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Transmission of Flood Damage to the Real Economy and Financial Intermediation: Simulation Analysis using a DSGE model

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Abstract

This paper quantitatively assesses the indirect effect of floods on the real economy and financial intermediation in Japan by estimating a dynamic stochastic general equilibrium (DSGE) model that incorporates a mechanism through which floods cause the capital stock and the public infrastructure to depreciate exogenously, using the data on flood damage recorded in the Flood Statistics released by the Japanese government. The result of the analysis is twofold. First, flood shocks dampen GDP from the supply side by reducing the capital stock inputs. The decline in GDP then impairs the balance sheets of firms and financial intermediaries, resulting in disruptions to financial intermediation and thus dampening GDP further from the demand side. Even when the direct damage due to floods is fully covered by insurance, the downward pressure on GDP endogenously deteriorates the balance sheets of these sectors, causing the same mechanism to operate. Second, the quantitative impacts of flood shocks on GDP up to now have been minor compared to the standard structural shocks that are considered important in existing macroeconomic studies, including shocks to total factor productivity (TFP) and the subjective discount factor. According to the estimates that use the relationship between the key variables in our model together with climate change scenarios published by an external organization, the impacts of these shocks could become somewhat larger in the future.

JEL classification: E32; E37; E44; Q54

Keywords: Climate change; Natural disaster; Physical risk; Financial system; DSGE model

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1 Introduction

In recent years, there has been growing global interest in the impact of natural disasters on economic activity as many countries see noticeable climate change and more frequent and larger natural disasters taking place, and theoretical and empirical studies have been rapidly accumulating. In the area of financial transactions, international discussion has become active regarding what has been coined "climate-related financial risk"—the risk of natural disasters such as drought and floods resulting from climate change, as well as the impact of the introduction of regimes, policies, and technological innovations to cope with climate change—on the stability of financial intermediation and financial systems through changes in the balance sheets of financial institutions. For example, in June 2021, the Network for Greening the Financial System (NGFS) released long-term climate change scenarios and estimates of the damage caused by natural disasters as well as economic activity under these scenarios. In addition, in the following month, the Financial Stability Board (FSB) published a roadmap that encompasses related efforts by standard setters on financial regulations, NGFS, and other international organizations.

In this paper, using the data from Japan, we quantitatively assess the impact of natural disasters on financial intermediation and the financial system through changes in the credit and collateral values of firms and households; namely, the "physical risk" of climate-related financial risks. To do this, we construct a dynamic stochastic general equilibrium (DSGE) model and estimate the indirect impact of direct damage to the capital stock and public infrastructure caused by floods on the macroeconomic activity through endogenous responses of the household, goods-producing, and financial intermediary (FI) sectors (the indirect effect).[1]

Our model differs from the standard New Keynesian models (hereinafter referred to as NK models) in two respects. First, in addition to the technology and demand shocks already introduced in the standard model, the model explicitly incorporates a "flood shock" that exogenously depresses the levels of capital stock and total factor productivity (TFP) at the same time. As described in previous studies such as Bakkensen and Barrage (2018), the occurrence of floods is considered as damaging to the tangible assets held by private firms due to the physical phenomena as well as public infrastructure such as bridges and roads.

[1] Unless otherwise noted, throughout the paper, to avoid confusion, we refer to capital stocks held by the private sector as "capital stocks" and to various capital stocks held by the public sector as "public infrastructure."

Second, the model assumes the credit contracts between the household sector and the FI sector, as well as those between the FI sector and the goods-producing sector, following Hirakata et al. (2011, 2017, hereinafter HSU). The FIs raise the external funds from the household sector and extend them as credit to the goods-producing sector together with their own net worth, and the goods-producing sector invests in capital goods using what credit they can borrow together with their own net worth. Similar to the credit contract in Bernanke et al. (1999, hereinafter BGG), upon which the HSU is built, the borrower of funds collects external funds from the lender under the credit contract. However, given the friction associated with asymmetric information, the borrowing rate faced by the borrower depends on the condition of the balance sheet. In this framework, direct damage to the capital stock caused by a flood event or changes in economic activity after the event hampers financial intermediation through changes in the balance sheets of the goods-producing and FI sectors, which subsequently affects the real economy. Our model can capture this type of transmission mechanism, which is generally called the "financial accelerator mechanism," concerning flood shocks.

Apart from the usage of data on flood damage to the capital stock in Japan reported in the Flood Statistics, our estimation strategy is quite standard. That is, we also use the macroeconomic variables for Japan and employ the Bayesian method—the standard method established in the literature for estimating a DSGE model since Smets and Wouters (2007). While flood damage to the capital stock from the Flood Statistics is treated as observable, the extent to which the floods exogenously push down TFP through damage to public infrastructure is not treated as observable, but instead is estimated. The sample period covers from 1980 to 2019.

The results of the analysis are twofold. First, the direct effect of floods, i.e., the damage to the capital stock and the decline in TFP caused by floods, has a persistent and statistically significant downward impact on GDP, through the following channels: (1) a decline in the capital inputs as the capital stock depreciates in the wake of floods and recovers only with a delay; (2) a decline in TFP and the resulting lower labor inputs due to lower real wages reflecting a lower TFP; and (3) the financial accelerator mechanism, i.e., an economic downturn due to disruptions to financial intermediation through impaired balance sheets of the goods-producing and FI sectors, which in turn hampers the capital stock input accumulation following floods. Indeed, the size of this last effect depends on which agents in the economy bear the economic losses associated with the direct effect of floods. If there are no insurance contracts ex-ante and the damage to the capital stock is translated one-for-one to impairments of the goods-producing sector's balance sheet, then the indirect effect can become large. However, even when floods do not impair the balance sheet of the sector directly, thanks to insurance, the downward pressure on GDP through disruptions to financial intermediation still manifests itself to the extent that the balance sheets of the goods-producing and FI sectors are endogenously impaired by the economic downturns following floods.

Second, based on the data available to date, compared to the standard macroeconomic shocks such as shocks to technology and the subjective discount rate incorporated in the standard DSGE models, flood shocks do not contribute significantly to variations in GDP, as a fall in the capital stock and TFP caused by these shocks are limited in size and short-lived. The impacts of these shocks in the future, however, according to the estimates that use the relationship between the key variables in the model together with climate change scenarios published by the NGFS, could become somewhat larger.

This paper is organized as follows. Chapter 2 summarizes the previous studies and compares them with the analysis in this paper. Chapter 3 provides an overview of our model and the estimation methodology. Chapter 4 discusses the impact of floods on financial intermediation and the real economy based on the estimation results. Chapter 5 concludes the paper and provides notes for further research.

2 Literature Review

Our study is built on studies that empirically and theoretically analyze the impact of natural disasters on economic activity.[2]

Empirical analyses include, for example, Tran and Wilson (2020), which estimates the impact of several types of natural disasters, including floods, on economic variables such as household income using the regional data for the United States, and Hsiang and Jina (2015), which estimates the impact of cyclones on medium- and long-term economic growth using global data. For Japan, Yamamoto and Naka (2021) estimate the impact of floods on corporate finance in Japan using the same Flood Statistics as in this paper. Similar to this paper, these

[2] The transmission channels of the economic impacts of the occurrence of, and increase in, natural disasters associated with climate change are detailed in Batten (2018), which covers existing studies on the transmission channels of extreme weather on the demand side (investment, consumption, imports, and exports) and the supply side (labor supply, electricity supply, capital stock, and production technology), respectively.

studies focus on estimating the indirect effects of the disaster, i.e. how the economies of the affected areas and firms located in such areas responded to the direct damage, rather than estimating the direct damage caused by natural disasters.

In terms of the relationship between natural disasters and financial intermediation, there are, for example, works by Klomp (2014) and Noth and Schüwer (2018) that study the impact of natural disasters on the balance sheets of financial intermediaries and works by Collier et al. (2019) and Brown et al. (2020), among others that study the impact of impaired balance sheets of financial institutions as a result of natural disasters on financial intermediation.[3,4] These studies generally report that large-scale natural disasters can impair the balance sheets of financial institutions, leading to higher interest rates and credit tightening.[5]

Regarding the role of insurance, there are works, for example, by von Peter et al. (2012) and Rousová et al. (2021), where the former find that, out of the total damage due to natural disasters, it is the uninsured losses that primarily depress economic growth.

