p_t^{M^*}.$$

A.4 Marginal costs

Marginal costs (P_t^*) in the model needs to be consistent with the production function specified above. It is derived using the dual approach to the firm's problem by inserting the optimal input demands into the constraint. Marginal costs are thus a function of the various factor costs - wages (W_t) and the rental rate (R_t), which in this case is the price of labor and capital

$$P_t^* = \left(\frac{1}{A_t}\right)\left(\frac{W_t}{\alpha}\right)^{\alpha}\left(\frac{R_t}{1-\alpha}\right)^{1-\alpha}.$$

A.5 Producer prices

Producer prices follow a New-Keynesian setting. Prices are sticky and markups are assumed to vary with the output gap, $\tilde{y}_t$. Note that in an econometric framework there exists a price-wage loop. Wages are indexed to prices, but marginal costs are a function of wages. Given that both wages and prices are I(1) variables, we also have a cointegrating vector (i.e., one common stochastic trend). We thus write either the price or the wage equation in error correction form while the other is specified as a growth rate. In the model, wages represent the error-correction model while producer prices are written as a function of lagged inflation but converges to inflation expectations,

$$\pi_t^{FCST} = \beta_1 \pi_{t-1}^{FCST} + (1-\beta_1)(\beta_2 E_{t-1}\pi_t^e + (1-\beta_2)\Delta \text{ln} P_t^*) + \beta_3 \tilde{y}_t + \varepsilon_t^{\pi}.$$

The reduced-form price stickiness parameter is β_1.

A.6 Labor demand (employment)

The private employment equation is a function of aggregate wages and the structural employment, N^*, which is defined below

$$\begin{aligned}\Delta \ln N_t = c + \theta \left[\ln(N_{t-1}) - \ln(N_{t-1}^*)\right], \\ - \beta_1 \left(\underbrace{\Delta \ln\left(\frac{W_t}{P_t^{Fcst}}\right) - \frac{\Delta \ln A_t}{\alpha}}_{\text{(MPL-productivity)}}\right) + \beta_2(\Delta ln(Y_t) - \Delta ln(Y_t^*)). \quad (32)\end{aligned}$$

A.7 Wage-price loop

The solution of wages should equal the marginal productivities (i.e. reflect labor productivity)

$$\begin{aligned}\Delta \ln(W_t) = c + \theta \left[\ln(W_{t-1}) - \underbrace{\ln(P_{t-1}^{FCST}) - \ln\left(\frac{Y_{t-1}^*}{N_{t-1}^*}\right)}_{\text{nominal MPL}}\right], \\ + \beta_1 \Delta ln(W_{t-1}) + (1-\beta_1)\left(\Delta ln(P_t) + \Delta ln\left(\frac{Y_t^*}{N_t^*}\right)\right) + \beta_2[UNR_t - UNR_t^*] + \varepsilon_t^W. \quad (33)\end{aligned}$$

A.8 Determining labor supply (the labor force)

Labor supply is expressed as the ratio of the labor force over the working age population (which pins down the labor participation rate) and unemployment deviations from the NAWRU to proxy discouraged worker effects

$$\frac{LF_t}{WPOP_t} = c + \beta_1 \frac{LF_{t-1}}{WPOP_{t-1}} + \beta_2 \Delta ln\left(\frac{W_t}{P_t}\right) - \beta_3[UNR_t - UNR_t^*] + \varepsilon_t^{LF}.$$

A.9 The NAWRU and structural unemployment

Estimating the structural unemployment rate is hard and is driven by theoretical assumptions. The existence of a natural rate of unemployment is assumed on the basis of various real rigidities (search and match (e.g., Daly et al., 2012; Pissarides, 2000), efficiency wages (Shapiro and Stiglitz (1984)), minimum wages (Fields (1997)), labor union pressure (e.g., Johnson and Layard, 1986; Pissarides, 1986). For a useful empirical method based on a wage Phillips curve relationship, see (Blanchard and Katz (1999)).

The approach used in this model is based on distortions in prices and wages as well as taxes.

Assume that the production is generated by labor, N, and TFP A, (capital is assumed to equal unity)

$$Y_i = AN_i^{1-\alpha},$$

where $(1-\alpha)$ is the labor income share.

The marginal product of labor is:

$$MPL_i = (1-\alpha)AN_i^{-\alpha}$$

The firm produces differentiated goods as above and demand for each good is,

$$Y_i = D(P_i) = \frac{P_i}{P}^{-\sigma} \frac{Y}{n},$$

where σ is the elasticity of substitution between goods.

Marginal revenue can be calculated from total revenue $(TR_i = P_i Y_i)$

$$MR_i = \frac{dTR_i}{dY_i} = P_i + Y_i \frac{dP_i}{dY_i} = P_i \left(1 + \frac{dP_i}{dY_i}\frac{Y_i}{P_i}\right) = P_i \left(1 - \frac{1}{\sigma}\right).$$

This firm will expand output up until marginal revenue equals marginal costs (in this case the MPL),

$$MC_i = \frac{W_i}{MPL_i},$$

$$P_i\left(\frac{\sigma-1}{\sigma}\right) = \frac{W_i}{(1-\alpha)AN_i^{-\alpha}}.$$

$$P_i\left(\frac{\sigma-1}{\sigma}\right) = \frac{W_i}{(1-\alpha)AN_i^{-\alpha}} = \frac{m^p W_i}{(1-\alpha)AN_i^{-\alpha}}.$$

This standard equation suggests that prices are a markup over marginal costs.