Among theoretical studies on natural disasters, most of the existing studies focus on the risks associated with natural disasters and a few studies examine implications of disruptions to production inputs due to natural disasters. In particular, to the best of our knowledge, the only study that incorporates natural disasters into a DSGE model and estimates the model is Gallic and Vermandel (2020), which estimates a two-sector NK model consisting of agriculture and other industries using data from New Zealand, including the drought index.[6,7] Our analysis is similar to Gallic and Vermandel (2020), in that it incorporates shocks related to natural disasters

[3] For a survey of the interactions between climate change and the financial system, see, for example, Furukawa et al. (2020).

[4] Hosono et al. (2016) documents that a decline in the lending capacity of banks affected by the Great Hanshin-Awaji Earthquake in Japan led to a decline in lending to firms located outside the disaster area, as compared to the lending extended by banks that were not affected.

[5] Obviously, even when financial intermediation does not function well after a natural disaster, it is considered that the impact on the real economy would have been mitigated compared to the case where financial intermediation does not function at all. There are studies that point to the essential role of financial intermediation in the recovery phase of a natural disaster. See, for example, Berg and Schrader (2012) and Cortés and Strahan (2014).

[6] Evgenidis et al. (2012) quantitatively analyzes the impact of the 2011 Great East Japan earthquake using a calibrated DSGE model.

[7] For the transition risk—one other pillar of climate-related financial risks—somewhat more theoretical analysis has been accumulated. For example, Annicchiarico and Di Dio (2015) analyzes the impact of environmental regulations, such as the cap on carbon dioxide emissions, on economic activity in the framework of an NK model similar to this paper. Another theoretical study of the interaction between environmental regulations and financial frictions is Carattini, Heutel, and Melkadze (2021), which points out that financial sector frictions may amplify the effects of environmental regulations on the macroeconomy. For the transition risk faced by the Japanese economy, see Kurachi et al. (2022).

in a standard DSGE model. On the other hand, our analysis differs in that it focuses on floods rather than droughts and sheds light on the role of financial intermediation in the transmission of the effect of flood damage to the real economy.[8]

3 Model and Estimation

3.1 Model Overview

Most of the settings employed in our model are taken from Okazaki and Sudo (2018). In this chapter, therefore, we only explain part of the settings that differ from Okazaki and Sudo (2018); namely, the transmission channels through which natural disasters affect production activities by lowering the level of capital stock and TFP and impairing corporate balance sheets. See Appendix A and Figure 1 for details of the model and a conceptual diagram of transaction flows in the model, respectively.

In summary, we incorporate in the model of Okazaki and Sudo (2018) three channels through which the impacts of floods translate to the real economy:

1. Declines in capital stock
2. Disruptions to financial intermediation through impairment of entrepreneurs' balance sheets
3. Declines in TFP

3.1.1 Declines in Capital Stock

The occurrence of floods is considered to primarily cause depreciation in capital stock held by private entities. For example, Typhoon Hagibis in October 2019 (also known as Reiwa 1 East Japan Typhoon in Japan), the first typhoon to be designated as a "Specified Emergency Disaster," caused damage to facilities in the agriculture, forestry, and fisheries industries in several prefectures, as well as to production facilities in the manufacturing industry, including

[8] In terms of analytical methodology, the analysis in this paper is similar to that using estimated DSGE models, in particular analysis that incorporates the interaction between financial friction and the real economy, such as Christiano, Motto, and Rostagno (2010, 2014, hereinafter CMR). See also HSU for studies that estimate a similar model using Japan's data.

flooding in industrial parks.[9,10] More than 300 municipalities, mainly those in the Fukushima and Tochigi prefectures, were affected by the typhoon, and the total damage to general assets[11,12] amounted to 1.15 trillion Japanese yen (JPY), or around 10 billion USD, according to the Flood Statistics. This damage was equivalent to about 0.1% of the nation's private-sector fixed capital stock (1,128 trillion JPY in Q3 2019), making it the largest single flood event in history, excluding tsunamis.

Numerous previous studies have focused on the depreciation in capital stock caused by floods. For example, Hsiang and Jina (2015) analyzes the depreciation rate of capital stock due to typhoons by country/region in the Pacific region and reports that the depreciation rate due to typhoons differs significantly by country, ranging from around 0% to 1.5%, reflecting the respective geographical conditions. Strobl (2011) analyzes the relationship between hurricane magnitude and economic growth in the Gulf Coast region of the United States and the national level from 1975 to 2005 under the assumption that hurricanes deteriorate residential buildings and capital stock, which in turn depresses the economic growth rate of the affected region, or of the nation.[13]

Against this backdrop, we consider a transmission channel of flood damage through a change in the depreciation rate of capital stock in the private sector. Specifically, we assume that, at the

[9] Typhoon Hagibis occurred on October 6, 2019 near Minami-Torishima Island and made landfall on Izu Peninsula on October 12 with a large and strong force. As the typhoon approached, a wide number of regions, including the Kanto Koshin, Tokai, Hokuriku, and Tohoku regions, experienced record-breaking heavy rainfalls, with the highest amount of precipitation ever recorded. The typhoon was classified as Category 5, the highest category in the Safa-Simpson Hurricane Wind Scale, which measures the intensity of typhoons and hurricanes. According to AON (2020), the economic losses from Typhoon Hagibis amounted to 15 billion USD, making it the largest natural disaster in the world in 2019. It was also one of the largest economic losses ever recorded for a typhoon in the Pacific region.

[10] Comparing the economic losses and affected area of Typhoon Hagibis with those of Hurricane Irma, which caused major damage in the United States in 2017, the economic losses (relative to GDP) of both typhoons was about the same (0.3-0.4%), while the affected area was 170,000 ㎢ for Hurricane Irma compared to 120,000 ㎢ for Typhoon Hagibis.

[11] Damage to the general assets in the Flood Statistics includes damage to the general assets owned by private entities, such as depreciable and inventory assets of businesses, agricultural and fishing households, and residential and business buildings, and does not include damage to public infrastructure or the business interruption damage (lost earnings) of private businesses.

[12] Note that the damage to the general assets includes damage to residential houses, and such damage accounts for an important share of the total amount of damage caused by floods. In our model, we include private housing in capital stock in the private sector so as to maintain consistency between the data and the model. Note that this treatment also accords well with Hayashi and Prescott (2002) where both corporate and non-corporate capital stock is counted as capital stock.

[13] The major difference between this paper and Hsiang and Jina (2015) and Strobl (2011) is that, while these two papers estimate the degree of the capital depreciation based on the maximum wind speed of typhoons and hurricanes, our paper utilizes the Flood Statistics, a comprehensive survey of flood damages in Japan, to directly identify the economic size of the capital depreciation caused by floods.

beginning of each period, a flood shock causes an exogenous change in the depreciation rate regarding the private capital stock at the size of fdr_t, which in turn leads to a decline in the capital stock carried from the end of the previous period K_{t-1} by $fdr_t K_{t-1}$.[14]

$$K_{t-1} \quad \rightarrow \quad (1 - fdr_t)K_{t-1}$$

As a result, the total amount of capital stock that can be used in production in period t is mechanically reduced by $fdr_t K_{t-1}$.[15]

Unlike some standard structural shocks such as shocks to technology and the subjective discount factor, we assume that shocks to the depreciation rate in the capital stock caused by flood shocks fully diminish within the impact period. Flood damage is mainly caused by torrential rains, localized heavy rains, typhoons, etc., which typically subside within a few weeks at most, and are contained within one period (one quarter) in our model. Thus, there is no AR(1) term for the changes in the depreciation rate induced by flood shocks, contrasting with these standard shocks, and the changes in the rate are simply expressed by the shock term $\epsilon_{fdr,t}$, which we assume follows i.i.d.[16]

$$fdr_t = \epsilon_{fdr,t} \tag{1}$$

As a result of the flood shock, the accumulation of capital stock used in period $t+1$, K_t, is also hampered. Denoted by δ, the depreciation rate caused by factors other than flood damage, and using the flood-induced depreciation rate fdr_t, the dynamics for the aggregate private capital stock K_t are expressed as follows.

$$K_t = \left(1 - F_I(I_t, I_{t-1})\right)I_t + (1-\delta)(1 - fdr_t)K_{t-1} \tag{2}$$

where F_I is defined as follows.

$$F_I\left(I_{t+q}, I_{t+q-1}, Z_{I,t+q}\right) \equiv \frac{\kappa_I}{2}\left(\frac{I_{t+q}}{I_{t+q-1}} Z_{I,t+q} - \bar{\pi}\bar{\gamma} g_{Z_{d,SS}}\right)^2 \tag{3}$$

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[14] In Japan, earthquakes account for the largest amount of economic damage by type of disaster, followed by floods. Because earthquakes can affect the production factors in a similar way to floods, we incorporate earthquake shocks in the model as well and estimate earthquake-induced changes in the depreciation rate of the capital stock edr_t and those in TFP $\Omega_t\left(e_{edr_t}\right)$ in a manner similar to flood shocks.

[15] Treating changes in the capital depreciation rate as a driver of GDP fluctuations works well with the treatment of the standard macroeconomic models. For example, in the model of Hayashi and Prescott (2002), the depreciation rate is included as a time-varying exogenous variable.

[16] Flood shock $\epsilon_{fdr,t}$ is assumed to follow a probability distribution that takes values between 0 and 1 with a mean of 0.006%, which is the average flood damage from 1980 to 2020 (standardized by outstanding private capital stock).

Here, κ_I and $Z_{I,t+q}$ are the terms that represent the investment adjustment cost and the size of the investment-specific technology, respectively, and $g_{Z_{d,ss}}$ is the growth rate of the investment-specific technology at the steady-state.

3.1.2 Disruptions to financial intermediation through impairments of the entrepreneurs' balance sheets

As shown in Figure 1, in our model, the private sector is broadly divided into the household sector, the goods-producing sector, and the FI sector. The goods-producing sector further consists of entrepreneurs, goods producers, and capital goods producers. Within the goods-producing sector, the entrepreneurs own the balance sheet and are responsible for raising external funds from the FI sector through credit contracts. At the end of each period, the entrepreneurs purchase capital stock from the capital goods producers, using their own net worth and the external funds borrowed from the FI sector, rent it to goods producers, and receive the rental cost. At the end of the period, the capital stock is sold back to the capital goods producers.[17]

We assume that the timing of flood-induced changes in the depreciation rate of the capital stock is after the entrepreneurs purchase the capital stock from the capital goods producers and before they rent it to the goods producers, as seen in Figure 2. As described below, this implies that the balance sheets of the goods-producing sector are impaired, as the economic losses due to floods are attributed to entrepreneurs. As pointed out by the Swiss Re Institute (2021) and others, while insurance against economic losses associated with natural disasters does exist in Japan, not all firms have made ex-ante insurance contracts.[18]

Specifically, in our model, the ex-post real return on capital obtained by the entrepreneurs

[17] The assumption that the entrepreneurs purchase the capital stock from the capital goods producers at the beginning of each period and sell it back to the capital goods producers at the end of each period is taken from BGG. Under this assumption, the adjustment costs that occur when producing the capital goods from the final goods ("Tobin's Q") are externalized to the entrepreneurs, and changes in the adjustment cost affect the value of the entrepreneurs' balance sheets, and hence the financial intermediation.

[18] Swiss Re Institute (2021) points out that the total premium paid for business insurance in Japan is 0.84% of GDP in 2019, which is low compared to the United States (1.61%), the United Kingdom (0.96%), and Canada (0.95%). It also reports that only 0.17% of that amount, or approximately just around 20%, was related to insurance covering damage to properties caused by natural disasters, and that 37% of economic losses caused by natural disasters in FY2020 were insured. According to Sawada et al. (2017) and Inoue and Naganuma (2021), property insurance coverage is lower for small and medium enterprises. Along this line, Cabinet Office (2020) documents show that insurance and mutual aid alleviated around 20% of the total property damage to firms in the 2018-2019 torrential rains and typhoons.

from holding capital stock K_{t-1} is expressed by the following equation. Under this formulation, as the capital stock purchased at the end of the previous period K_{t-1} depreciates more due to floods, calculated using $fdr_t K_{t-1}$, the real net return on capital declines accordingly.

$$R_{E,t} = \left[\frac{U_t \tilde{R}_{E,t}}{P_t} - \frac{\kappa_U\left(U_t^{\Upsilon_U+1} - 1\right)}{\Upsilon_U + 1} + (1-\delta)Q_t\right]\frac{(1 - fdr_t)}{Q_{t-1}} \tag{4}$$

$\tilde{R}_{E,t}$ is the nominal gross return to the utilization-adjusted capital inputs $(1 - fdr_t)K_{t-1}(l)U(l)$. As in HSU (2011, 2017), the goods-producing and FI sectors respectively receive a portion of the proceeds from the capital, excluding repayments to the household sector, according to predetermined credit contracts. A decline in the real return on the capital reduces the retained earnings of both sectors, in particular for the goods-producing sector, pushing up the borrowing rate faced by the goods-producing sector through impairments to the balance sheets. As a result, the goods-producing sector's demand for investment declines, and economic activity is depressed.[19]

$$N_{F,t+1} = \gamma_F V_{F,t+1} + \frac{W_{F,t}}{P_t} + \varepsilon_{N_{F,t+1}} \tag{5}$$

$$N_{E,t+1} = \gamma_E V_{E,t+1} + \frac{W_{E,t}}{P_t} + \varepsilon_{N_{E,t+1}} \tag{6}$$

Note that $V_{F,t+1}$ and $V_{E,t+1}$ are expressed by the following equations.

$$V_{F,t+1} \equiv \left(1 - \Gamma_F\left(\overline{\omega}_{F,t+1}\right)\right)\Phi_{\mathrm{E}}(\overline{\omega}_{Et+1})R_{E,t+1}Q_t K_t$$

$$V_{E,t+1} \equiv \left(1 - \Gamma_E\left(\overline{\omega}_{E,t+1}\right)\right)R_{E,t+1}Q_t K_t$$

The equation regarding the real return on capital assumes that all direct damage from floods is attributed to the goods-producing sector. However, supposing more firms are insured, the balance sheet conditions of the goods-producing sector become less susceptible to the direct damage of floods. To see the implications of an increase in the insurance coverage of firms, we conduct an alternative simulation under the assumption that the flood-induced direct damage to

[19] As discussed in HSU (2017), holding other conditions constant, the less net worth entrepreneurs have, the smaller the share of capital income that goes to the goods-producing sector, thus impeding capital accumulation in the sector.

capital stock is entirely passed on to the household sector.[20] In this case, the ex-post real return that entrepreneurs gain from holding the capital stock K_{t-1} is reduced to what entrepreneurs gain in Okazaki and Sudo (2018), and entrepreneurs' balance sheets see no direct effects of floods.

$$R_{E,t} = \left[\frac{U_t \tilde{R}_{E,t}}{P_t} - \frac{\kappa_U \left(U_t^{\Upsilon_U+1} - 1\right)}{\Upsilon_U + 1} + (1-\delta) Q_t\right] \frac{1}{Q_{t-1}} \tag{7}$$

In this case, the damage is attributed to the capital goods producers, ultimately reducing households' income. Since floods reduce the total amount of capital stock available as production input, as in the baseline case, the goods-producing and FI sectors are affected in the form of a fall in retained earnings due to the production decline, and households suffer from the decline in labor income.

3.1.3 Declines in TFP

In addition to the depreciation of the capital stock, floods can damage public and social infrastructure. For example, Typhoon Hagibis caused disruptions and interruptions in highways. The disruption of logistics and supply chains due to the suspension of production by business partners could have lowered TFP, in the sense that the productivity of production factors falls.[21]

Previous studies, e.g., Nordhaus (2011), Gallic and Vermandel (2020), and Bakkensen and Barrage (2018), argue that there are various transmission channels through which climate

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[20] Insurance in our model is described as transfers from the households to the entrepreneurs, compensating the entire damage to the entrepreneurs' balance sheets. Insurance premiums as a fee of such transfers are not explicitly incorporated.