Next we derive the employment needed to produce output. First divide the price of each good by the aggregate price,

$$\frac{P_i}{P} = \frac{m^p}{P}\frac{W_i}{(1-\alpha)AN_i^{-\alpha}}.$$

Insert the equation above into the demand equation,

$$Y_i = \left(\frac{m^p}{P}\frac{W_i}{(1-\alpha)AN_i^{-\alpha}}\right)^{-\sigma}\frac{Y}{n}.$$

Insert this equation into the production function and solve for employment,

$$Y_i = AN_i^{1-\alpha} \Rightarrow N_i = \left(\frac{Y_i}{A}\right)^{\frac{1}{(1-\alpha)}},$$

$$N_i = \left(\frac{\left(\frac{m^p}{P}\frac{W_i}{(1-\alpha)AN_i^{-\alpha}}\right)^{-\sigma}\frac{Y}{n}}{A}\right)^{\frac{1}{(1-\alpha)}}.$$

$$N_i = \left(\frac{W_i}{P}\right)^{\frac{-\sigma}{(1+\alpha(\sigma-1))}}\left(\frac{Y}{nA}\right)^{\frac{1}{(1+\alpha(\sigma-1))}}\left(\frac{(1-\alpha)A}{m^p}\right)^{\frac{\sigma}{(1+\alpha(\sigma-1))}}.$$

Next we derive the union's objective function which is to maximize the income of its members by either choosing wages or labor. Note that the union makes its decision after receiving wage signals from the employer,

$$\Gamma(w_i) = (1-\tau)(w_i - b)N_i(w_i)^{\zeta}.$$

where ζ is a parameter that weights the union's objective of either achieving a higher wage for its members or higher employment.

The union will attempt to set the wage to maximize the utility function taking the firm's labor demand decision into account

$$\frac{\partial\Gamma(w_i)}{\partial w_i} = N_i^{\zeta} + (1-\tau)(w_i-b)\zeta N_i^{\zeta-1}\frac{\partial L_i}{\partial w_i} = 0.$$

$$1 + \frac{(1-\tau)(w_i-b)\zeta}{w_i\frac{\partial N_i}{\partial w_i}\frac{w_i}{N_i}} \Rightarrow \ w_i = \frac{1-\tau\zeta\varepsilon}{(1-\tau)\zeta\varepsilon - 1)b}.$$

Or in nominal terms indexed to expected prices,

$$w_i = \frac{(1-\tau)\zeta\varepsilon}{((1-\tau)\zeta\varepsilon - 1)}bP^e = m^w * b * P^e.$$

This implies that under a dominant union, there will be a markup over the expected price. This markup is a function of taxes and the elasticity of labor demand $\frac{(\partial N_i)}{(\partial w_i)}\frac{w_i}{N_i} = \varepsilon$.

Substituting the real wage into the labor input schedule,

$$N_i = \left(\frac{Y}{nA}\right)^{\frac{1}{(1+\alpha(\sigma-1))}}\left(\frac{(1-\alpha)A}{m^p m^w b}\frac{P}{P^e}\right)^{\frac{\sigma}{(1+\alpha(\sigma-1))}}.$$

Total employment is $N = nN_i$ and using $Y = nY_i = nBN_i^{1-\alpha}$,

$$N = n\left(\frac{(1-\alpha)A}{m^p m^w b}\frac{P}{P^e}\right)^{\frac{1}{\alpha}}.$$

The natural rate of employment in equilibrium (when prices equal expectations),

$$N^* = n\left(\frac{(1-\alpha)A}{m^p m^w b}\right)^{\frac{1}{\alpha}}.$$

Or we can write the natural unemployment level as,

$$U^* = (1-N^*)LF.$$

Or in terms of a rate,

$$u^* = (1-N^*) = 1-\left(\frac{(1-\alpha)A}{m^p m^w b}\right)^{\frac{1}{\alpha}},$$

$$u^* = 1-\left(\frac{(1-\alpha)A}{\left(\frac{\sigma}{\sigma-1}\right)\left(\frac{(1-\tau)\zeta\varepsilon}{(1-\tau)\zeta\varepsilon-1}\right)*b}\right)^{\frac{1}{\alpha}}.$$

The natural rate of unemployment is a function of TFP, taxes, price markup (determined by the price elasticity of demand), the weight unions place on wages over employment, the labor demand elasticity, the labor income elasticity and the non-labor income.