[21] Since our model does not include infrastructure provided by the public sector in the production function, fluctuations in outputs that are not attributed to production factors provided by the private sector (in our model, capital stock, labor, and intermediate inputs) must come from fluctuations in TFP.
Indeed, what is included in TFP depends on how production function inputs are modelled. For example, in the model used in Baxter and King (1993), the government capital stock is explicitly modelled, and the production function is given as follows:

$$Y_{g,t}(l) = A_{a,t} K_{t-1}(g)^{\alpha_{kg}} K_{t-1}(p)^{\alpha_{kp}} L_t^{\alpha_l}$$

where $K_{t-1}(g)$, $K_{t-1}(p)$, L_t represent the government and private capital stock and private labor inputs, respectively, and α_{kg}, α_{pg}, α_l are the respective production shares. In this case, since the capital stock held by the public sector is explicitly included in the production function, TFP can be defined as variations in $A_{a,t}$, which corresponds to variations in output that cannot be explained by variations in the production factors above, including those of public capital. In this paper, unless otherwise noted, TFP represents the fluctuations of outputs that cannot be attributable to variations in the (utilization-adjusted) private capital stock, labor and intermediate inputs, which correspond to $Z_{a,t} A_{a,t} / \Omega_t(e_{fdr_t})$ in the right-hand term of Equation (8).

change affects productivity. Nordhaus (2011) incorporates variations in TFP due to climate change into the analysis, assuming that temperature increases have a quadratic downward effect on TFP. Along this line, in NGFS (2021), higher temperature reduces TFP through increases in heat-induced diseases and other reasons. Gallic and Vermandel (2020) consider TFP fluctuations similar to the model of Nordhaus (2011), assuming that soil humidity affects productivity in the agricultural sector.[22] Bakkensen and Barrage (2018) report that natural disasters affect TFP, pointing out that the size of cyclones hitting a country are empirically negatively correlated with TFP fluctuations of the country. Moreover, Stern (2013) and Pindyck (2013) discuss transmission channels through which climate change damages existing public infrastructure and reduces economy-wide productivity, with a part of the investment that would have otherwise been used to accumulate capital stock instead being used in response to climate change.[23]

Based on these discussions, we aim to capture the impact of flood shocks on public and social infrastructure, which cannot be attributed to a fall in the capital stock held by the private sector, in the form of flood-induced changes in TFP. Specifically, we assume that the productivity of intermediate goods producers changes in response to flood shocks $\Omega_{\mathrm{t}}\left(e_{fdr_t}\right)$ as follows.

$$Y_{g,t}(l) = \frac{Z_{a,t}A_{a,t}}{\Omega_t\left(e_{fdr_t}\right)} \Psi_{\mathrm{t}}(l)^{\gamma}[L_t(l)^{\alpha}]^{1-\gamma}\left[\left((1-fdr_t)K_{t-1}(l)U_t(l)\right)^{1-\alpha-\alpha_E-\alpha_{FI}}\right]^{1-\gamma} - F_t \quad (8)$$

where $Z_{a,t}$ and $A_{a,t}$ respectively refer to the non-stationary and stationary components of the TFP fluctuations that are not attributed to floods, and $L_t(l)$, $(1-fdr_t)K_{t-1}(l)$, and $U_t(l)$ are the labor input of intermediate goods producers l, capital stock input after flood-induced depreciation, and capital stock utilization rate[24], respectively. Parameters γ and α are the shares of intermediate inputs in the production function and labor input by households. F_t is the fixed cost exogenous to intermediate goods producers l.

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[22] Nordhaus (2011), following Tol (2009) and others, points out that rising temperatures are likely to damage regions, industries, and public infrastructure that are considered vulnerable to climate change (e.g., subtropical regions, agriculture, forestry, fisheries, port facilities, and river embankments, respectively), through increased extreme weather events such as heavy rains and typhoons. In Gallic and Vermandel (2020), the impact of reduced soil humidity on the agricultural land reduces productivity in the agricultural sector.

[23] In an attempt to quantify the costs of repairing and maintaining public infrastructure in the face of climate change, Schweikert et al. (2014) estimate the maintenance costs of road infrastructure in ten countries, including Japan, at the end of the 21st century using climate models. According to the estimate, Japan, which has the longest total road length, will face the highest maintenance costs among the ten countries analyzed, about $450 million to $1.7 billion at most around 2100.

[24] The impact of floods on the economy may include a reduction in capital stock utilization rate, such as the suspension of power supply due to flooding of power facilities. For example, Hagibis and Faxai, two large typhoons in 2019, caused widespread power outages for hundreds of thousands of households.

Compared with how the private capital stock works in the economy, there is less agreement in the literature regarding how the public and social infrastructure affect the output production. For this reason, we incorporate into the model flood-induced changes in TFP $\Omega_{\mathrm{t}}\left(e_{fdr_t}\right)$ as a function of flood-induced depreciation in the capital stock e_{fdr} multiplied by a constant scaler θ_{fdr}. To examine whether floods actually affect TFP and, if so, to what extent they do, we include the time-series data of TFP as one of the observables in the estimation process and empirically ask if the estimated parameter of the interest θ_{fdr} is significant.

$$\Omega_{\mathrm{t}}\left(e_{fdr_t}\right) = \exp\left(\theta_{fdr} e_{fdr_t}\right) \tag{9}$$

Here, θ_{fdr} is the parameter concerning flood-induced TFP changes, and e_{fdr_t} follows an AR(1) process governed by the coefficient $\rho_{fdr} \in (0,1)$ as follow.

$$e_{fdr_t} = \rho_{fdr} e_{fdr_{t-1}} + fdr_t \tag{10}$$

3.2 Estimation Overview

The estimation method employed in this paper follows the standard method used in the previous studies on Bayesian estimation of DSGE models, such as Smets and Wouters (2007), while some of the observable variables used in the estimation are different from those in the standard method. Please refer to Appendix B for the details of the estimation methodology, and see Table 1 and Table 2 for the calibrated and estimated parameters, respectively.

Data

We use the time series of twelve variables as the observables from 1980:2Q to 2019:4Q. The data include seven series of macroeconomic variables, two series of the net worth of the FI and goods-producing sectors, and two series of capital depreciation rates due to floods and earthquakes: (1) real GDP Y_t, (2) real private capital investment I_t, (3) GDP deflator P_t, (4) deflator of investment goods $P_t Z_{d,t}^{-1} A_{d,t}^{-1}$, (5) nominal wages per unit of labor input W_t, (6) per capita working hours L_t, (7) the short-term nominal interest rate $R_{n,t}$, (8) measured TFP (computed as the Solow residual) λ_t, (9) real net worth of the banking sector $N_{F,t} P_t^{-1}$, (10) real net worth of the goods-producing sector $N_{E,t} P_t^{-1}$, (11) flood-induced capital depreciation rate fdr_t, and (12) earthquake-induced capital depreciation rate edr_t. The time series of the data in (1) to (11) are shown in Figure 3.

Most of the macroeconomic variables are prepared based on the System of National Accounts (hereinafter SNA) released by the Cabinet Office. Series (5) is calculated by dividing the compensation of employees based on the SNA by (6), and series (6) is calculated by multiplying the number of employed persons based on the Labour Force Survey by hours-worked per employee based on the Monthly Labour Survey and then dividing by the working-age population.

Series (9) and (10), the two net worth series, are constructed from the outstanding shares issued by the depository and non-financial corporations, respectively, based on the Flow of Funds Accounts. In the Flow of Funds Accounts, however, the reported series of outstanding shares are those evaluated not at market value, but book value before 1995:4Q for depository corporations, and before 1994:4Q for non-financial corporations. We therefore extend each series evaluated at market value backward using the quarterly growth rates of the market capitalization of banks and non-financial firms. Also, given that these variables reflect stock price fluctuations, we follow the methodology of Barsky et al. (2014) to take into account the existence of measurement errors when estimating the model.

Series (11) and (12) are constructed by dividing the amount of damage caused by floods and earthquakes by the size of the capital stock. For the amount of flood damage, we used the series of damage to general assets from the Flood Statistics published by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), which is deflated by the flood damage deflator.[25] Given that the Flood Statistics are released annually, the annual series of flood damage is converted into a quarterly series using the Automated Meteorological Data Acquisition System (AMeDAS) observation data published by the Japan Meteorological Agency.[26] The amount of damage caused by earthquakes is based on estimates by the MLIT for the five disastrous earthquakes, i.e. the Great Hanshin-Awaji Earthquake (January 1995), the Niigata-Chuetsu Earthquake (October 2004), the Great East Japan Earthquake (March 2011), and the Kumamoto Earthquake (April 2016). The private capital stock is based on the Quarterly Estimates of Net Capital stock of Fixed Assets published by the Cabinet Office.

In estimating the model, we take the first difference and demean all of the series to obtain the stationary series and remove the deterministic trend respectively, except for the nominal

[25] The flood damage deflator is a deflator published in the Flood Statistics to evaluate nominal flood damage in base year prices (currently the 2011 price). It is calculated based on the GDP deflator in SNA released by the Cabinet Office.

[26] See Appendix C for more details on how the quarterly series are constructed.

short-term interest rate (7) and the depreciation rates (11) and (12). The GDP deflator is used to convert nominal series to quantity series. All real series are converted to a per capita basis by dividing by the working-age population.

Estimation Result

The posterior distributions of the parameters are shown in Table 2. For all parameters except those related to floods, the values of the parameters for the goods-producing sector, household sector, FI sector, and government sector are largely consistent with those estimated by Okazaki and Sudo (2018). As for the impact of floods on TFP, the scaling parameter θ_{fdr} is statistically significantly greater than zero, indicating that the data imply the existence of transmission channels in which floods reduce TFP through depreciation in public infrastructure.

4 Analysis

4.1 Response of Financial Intermediation and Real Economy to Flood Shocks

Baseline Simulation Result

Using the parameters obtained from the estimation, Figure 4 presents the impulse response functions of the main variables to a flood shock with a size calibrated to a value equivalent to what happened when Typhoon Hagibis occurred. As shown in Equations (2) and (8), in period 0, a flood shock reduces capital stock available for the production at that period and also depresses TFP. As described above, the reason for the TFP decline is interpreted as reflecting damage to the public infrastructure, such as roads. A flood shock in period 0 is exogenous to the economy and its impact on the capital stock and TFP correspond to the direct effect in existing studies. Movements in the capital stock and other variables from period 1 onward reflect the endogenous reactions of the economy to the shock, corresponding to the indirect effect of floods.

First, looking at the movements of production inputs, in addition to a decline in capital stock and TFP, labor input drops in the short term due to reduced real wages. While all of these three production inputs continue to stay at a value below the steady-state after period 1, compared to labor input and TFP, capital stock stays at a low value longer, even five years after the impact period. Consequently, it takes more than five years for GDP to return to its pre-shock level.

On the demand side, while investment and consumption both decline after the shock, investment recovers relatively quickly, two years after the shock, and then turns positive, contributing to the recovery of capital stock. This dynamic is driven by two forces: (1) the downward pressure on the investment from the demand side due to the deterioration in the balance sheets of the goods-producing and FI sectors, which is described below, and (2) the upward pressure on the investment due to the increase in the expected rate of return from capital investment as a result of the fall in the capital stock, which works as an added incentivize for investment. The former force gradually dissipates as the balance sheets recover. As a result of the quick recovery of the investment in the face of declining GDP, the consumption continues to be pushed down. During the simulation horizon (ten years), the consumption and GDP are pushed down by up to 0.05% and 0.10% from their respective steady-state levels.[27]

This downturn in the real economy is also amplified by disruptions to financial intermediation. As shown in Equation (4), the unexpected physical depreciation of capital stock in period 0 impairs the balance sheet of the goods-producing sector that holds it economically. As in other financial accelerator models such as BGG, impairments of the balance sheets of the borrowers of the external funds increase the borrower's expected default probability from the lender's perspective, leading to a rise in the lending rate. As a result, investment is dampened through a reduction in the volume of loans.

The reduced investment demand further impairs the goods-producing sector's balance sheet through lowered economic activity, and also impairs the FIs' balance sheet via a decline in retained earnings from financial intermediation. As suggested by the HSU or Okazaki and Sudo (2018), the endogenous balance sheet deterioration of the goods-producing and FI sectors further depresses the real economy through endogenous disruptions to financial intermediation.

[27] In Appendix D, we compare the effects on GDP caused by flood shocks in our model with that of Hayashi and Prescott (2002), a pioneering study that theoretically explains Japan's GDP variations from the 1960s to the 1990s, including the lost decade. We give the same shock to the capital stock and TFP as that in Figure 4 to the neoclassical growth theory model used in Hayashi and Prescott (2002) and compute the impulse responses of GDP. Whereas the results from the two models do not differ significantly, even quantitatively, the GDP response in our model shows a relatively slower recovery after the shock.

Role of Insurance

Next, we analyze the impulse response functions of the main variables to a flood shock under a hypothetical economy where entrepreneurs' economic losses that arise from the initial impairments to capital stock due to flood shocks are fully insured and these losses are attributed to the household sector. The results are shown in Figure 5. For comparison, the point estimates in Figure 4 are also provided.

It is shown that the presence of the insurance scheme mitigates the downward pressure of a flood shock on macroeconomic and financial variables. As for GDP, for example, the downward pressure in period 0 is smaller, and the pace of recovery to the steady-state is faster. The investment has also turned positive sooner than in the case of the baseline simulation.

The reason behind the difference in the economic dynamics from what is shown in Figure 3 is that the insurance scheme mitigates the decline in the entrepreneurs' net worth at period 0, and as a result, the financial accelerator mechanism—through which deteriorations to borrowers' net worth increase the borrowers' expected default probability and raise the borrowing rates, leading to disruptions to lending volume and further deteriorations of the borrowers' net worth—does not work as strongly as in the baseline simulation. Furthermore, this insurance scheme may also have a negative wealth effect by transferring flood-induced damage to the household sector, which in turn adds to households' incentives to reduce leisure and consumption and increase labor inputs.

However, as Figure 4 shows, it should be noted that even if the direct damage to the capital stock due to flood shocks is attributed to the household sector by insurance, flood shocks continue to depress economic activity. This is because flood shocks reduce the total amount of capital stock available for the production falls, and TFP also falls regardless of which sectors ultimately bear the costs.

In addition, it is important to note that even if the insurance scheme is operative the balance sheets of the entrepreneurs and FI sectors are endogenously damaged by the downward pressure on GDP, leading to disruptions to financial intermediation, which further depresses GDP, albeit not by as much as it would without the insurance scheme. Due to the endogenous damage of the balance sheets, flood shocks persistently depress GDP under this hypothetical scenario.

Comparison of Contributions of Flood Shocks with Other Structural Shocks

Lastly, we compare the magnitude of the contribution of flood shocks to the economic fluctuations with that of standard macroeconomic structural shocks such as TFP shocks and subjective discount factor shocks. To do this, we compute the variance decomposition of GDP into shocks of one standard deviation for structural shocks including flood shocks. The result is shown in Table 3. It shows that the share of flood shocks in terms of variations in GDP is minor, ranging from 0.1 to 0.3 percent.

4.2 Projections based on Climate Change Scenarios up to 2100

Assumptions

As pointed out in recent studies, e.g. European Central Bank (2021), NGFS (2021), among others, the impact of natural disasters on the real economy may become larger as a result of increasing size and frequency of natural disasters given possible significant changes in the climate in the future. In this section, we conduct a long-term projection of major economic variables from 2020 to 2100 using the model, taking as given potential flood shocks under the climate change scenarios published by NGFS in June 2021 combined with some additional assumptions regarding flood damage in Japan.

Among the NGFS scenarios, we focus on two: (1) a scenario in which the current policies are maintained and no additional climate change mitigation policies are implemented (Current Policies), and (2) a scenario in which prompt and flexible climate change mitigation policies are implemented and CO2 emissions become net zero by 2050 (Net Zero 2050).