Note that the labor demand elasticity is pinned down by the income share and elasticity of substitution for goods,

$$\varepsilon = \frac{\sigma}{1+\alpha(\sigma-1)}.$$

A.10 The monetary policy block

We assume that the authorities set interest rates according to a Taylor rule,

$$i_t^{MP} = \underbrace{r^n + \pi^*}_{i^n} + \theta(\pi_t^e - \pi^*) + \beta\tilde{y}_t + \varepsilon_t^{MP}.$$

where r^n is the real natural rate of interest, π^* is the inflation target and ε_t^{MP} is an iid innovation.

The natural rate of interest

With no taxes and no capital market frictions, an investor is indifferent between putting money in the bank and earning an interest rate r^b or buying a unit of capital and renting it out at the MPK or r_t^K. The unit purchase price of the good is P_t^I where the rate of change is pi_t. Note that capital depreciates at a rate of δ. The net profit over time is equal to the rental income received (less taxes), less loss in depreciation plus the capital gain from the change in prices: $r_t^K - \delta P_t + \pi_t$. The no arbitrage condition is simply (see Jorgenson (1996)),

$$MPK_t\,(1-\tau_t^{CIT}) = P_t^I\, r_t^b + \delta P_t^I - \pi_t$$

.

Or in terms of r_t^K,

$$(1-\alpha)\,\frac{P_tY_t^*}{K_t}(1-\tau_t^{CIT}) = P_t r^K(1-\tau_t^{CIT}) = P_t^I r_t^b \, + \delta P_t^I - \pi_t,$$

$$r_t^K = \frac{P_t^I}{P_t}\,\frac{[(r_t^b+\delta)]-\pi_t}{(1-\tau^{CIT})}.$$

Now we can use our monetary policy reaction function,

$$i_t^{MP} = \underbrace{r^n + \pi^*}_{i^n} + \theta(\pi_t^e - \pi^*) + \beta\tilde{y}_t + \varepsilon_t^{MP}.$$

For $(mpk_t - rl_t\ ) = 0$ in the long-run it must mean that $i_t^M P = i^n$ and that $(\pi_t - \pi^*) = 0$. Thus, the nominal natural rate of interest is,

$$\left(\frac{P_t^I[(i_t^{MP}+\delta)]-\pi_t}{P_t(1-\tau_t^{CIT})}\right) = (1-\alpha)\frac{Y_t^*}{K_t} \to i^n = \frac{\left[P_t(1-\tau_t^{CIT})\left[(1-\alpha)\frac{Y_t^*}{K_t}+\pi_t^{TRG}\right]\right]}{P_t^I} - \delta.$$

Note that the cost of capital requires us to specify how the investment deflator evolves. Justiniano et al. (2011) show that the investment deflator is proportional to the consumption price deflator for a cost minimizing investor. We follow this approach and add a nominal price rigidity, but assuming that the consumption and the investment good has the same marginal cost. This deflator, when expressed as a share of aggregate marginal cost is equal to an investment specific technological process (which is exogenous). The investment price deflator is modelled as an error-correction term and shares a common stochastic trend the consumer prices. The long-run level of the investment deflator converges to a constant ratio to the consumption deflator. In the short run, however, the growth rate of the investment deflator is a weighted average of nominal consumption inflation and its own lag, where the weight attached to past inflation, β, is estimated econometrically. Since there is no independent data on price deflators for public investment as distinct from private investment, nor for productive or adaptation investment, the four deflators are assumed to be equal

$$\pi_{j,t}^i = \theta\left[p_{j,t-1}^i - p_{t-1}^C - \ln(\alpha)\right] + \beta\pi_{j,t-1}^i + (1-\beta)\pi_t^C + \varepsilon_{j,t}^{PI},$$

where α is the wedge between the investment and consumption deflator (or equivalent to the investment specific technological process) and θ is the error correction parameter.[19] Note that all price indices are perfectly consistent with the aggregate capital stock from the production function and the different nests, as they have similar dynamics.

Connecting the implicit interest rate to average debt interest rates

Monetary policy interest rates are connected to both the public and private sector interest rates too. For the public sector we know that the term structure should, on average, equal the expected short-term interest rates over a bond's life cycle,

$$i_t^k = 1/k\ \sum_{j=1}^{k} i_{t+j}^{SR} + term_t^k,$$

---

[19] Lower case letters denote variables in logs.

where i^k_t is the yield of a k period bond.

We do not have interest yields by bond maturity and thus approximate the average implicit bond rate as the ratio of government interest expenses to the previous stock of debt,

$$i^b_t = \frac{G^{Int}_t}{D_{t-1}}.$$

This average interest rate on debt is a function of the risk-free rate and the short-term rate,

$$\Delta i^b_t = \alpha + \theta(i^b_{t-1} - i^{MP}_{t-1}) + \beta_1 \Delta i^{MP}_t + \Delta term_t + \varepsilon^{i^b}_t,$$

where the historical term premium is simply derived as

$$term_t = i^b_t - i^{RFREE}_t.$$

The term structure is assumed to increase if debt breaches a user-defined threshold,

$$term_t = \alpha * (e^{D_t - D^*} - 1),$$

where $D^* =$ target threshold. We can map the term to real rates via the Fisher equation where real rates enter the household decision:

$$r^{SR}_t = i^{SR}_t - E_{t-1}\, \pi_t.$$

$$r^B_t = i^B_t - E_{t-1}\, \pi_t.$$

The yield curve is then the difference between the short and long-run interest rates,

$$r^{yield}_t = r^B_t - r^{SR}_t.$$

Credit demand

Real credit demand for households and firms is a function of real economic activity and negatively related to interest rates,

$$\Delta ln\left(\frac{CR_t}{P^c_t}\right) = \alpha + \theta\left[ln\left(\frac{CR_{t-1}}{P^c_{t-1}}\right) - y_{t-1} + \phi(i^{CR}_{t-1} - i^{MP}_{t-1})\right] + \beta_1 \tilde{y}_t + \beta_1 \Delta i^{CR}_t + \varepsilon^{CR}_t.$$