For the purpose of evaluating the role of insurance or the amplification effects of changes in the balance sheets of the entrepreneurs and FI sector, i.e., the financial accelerator mechanism, we formulate an economic projection that is based not only on the baseline model but also the model that explicitly incorporates the insurance mechanisms against flood damage and the neoclassical growth model in Hayashi and Prescott (2002), for both scenarios.[28]

The key input needed for the projection in each scenario is the size of the flood-induced

[28] Please refer to Appendix D for the responses of economic variables to “flood shocks” in the model of Hayashi and Prescott (2002).

exogenous capital depreciation rate from 2022 to around 2100, which is calculated as follows: (1) the annual growth rate of flood damage is calculated from the rate of change in flood damage published by NGFS every five years until 2100 (relative to 2020)[29], and (2) the flood-induced capital depreciation rates after 2020 are computed from the difference between the annual growth rate of flood damage and that of private fixed capital stock.[30]

Scenario 1: Current Policies

> This scenario assumes that only the climate change mitigation policies that are already in place are maintained and no additional emission reduction measures are implemented in the future. Under this scenario, CO2 emissions will continue to increase, and the global temperature will rise by 3 degrees Celsius by around 2100 compared to the 1986-2006 average. As a result, Japan will see rises in temperature and precipitation, and flood damage in 2100 will be nine times greater than in 2020. Taking this forecast as given, the assumption described above implies that the flood-induced capital depreciation rate in 2100 is 6.4 times higher than that in 2000.

Scenario 2: Net Zero 2050

> This scenario assumes that CO2 emissions will be reduced to net-zero by 2050 through the implementation of more stringent climate change mitigation policies and rapid technological innovation. As a result, the global temperature rise by 2100 will be limited to about 1.5 degrees Celsius, and flood damage in Japan by 2100 will increase only about 2.3 times compared to 2020. Under this scenario, the flood-induced capital depreciation rate in 2100 will increase to about 1.6 times the rate in 2000.

The simulations for each scenario are based on the 5000 sets of flood-induced capital depreciation rate series, which follows the sample distribution of the observed depreciation rates (1980Q1 – 2019Q4) and is adjusted so that the average depreciation rate around 2100 (relative to the average in the 2000s) becomes the multiple assumed in each scenario. We feed these shocks into the three models and evaluate the median and confidence intervals of the endogenous movements of GDP and capital stock.[31] In the simulations, all other structural

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[29] Missing values are linearly interpolated.

[30] The per capita private capital stock in the SNA series, which corresponds to capital stock held by the entrepreneurs in the goods-producing sector in our model, has increased by about 0.7 percent per annum on average from 2010 to 2020. In setting the time path of flood-induced capital stock depreciation from 2022 and beyond, we assume that this growth rate will continue until 2100 for the private capital stock.

[31] For the distribution of the capital depreciation rate shock series for each scenario, see Figure 6.

shocks are assumed to be zero.

Simulation Result

The simulation results are provided in Figure 7. The numbers are shown in terms of the deviation from the non-stochastic steady-state where no flood shocks or other structural shocks occur throughout the simulation period, namely the first quarter of 1980 onward. As documented in Appendix C, the sizes of the flood-induced capital depreciation rate in 2004, 2018, and 2019 were higher than the historical average and Figure 7 shows that the downward pressure caused by these past large-scale flood shocks remains in the years after 2020, since the impact of flood shocks on GDP is persistent, as indicated in Figure 4.

Scenario 1: Current Policies assumes that the capital depreciation rate due to flood shocks will increase rapidly after 2080 as a result of the absence of additional climate protection measures. In the baseline model (the upper panel of Figure 7), the median deviation of capital stock and GDP from the steady-state levels deteriorates sharply, reaching -0.75% and -0.18%, respectively.

On the other hand, under Scenario 2: Net Zero 2050, the size and frequency of flood shocks are suppressed after 2050 when net-zero emissions are achieved. As a result, the flood-induced capital depreciation rate remains low and the downward deviation of the capital stock and GDP from the steady-state levels remains roughly the same as in the current years. While all scenarios are associated with wide confidence intervals and therefore carry high uncertainty, it is seen that increasing the capital depreciation rate would depress the real economy variables in general. Quantitatively similar results are obtained in other two models: the model with the insurance scheme and the neoclassical growth model in Hayashi and Prescott (2002) (the bottom panel of Figure 7).

One difference from the model in Hayashi and Prescott (2002) is that the baseline model exhibits a larger dispersion of predicted values in each period, particularly for GDP. This is because endogenous variations in the balance sheets of the entrepreneurs and FIs amplify the impact of flood shocks on the real economy. In the model of Hayashi and Prescott (2002), for example, the bottom 10% of the value of GDP is about 0.3% below the steady-state level in 2100, whereas in the baseline it is about 0.4% below its steady-state value.

It is also seen that the role of insurance described in the previous section will become even more important if large-scale floods continuously damage the capital stock. That is, when the return on capital faced by the entrepreneurs is fully compensated for by insurance (middle panel of Figure 7), the median deviations of the capital stock and GDP from the steady-state level are mitigated compared to the baseline model, remaining at around -0.37% and -0.03%, respectively.

5 Conclusion

With an elevated global interest in climate change and natural disasters resulting from climate change, the impact of natural disasters on the macroeconomic activity has been the subject of an increasing number of studies. In the field of finance, there are growing concerns about the risk that climate change undermines financial system stability through damage to assets of financial institutions (climate-related financial risk), leading to international discussions or attempts by individual financial institutions to quantitatively assess climate-related financial risk.

This paper uses a DSGE model, a standard analytical tool in the field of macroeconomics, to quantitatively evaluate the impact of natural disasters such as floods on the real economy and financial intermediation activities. The occurrence of floods is classified as a "physical risk" of climate-related financial risks. To the best of the authors' knowledge, there have been no previous studies that evaluated the magnitude of physical risk to the FI sector using a DSGE model. Furthermore, our analysis is unique in that it theoretically assesses the role of insurance against damage from natural disasters on the real economy. The model in this paper is a standard DSGE model, except that it explicitly incorporates the balance sheets of the entrepreneurs in the goods-producing sector as well as those of the FI sector. The parameters are estimated using time series data on the amount of flood damage in Japan in addition to key macroeconomic variables. In terms of the channels through which floods affect economic activity, we consider not only the effects of physical damage—namely, damage to the capital stock held by the private and public sectors, which are highlighted in previous studies such as Hsiang and Jina (2015) —but also the secondary effects of physical damage—namely, damage to the balance sheets of the entrepreneurs and its impact on the rest of the economy through the financial accelerator mechanism.

The takeaway of the analysis is twofold. First, flood shocks have a statistically significant downward impact on GDP through an initial decline in the capital stock inputs and subsequent endogenous declines in the production factors due to lower TFP. Under the assumption that economic losses in the capital stock due to floods are generally absorbed by the entrepreneurs in the goods-producing sector, rather than being passed on to other sectors by the insurance scheme or other means, financial intermediation activities are impeded through the impairments to the balance sheet of the goods-producing sector, which further reduces GDP. However, even if flood damage does not directly deteriorate the balance sheet of the goods-producing sector due to, for example, the insurance scheme, the GDP decline caused by floods endogenously deteriorates the balance sheets of the goods-producing and FI sectors and dampens the economic activity.

Second, based on the data available to date, the quantitative impact of a direct decline in TFP and capital stock due to the occurrence of floods has not been as large as typical structural shocks, such as technology shocks and subjective discount factor shocks, which are considered to be the main drivers of GDP fluctuations in standard DSGE model analysis. By contrast, based on a hypothetical long-term economic projection that exploits the predicted time path of floods calibrated in line with the climate change scenario published by the NGFS, the impact of flood shocks in the future may be reasonably larger than at present.

The following three points should be noted regarding the current study. First, the purpose of our analysis is not to comprehensively and exhaustively capture the wide range of transmission channels through which climate change affects the real economy, but rather to provide an example of the possible consequence of climate change on economic activity by studying the indirect effects of floods in Japan, where the actual amount of flood damage is available. For this reason, some channels highlighted in existing studies such as Nordhaus (2011), such as those through falling labor productivity due to rises in temperature, are outside the scope of this analysis.

Next, the interconnectedness of economic activity and climate change is also absent in our model. The typical Integrated Assessment Model explicitly assumes that increases in atmospheric and oceanic carbon dioxide concentrations resulting from economic activity from the past to the present affect production factors, including labor productivity, through increases in current temperatures. To conduct quantitatively sophisticated analysis of such interconnectedness, it is vital to have the detailed data for estimating the loss function, which measures the impact of rising temperatures on economic activity, in addition to the medium- to long-term impact of economic activity in various regions, including those outside Japan, on temperatures.

Lastly, the analysis in this paper attempts to analyze individual and heterogeneous flood damage that has occurred in different parts of Japan, by implicitly assuming some degree of homogeneity across them and applying the analytical framework of a standard DSGE model, in particular a linear approximation of model dynamics. On the former point, while the impact of natural disasters, including floods, is considered to be highly individualized, as long as the flood-induced capital depreciation rate is the same, the impact on economic activity in the Japanese economy as a whole is considered the same in the model, regardless of where they occur. Concerning the latter, potential non-linear effects associated with large-scale flood occurrence, in particular in the simulation analysis of future impacts, may not be captured. Theoretically examining the individual and regional characteristics of flood damage and the nonlinearity and comprehensively incorporating them into the model are part of the future research agenda.

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A. Model

The economy consists of four sectors: the household sector, the FI sector, the goods-producing sector, and the government sector.

- Household sector: The household sector consists of a continuum of households and investors. Each household is composed of H_t identical workers and supplies labor inputs to the goods-producing sector, earns wages, makes deposits to the investors, and receives repayments in return from deposits. The investors collect deposits from the households at risk-free rates and lend them to the FI sector by making credit contracts with the FI sector, which we call IF contracts.

- FI sector: the FIs raise external funds from the investors through the IF contracts and lend these funds, as well as their net worth, to the entrepreneurs in the goods-producing sector by making credit contracts, which we call FE contracts.

- Goods-producing sector: the goods-producing sector consists of the entrepreneurs, the capital goods producers, and the goods producers. The entrepreneurs raise external funds from the FIs, purchase capital goods from the capital goods producers, and lend them to the goods producers for the rental price. The capital goods producers purchase final goods from the goods producers and convert them into capital goods. The goods producers produce goods from labor inputs, capital inputs, and intermediate goods.

- Government sector: the government sector consists of the government, which collects taxes from households and spends them on government purchases, and the central bank, which adjusts the nominal interest rate to stabilize the inflation rate.

A.1 Credit Contracts

The model considers two types of credit contracts. The first type of contract is a deposit contract made between households' agents, which we call investors, and FIs. This type of contract is called IF contracts. The second type of contract is made between the FIs and entrepreneurs in the goods-producing sector, and is referred to as FE contracts. FIs behave monopolistically in the two contracts and choose the borrowing rates to maximize their profits.

A.1.1 FE Contracts

Setting

In period t, each type i FI offers a loan contract to an infinite number of group j_i entrepreneurs.[32] An entrepreneur in a group j_i owns net worth $N_{E,j_i,t}$ and purchases capital of $Q_t K_{j_i,t}$, where Q_t is the price of capital and $K_{j_i,t}$ is the quantity of capital purchased by a group j_i entrepreneur. If the net worth $N_{E,j_i,t}$ is smaller than the amount of the capital purchase $Q_t K_{j_i,t}$, the entrepreneur raises the rest of the fund $Q_t K_{j_i,t} - N_{E,j_i,t}$ by making a credit contract with the type i FI.[33] In period $t+1$, a group j_i entrepreneur receives a return of $R_{E,t+1}\omega_{E,j_i,t+1}$ from holding the capital $K_{j_i,t}$, where $R_{E,t+1}$ is the aggregate return on capital and $\omega_{E,j_i,t+1}$ is an idiosyncratic productivity shock that is specific to the group j_i entrepreneurs.[34] There are informational asymmetries, and a type i FI cannot observe the realization of its borrower's idiosyncratic productivity shock $\omega_{E,j_i,t+1}$, unless it pays the monitoring cost. As in the conventional costly state verification problem, a type i FI specifies:

- Amount of debt a group j_i entrepreneur borrows from a type i FI, $Q_t K_{j_i,t} - N_{E,j_i,t}$
- Cut-off value of idiosyncratic productivity shock $\omega_{E,j_i,t+1}$, denoted as $\bar{\omega}_{E,j_i,t+1}$, such that a group j_i entrepreneur repays its debt if $\omega_{E,j_i,t+1} \geq \bar{\omega}_{E,j_i,t+1}$ and declares a default if otherwise.

Entrepreneur's Participation Constraint

A group j_i entrepreneur joins an FE contract only when the return from joining the contract

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[32] The model assumes that the size of the monitoring cost associated with the credit contracts between a type i FI and group j_{i^*} entrepreneurs for $i \neq i^*$ is so high that j_{i^*} entrepreneurs do not choose to raise funds from a type i FI. By the same assumption, a direct credit contract between the investors and the entrepreneurs is left out from the presented analysis.

[33] As in BGG (1999), the model assumes that net worth does not accumulate infinitely and that the entrepreneurs always raise external funds at the equilibrium. The same argument applies to FIs in the IF contracts.

[34] Following BGG (1999), the idiosyncratic productivity shock is a unit mean, lognormal random variable distributed independently over time and across entrepreneurs. The model denotes its density function and cumulative distribution function by $f_E(\cdot)$ and $F_E(\cdot)$, respectively.

is at least equal to the opportunity cost. In the FE contract, if the entrepreneur does not default, ex-post, it receives

$$\left(\omega_{E,j_i,t+1} - \bar{\omega}_{E,j_i,t+1}\right) R_{E,t+1} Q_t K_{j_i,t}$$

The entrepreneurial loan rate $r_{E,j_i,t+1}$ is therefore given by

$$r_{E,j_i,t+1} \equiv \frac{\bar{\omega}_{E,j_i,t+1} R_{E,t+1} Q_t K_{j_i,t}}{Q_t K_{j_i,t} - N_{E,j_i,t}} \tag{11}$$

Instead of participating in the contract, a group j_i entrepreneur can purchase capital using its own net worth $N_{E,j_i,t}$ and receive the return from holding the capital. In this case, ex-ante, the entrepreneur expects to receive the earning $\mathrm{E}_t\left[\omega_{E,j_i,t+1} R_{E,t+1} N_{E,j_i,t}\right]$, which is equal to $\mathrm{E}_t\left[R_{E,t+1} N_{E,j_i,t}\right]$, and ex-post it receives the earning $\omega_{E,j_i,t+1} R_{E,t+1} N_{E,j_i,t}$. Therefore, the FE contract is agreed by a group j_i entrepreneur only when the following inequality holds:

$$\mathrm{E}_t\left[\left(\int_{\bar{\omega}_{E,j_i,t+1}}^{\infty} \left(\omega_E - \bar{\omega}_{E,j_i,t+1}\right) dF_E(\omega_E)\right) R_{E,t+1} Q_t K_{j_i,t}\right] \geq \mathrm{E}_t\left[\omega_{E,j_i,t+1} R_{E,t+1} N_{E,j_i,t}\right] \tag{12}$$

Note that E_t is the expectation operator.

FIs' Earnings from FE Contracts

The earnings of a type i FI from FE contracts are repayments from non-defaulting entrepreneurs minus the monitoring cost paid to assess defaulting entrepreneurs' assets. The expected earnings of a type i FI from FE contracts with group j_i entrepreneurs are thus described as follows:

$$\mathrm{E}_t\left[\Phi_{E,i,t+1} R_{E,t+1} Q_t K_{j_i,t}\right]$$

where

$$\Phi_{E,i,t+1} \equiv \int_{\bar{\omega}_{E,j_i,t+1}}^{\infty} \bar{\omega}_{E,j_i,t+1} dF_E(\omega_E) + \int_0^{\bar{\omega}_{E,j_i,t+1}} \omega_E dF_E(\omega_E) - \mu_E \int_0^{\bar{\omega}_{E,j_i,t+1}} \omega_E dF_E(\omega_E) \tag{13}$$

$\Phi_{E,i,t+1}$ in equation (13) has three terms. The first stands for the repayment made by the non-defaulting entrepreneurs, the second stands for realized returns of the defaulting entrepreneurs, and the third stands for the monitoring cost that the FI pays. The total monitoring cost paid by the FI is given by the third term multiplied by $R_{E,t+1}Q_tK_{j_i,t}$, and the parameter μ_E governs the size of the monitoring cost.