Credit supply

Private sector credit interest rates move in line with monetary policy interest rates and with real credit demand,

$$\Delta i^{CR}_t = \alpha + \left[i^{CR}_{t-1} - i^{MP}_{t-1}\right] + \beta \Delta ln\left(\frac{CR_t}{P^c_t}\right) + \varepsilon^{i^{CR}}_t.$$

A.11 Exchange rates

Interest rates are assumed to follow an uncovered interest parity (UIP) framework. The interest rate that fixes the exchange rate is

$$\Delta \ln(FX_t\,) = \beta(r^{WORLD}_t - r^n - \rho^{FX}_t) + \gamma(\pi^{WORLD}_t - \pi_t).$$

where r^{WORLD}_t is the world real interest rate (proxied by the US Fed rate) and π^{WORLD}_t is the world inflation rate (also proxied by the US inflation rate). ρ^{FX}_t is the exchange rate risk premium, which is exogenous in our model.

A.12 Fiscal policy

One of the benefits of a macro-structural model allows one to comprehensively incorporate the fiscal dimensions of an economy. Apart from standard revenue and expenditure variables, one can easily embed the financing options of government too (primarily bond issuance, privatization or monetization).

The budget balance is equal to revenues less expenditures,

$$BB_t = R_t - G_t.$$

If the government runs a deficit then it finances it either via net domestic or foreign issuance,

$$BB_t = (FF_t^D + FF_t^E) \text{ if } BB_t < 0.$$

Net external issuance is equal to new loans less amortization in local currency,

$$FF_t^E = FX_t(FL_t^E - AMORT_t^E).$$

Net domestic issuance is equal to new loans less amortization and financialization,

$$FF_t^D = (FL_t^D - AMORT_t^D - FIN_t).$$

Amortizations in the model is determined via the implied average duration of debt, which is calculated as,

$$AMORT_t = \nu_t * D_{t-1}.$$

Government debt in the model is then equal to the previous stock of debt plus net issuance,

$$D_t = D_t^E + D_t^D = (D_{t-1}^E + FF_t^E) + (D_{t-1}^D + FF_t^E).$$

The risks to public finances are captured via changes to the maturity of debt ν, the interest on debt i^b and the exchange rate fx.

Fiscal expenditures

Total expenditure G_t is the model is the sum of compensation of employees, G_t^{COE}, use of goods and services, G_t^{GS}, net acquisition of non-financial assets, G_t^I, transfers to households, G_t^{SOC}, interest expenses, G_t^{INT}, adaptation investment, I_t^A and a residual other expenditures not captured by the main modeling equations, G_t^{OTH}. Leading to

$$G_t = G_t^{COE} + G_t^{GS} + G_t^I + G_t^{SOC} + G_t^{INT} + I_t^A + G_t^{OTH}.$$

Interest expenses are equal to domestic and foreign interest repayment (which are a function of their implied interest rates)

$$G_t^{INT} = G_t^{E,INT} + G_t^{D,INT},$$

$$G_t^{E,INT} = i_t^{E,b} D_{t-1}^E,$$

$$G_t^{D,INT} = i_t^{D,b} D_{t-1}^D.$$

The model allows for a set of discretionary choices. Fiscal policy can elect to follow a rule (which is important for model convergence) by keeping below a certain debt threshold,

$\bar{D}$, and reacting to various financing options in response to climate. The fiscal rule is applied to compensation of employees, use of goods and services and public investment

$$G_t^i = \beta G_{t-1}^i + (1-\beta)(\bar{gr}^i)(1-\bar{BB})(R_t - G_t^{INT}) - \psi_A^i I_t^A + \psi_B^i B_t^I,$$

where

- G_t^i is expenditure on category i
- β is the persistence/rigidity of expenditure (some countries have rolling budget cycles)
- $\bar{gr}^i = \frac{\bar{G}^i}{R - \bar{G}^{INT}}$ is the long-run share of expenditure i in terms of revenue
- $\bar{BB}$ is the targeted deficit (note that this needs to be in line with targeted debt)
- ψ_A^i is the share of disaster risk management of spending i. Note that there is a negative sign - this indicates that adaptation investment is financed via a reduction in other expenditures
- ψ_B^i is the share of expenditure allocated from the insurance payout
- Note that $\sum_i \psi_B^i = 1$ and $\sum_i \psi_A^i = 1$

Other expenditures are modeled as a function of GDP.

Fiscal revenues Total fiscal revenues are the sum of labor revenues, R_t^{WN}, corporate income taxes, R_t^{RK}, sales or VAT, R_t^{PC}, import duties or customs, R_t^M, insurance payout from natural disasters, B_t^A and other revenues, R_t^{OTH},

$$R_t = R_t^{WN} + R_t^{RK} + R_t^{PC} + R_t^M + B_t^A + R_t^{OTHR}.$$

Each revenue type, except of insurance payouts, is a function of the effective tax rate multiplied by the tax base,

$$R_t^i = \tau_{i,t}^e TB_t^i.$$

- The tax base for sales is nominal consumption $R_t^{PC} = \tau_{PC,t}^e (P_t^C C_t^{KN} + P_t^G G_t^{KN})$
- The tax base for profts is the nominal gross operating surplus $R_t^{RK} = \tau_{RK,t}^e (P_t^I R_t^K K_t)$
- The tax base for labor income is the nominal wage bill $R_t^{WN} = \tau_{WN,t}^e (W_t N_t)$
- The tax base for imports is nominal imports $R_t^M = \tau_{M,t}^e (P_t^M M_t^{KN})$

This formulation ensures that nominal revenues (and expenditures by definition above) grow at a constant rate in the long-run (i.e. at the rate of potential GDP plus the inflation target).

B Proof of the lemma

Lemma .1. *This framework is consistent with the intuitions of Hallegatte and Vogt-Schilb (2019) as reparation will always be preferred to building new capital.*

Proof. The marginal productivity of repairing is

$$-\frac{\partial Y_t^*}{\partial DS_{t-1}^p} = -\frac{\partial Y_t^*}{\partial KL_{t-1}}\frac{\partial KL_{t-1}}{\partial DS_{t-1}^p} = \frac{Y_t}{K_{S,t-1}}\frac{\partial KL_{t-1}}{\partial DS_{t-1}^P}$$

and the marginal productivity of adding new capital is

$$\frac{\partial Y_t^*}{\partial K_{S,t-1}^P} = \frac{\partial Y_t}{\partial K_{S,t-1}^P}\frac{Y_t^*}{Y_t} + \frac{Y_t}{K_{S,t-1}}\left[\frac{\partial KL_{t-1}}{\partial DS_{t-1}^P} - \frac{Y_t^*}{Y_t}\frac{\partial K_{S,t-1}}{K_{S,t-1}^P}\right].$$

One can note that

$$\frac{\partial Y_t^*}{\partial K_{S,t-1}^P} = -\frac{\partial Y_t^*}{\partial DS_{t-1}^p} + \frac{Y_t^*}{Y_t}\left[\frac{\partial Y_t}{\partial K_{S,t-1}^P} - \frac{\partial K_{S,t-1}}{K_{S,t-1}^P}\right]$$

where

$$\left[\frac{\partial Y_t}{\partial K_{S,t-1}^P} - \frac{\partial K_{S,t-1}}{K_{S,t-1}^P}\right] = \underbrace{\frac{\partial K_{S,t-1}}{\partial K_{S,t-1}^P}}_{>0}\underbrace{\left[\underbrace{\frac{\partial Y_t}{\partial K_{S,t-1}}}_{<1 \text{ because of decreasing return of the Cobb-Douglas in K}} -1\right]}_{<0}$$

Hence,

$$\frac{\partial Y_t^*}{\partial K_{S,t-1}^P} < -\frac{\partial Y_t^*}{\partial DS_{t-1}^p}.$$

In words, the marginal productivity of repairing is always higher than the marginal productivity of adding new capital stocks. □

C Key model parameters

For all other parameters and moments of the key model's equations, we refer the reader to Burns and Jooste (2019).

D Balanced growth path

The balanced growth path of the economy depends on our population and total factor productivity assumptions, both which are exogenous in this model. The projection period starts in 2021 using available and up to date data as of the time of writing this paper. A critical outcome for balanced growth path is that all real (in this case at constant prices) variables growth at the same rate. Figure 11 illustrates that the model reaches steady state by 2100.

Table 2: Key model parameters

Main model parameters				
Parameter	Description	Value	Std. Error	Note
α	Labor share in output	0.6		Calibrated
σ_1	Elasticity of substitution between infrastructure and non-infrastructure	0.57	0.17	Panel estimate
σ_2	Elasticity of substitution between government and private sector	2		Calibrated
δ	Capital depreciation (annual)	0.05		Calibrated
Δy^*	Steady state growth	3.0		Calibrated based on historical TFP and poulation growth
ω_1	Infrastructure share in capital	0.23		Calibrated $\left(\frac{K_S}{K}\right)^{\frac{1}{\sigma_1}}$
ω_2	Infrastructure share in capital	0.26		Calibrated $\left(\frac{K_N}{K}\right)^{\frac{1}{\sigma_1}}$
τ_{CIT}	Effective corporate income tax rate	0.1		Calibrated
β	Discount factor	0.94		Calibrated
θ	Taylor rule: inflation	1.5		Calibrated
β	Taylor rule: output gap	0.5		Calibrated
π^*	Inflation target	5		Calibrated

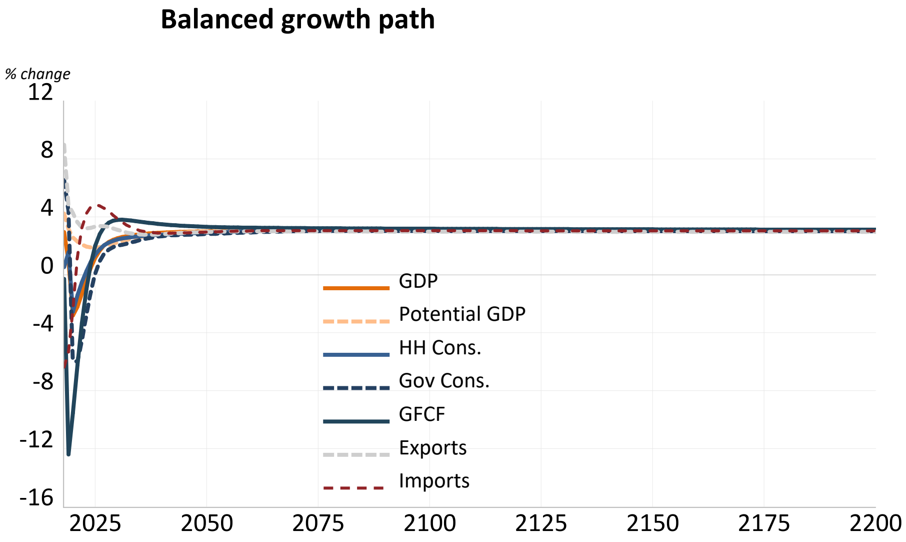

Figure 11: Balanced Growth: Baseline

E Illustrating shock uncertainty using spatial level earthquake data in Türkiye

In this Annex, we present the impact of a distribution of possible disasters, described by the probability of occurrence and intensity (expressed in asset losses).

The seismic risk assessment and retrofit scenarios for Türkiye are based on a Global earthquake model (hereafter; GEM) available in Rao et al. (2022). Using exposure model development, probabilistic seismic risk analysis, and retrofit intervention scenarios, GEM provided loss curves for sixteen building occupancies (e.g., government, industry, commerce, education, and healthcare). Assuming a mapping of public or private occupancies, we are able to derive the percentage loss of total infrastructure from the disaster effect for specific frequencies (1, 2, 5, 10, 20, 50, 100, 200, 250, and 500 years).

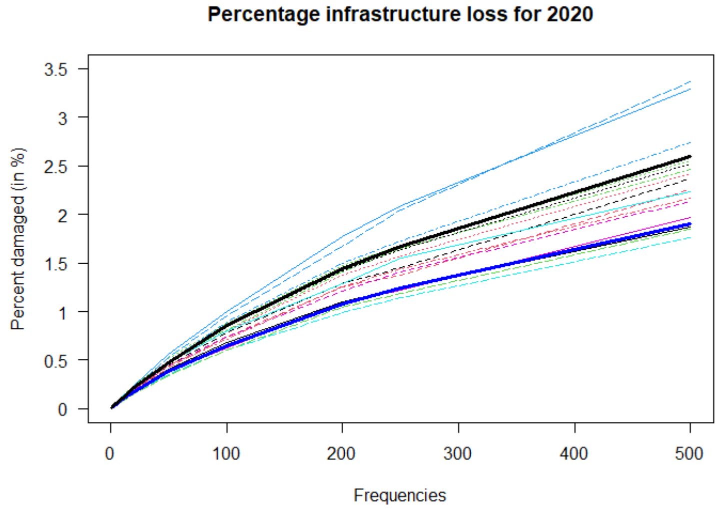

Figure 12: Percentage of infrastructure loss by seismic frequency event in 2020 given the current stock of infrastructure

Source: GEM. Note: The light colored lines represent the percentage losses by occupancy (13). The thick black line represents the aggregate for the private sector and the thick blue line represents the aggregate for the public sector.

Figure 12 shows that the maximum percentage loss for a seismic event below the 100-year frequency is relatively small, less than 1%. Looking at the effect of the lowest frequency, the 500-year frequency, the losses for the entire occupancy are between 1.5% and 3.5%, with an average of about 1.8% for the public sector and 2.5% for the private sector. Since the private sector is much larger than the public sector in terms of buildings, the global average is close to that of the private sector.

Two caveats are worth mentioning. First, the disaster coverage is for buildings only. Therefore, simulations based on these data will not provide impacts on infrastructure, for experiments with GEM infrastructure has to be understood as buildings. Second, these results are based on the 2013 Euro-Mediterranean seismic risk model. Early simulations of the 2020 Euro-Mediterranean seismic risk model for Türkiye may suggest higher overall impacts.

The loss curves provide us with empirical damages for Türkiye as opposed to assumed damages from the previous section. A deterministic scenario would take the weighted average of the loss curves, which is used for estimating annual expected damages. However, using the entire distribution function will yield uncertainty estimates that extend beyond averages. Consequently, we utilize the empirical distribution function and run several Monte Carlo simulations that draw from the empirical cumulative distribution function of the damages, F_X, and using the empirical inverse probability integral transform, $F_X^{-1}(u) = x$, we are able to generate hundreds of different shocks.[20] Our simulations start in 2021 as opposed to the steady state simulations earlier.

Figures 13a and 13b summarize the stochastic responses for GDP and consumption, respectively, between 2021 and 2091, assuming that reconstruction from the government

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[20] Probabilities were provided in discrete intervals. To simulate the full distribution of the data, the points between the probabilities were interpolated using cubic splines.

is financed by debt. The median macroeconomic impact of earthquakes is small, with consumption losses much smaller than GDP losses.

The distribution function has negative skewness and the tails are flat. This shape is due to the long-term impact of shocks in the system. Indeed, if the shocks had mostly a short-term impact, the distributions would have roughly the same shape over time. This result is consistent with empirical results suggesting that earthquakes have long-term impacts on GDP. For instance, Lackner (2018) uses earthquake data from 1973 to 2015 to estimate the long-term effects on GDP per capita and finds that an earthquake can reduce GDP per capita by up to 1.6% eight years later.

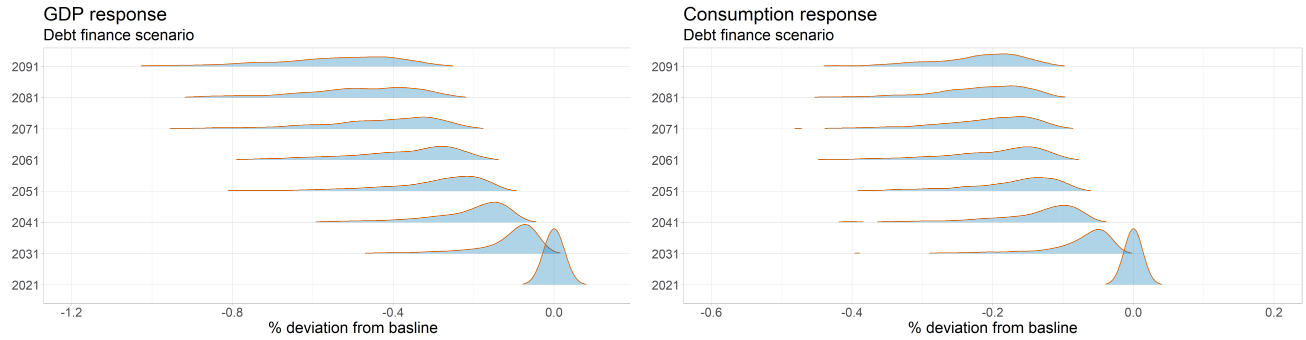

(a) GDP **(b)** Consumption

Figure 13: GDP and consumption responses to earthquakes

F Flood risks under different climate change scenarios

Flood damages are the second most frequent natural disaster in Türkiye following earthquakes. However, figure 14 shows that the direct capital losses from floods are quite small, even for rare events. For example, a 1 in 1500 year event destroys less than 1% of total capital.

Figure 14 represents historical damages. However, with climate change damages are expected to change. We assume that change in flood frequency due to climate change is taken from Myhre et al. (2019). The frequency of floods, F, is assumed to double with every degree in temperature rise T, consistently with basic physics:

$$F(T) = 2^{T-T_0} \times F_0.$$

The temperature rise scenarios are based on RCP 2.6 and RCP 8.5.

We map the temperature rise to the frequency of floods. Given that we have historical damages, we can estimate the changes in probabilities over different climate scenarios. The first column of Table 3 reports the expected damage to the capital stock arising from floods of increasing severity This is taken from the historical numbers from UNISDR (2015). As an example, a 1 in 1500 (this is a 0.067% chance of happening) year event leads to 0.65% loss total exposed capital. Column 2 shows the probability of each of those events under a 1°C of warming scenario. The columns for 2°C of warming and 3.7°C of warming show the increased probabilities based on the above formula.

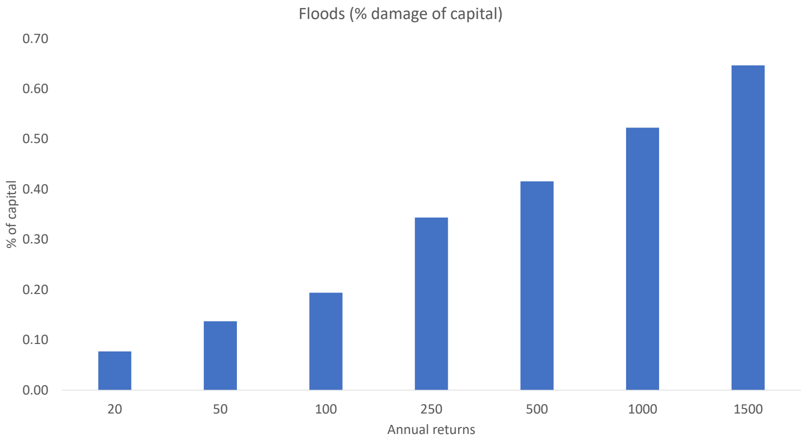


Figure 14: Exposed asset value loss for different return periods

Source: UNISDR (2015) and Myhre et al. (2019).
Notes: Annual returns indicate year events. An annual return of 250 implies a 1 in a 250 year event.

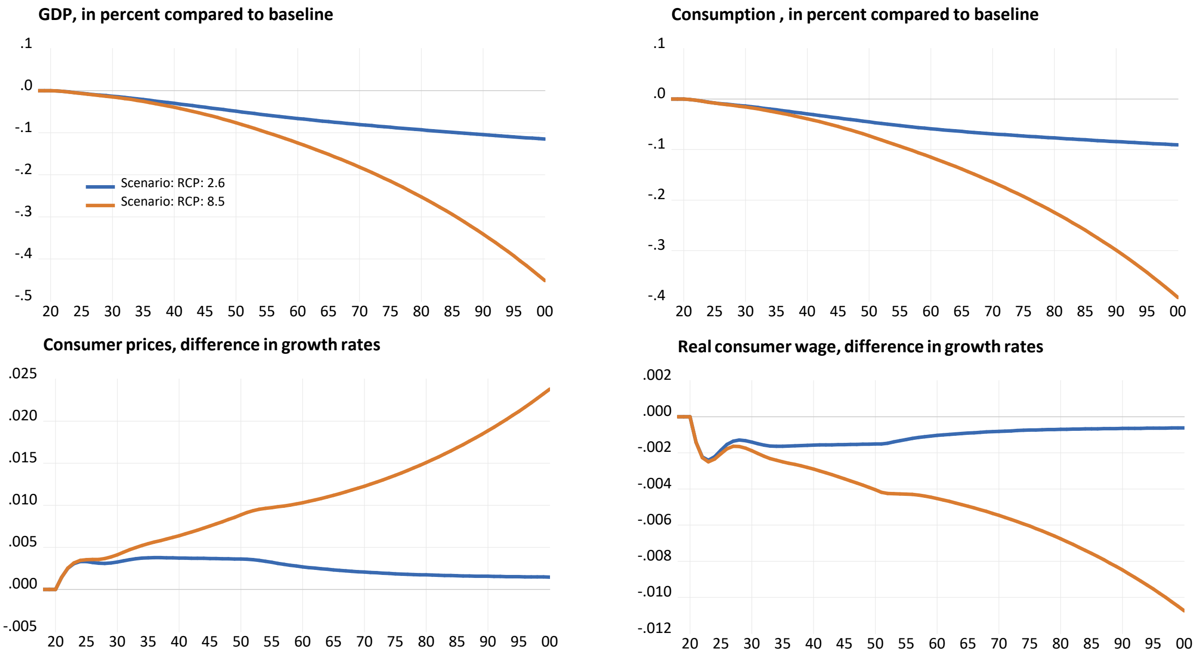
Damage	Prob for +1°C	Prob for 2°C	Prob for +3.7°C
0	91.23%	75.20%	19.44%
0.08%	5.00%	14.14%	45.95%
0.14%	2.00%	5.66%	18.38%
0.19%	1.00%	2.83%	9.19%
0.34%	0.40%	1.13%	3.68%
0.42%	0.20%	0.57%	1.84%
0.52%	0.10%	0.28%	0.92%
0.65%	0.07%	0.19%	0.61%
sum	100%	100%	100%

Table 3: Current and estimated probabilities for flood damages of a given size

Using the estimates of Table 3 allows us to generate different asset damage vectors related to floods. The annual temperature changes allows us to generate annual flood damages for the different climate change scenarios. We use these damage vectors as shock inputs. In this simulation we assume that public and private sector capital are equally destroyed. Figure 15 shows the impact of floods on a set of macroeconomic variables, namely GDP, consumption, private investment, consumer prices, real consumer wage, and real producer wage. The simulations start in 2020 and are presented until 2100. Under RCP8.5, median economic losses in terms of GDP and relative to the baseline grow to 0.5% by 2100, in contrast to losses of slightly larger than 0.1% under the RCP2.6 scenario.

Floods reduce both consumption and investment, a similar result for the earthquake analysis. However, due to the small economic impact of the shock, factor prices (in this case wages) do not change materially from the baseline. In other terms, the scale of the floods expected in Türkiye remains small enough to make the macroeconomic and monetary response negligible, and their frequency is small enough to ensure that they have limited cumulative impacts.

This does not mean that floods do not represent a significant economic and welfare cost (especially on local economies), but only that their assessment does not require to be done in a macroeconomic framework. This result echoes results from World Bank (2021), who explored the impact of floods and droughts in Argentina, and concluded that floods represented a major threat to poor people, in spite of a limited macroeconomic aggregate impact.


GDP, in percent compared to baseline

Consumption , in percent compared to baseline

Consumer prices, difference in growth rates

Real consumer wage, difference in growth rates

Figure 15: Economic responses due to floods under RCP 2.6 and RCP 8.5