It is also notable that, because of constant returns to scale in production and monitoring technology, a type i FI makes contracts with an infinite number of group j_i entrepreneurs with the same size of cut-off value $\overline{\omega}_{E,j_i,t+1}$. In what is described below, therefore, the subscript j_i is dropped.

A.1.2 IF Contracts

Setting

An IF contract is made between an investor and a continuum of the FIs. As explained above, in period t, each type i FI holding net worth $N_{F,i,t}$ makes loans to group j_i entrepreneurs at an amount of $Q_tK_{i,t} - N_{E,i,t}$, where $K_{i,t}$ is the total amount of capital purchased by group j_i entrepreneurs, and $N_{E,i,t}$ is the total amount of net worth held by group j_i entrepreneurs. An FI i's net worth is smaller than its loans to the entrepreneurs and it raises the external funds $Q_tK_{i,t} - N_{E,i,t} - N_{F,i,t}$ from the investor. After receiving earnings from the FE contracts, an FI is hit by an idiosyncratic productivity shock $\omega_{F,i,t+1}$ that represents technological differences across FIs regarding, for example, management of credit and liquidity risk or loan securitization. Consequently, ex-post, the FI's revenue from the FE contracts alter the realization of the idiosyncratic productivity shock is given by[35]

$$\omega_{F,i,t+1}\Phi_{E,i,t+1}R_{E,t+1}Q_tK_{i,t}$$

There are informational asymmetries between the investor and the FI. The investor can observe the realization of the idiosyncratic shock only if it pays the monitoring cost. Under these circumstances, as with FE contracts, the IF contract specifies:

- Amount of debt a type i FI borrows from the investor, $Q_tK_{i,t} - N_{E,i,t} - N_{F,i,t}$

[35] The model assumes that the FI's idiosyncratic productivity shock is a unit mean, lognormal random variable distributed independently over time and across entrepreneurs. The model denotes its density function and cumulative distribution function by $f_F(\cdot)$ and $F_F(\cdot)$, respectively.

- Cut-off value of idiosyncratic shock $\omega_{F,i,t+1}$, denoted by $\overline{\omega}_{F,i,t+1}$, such that the FI repays its debt if $\omega_{F,i,t+1} \geq \overline{\omega}_{F,i,t+1}$ and declares a default otherwise.

As a result of the IF contracts, a portion of the FIs $\int_{\overline{\omega}_{F,i,t+1}}^{\infty} dF_F(\omega_F)$ do not default, while the remainder does. Ex-post, a default FI i receives nothing and a non-default FI i receives the earning shown below:

$$(\omega_{F,i,t+1} - \overline{\omega}_{F,i,t+1})\Phi_{E,i,t+1}R_{E,t+1}Q_tK_{i,t} \tag{14}$$

The loan rate paid by a non-default FI i to an investor is therefore given by

$$r_{F,i,t+1} \equiv \frac{\overline{\omega}_{F,i,t+1}\Phi_{E,i,t+1}R_{E,t+1}Q_tK_{i,t}}{Q_tK_{i,t} - N_{E,i,t} - N_{F,i,t}} \tag{15}$$

Investor's Participation Constraint

An investor participates in an IF contract only when the IF contract is more advantageous. Denoting the risk-free rate in the economy by R_t, an investor's net receipt from the IF contracts must at least be equal to the return from a risk-free investment. That is, for $\forall i$,

$$\Phi_{F,i,t+1}\Phi_{E,i,t+1}R_{E,t+1}Q_tK_{i,t} \geq R_t\left[Q_tK_{i,t} - N_{E,i,t} - N_{F,i,t}\right] \tag{16}$$

where

$$\Phi_{F,i,t+1} \equiv \int_{\overline{\omega}_{F,i,t+1}}^{\infty} \overline{\omega}_{F,i,t+1} dF_F(\omega_F) + \int_0^{\overline{\omega}_{F,i,t+1}} \omega_F dF_F(\omega_F) - \mu_F \int_0^{\overline{\omega}_{F,i,t+1}} \omega_F dF_F(\omega_F) \tag{17}$$

$\Phi_{F,i,t+1}$ has a similar structure to $\Phi_{E,i,t+1}$ in Equation (13). In particular, it is notable that the third term of $\Phi_{F,i,t+1}$ multiplied by the term $\Phi_{E,i,t+1}R_{E,t+1}Q_tK_{i,t}$ shows the total amount of monitoring cost paid by an investor. These costs are used to monitor the outputs of defaulting FIs rather than those of defaulting entrepreneurs.[36,37]

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[36] The two terms $\Phi_{F,i,t+1}$ and $\Phi_{E,i,t+1}$ are interpreted as the net share of profits going to the lender in the IF and FE contracts, respectively.

[37] Note that, as in BGG (1999), the model assumes that both FE and IF contracts are contingent on aggregate states and the participation contracts (12) and (16) hold with equality state by state. See, for example, footnote 16 of CMR (2014) for a related discussion. Regarding the IF contracts, the model further assumes that the investors face perfect competition, and at the equilibrium, their earnings from the IF contracts are equal to the amount of repayment to households in every state of the economy.

A.1.3 Optimal Credit Contracts chosen by FIs

At the end of period t, given its own net worth $N_{F,i,t}$ and entrepreneurial net worth $N_{E,i,t}$, a type i FI chooses the terms of the IF and FE contracts to maximize its expected profit at the end of the period $t+1$. The terms consist of the amount of loans $Q_t K_{i,t} - N_{E,i,t}$, borrowings $Q_t K_{i,t} - N_{E,i,t} - N_{F,i,t}$, and the cut-off values $\bar{\omega}_{F,i,t+1}$ and $\{\bar{\omega}_{E,j_i,t+1}\}_{j_i=0}^{\infty}$. As shown in Equation (14), the FI's expected profit is given by the FI's revenue minus repayment to investors:

$$\mathrm{E}_t\left[\left(\int_{\bar{\omega}_{F,i,t+1}}^{\infty}\left(\omega_F - \bar{\omega}_{F,i,t+1}\right) dF_F(\omega_F)\right)\Phi_{E,i,t+1} R_{E,t+1} Q_t K_{i,t}\right] \tag{18}$$

The FI maximizes the term (18) subject to the investor's participation constraint (16) and entrepreneurial participation constraint (12) for all of the group j_i entrepreneurs. As discussed in HSU (2011, 2013), because of constant returns to scale in production and monitoring technology, the expected profit of a type i FI is the same as that of other types of FIs. In what follows, therefore, the subscript i is dropped as well.

A.1.4 Dynamic Behavior of Net Worth

The main source of net worth accumulation for the FIs and the entrepreneurs is the earnings from the credit contracts described above. In addition, there are two other sources of earnings. First, the FIs and entrepreneurs inelastically supply a unit of labor to the goods producers and receive in return labor income that is depicted by $W_{F,t}$ and $W_{E,t}$, respectively.[38] Second, the net worth accumulation is affected by exogenous disturbances $\varepsilon_{N_{F,t+1}}$ and $\varepsilon_{N_{E,t+1}}$. These shocks are i.i.d. and orthogonal to the earnings from the credit contracts. The aggregate net worth of FIs and the entrepreneurs then evolve according to the equations below:

$$N_{F,t+1} = \gamma_F V_{F,t+1} + \frac{W_{F,t}}{P_t} + \varepsilon_{N_{F,t+1}} \tag{19}$$

$$N_{E,t+1} = \gamma_E V_{E,t+1} + \frac{W_{E,t}}{P_t} + \varepsilon_{N_{E,t+1}} \tag{20}$$

[38] See BGG (1999) for the reason for introducing inelastic labor supply from the FIs and the entrepreneurs.

with

$$V_{F,t+1} \equiv \left(1 - \Gamma_F\left(\overline{\omega}_{F,t+1}\right)\right) \Phi_{\mathrm{E}}(\overline{\omega}_{Et+1}) R_{E,t+1} Q_t K_t$$

$$V_{E,t+1} \equiv \left(1 - \Gamma_E\left(\overline{\omega}_{E,t+1}\right)\right) R_{E,t+1} Q_t K_t$$

where $\Gamma_F\left(\overline{\omega}_{F,t+1}\right)$ and $\Gamma_E\left(\overline{\omega}_{E,t+1}\right)$ are expressed as follows.[39]

$$\Gamma_F\left(\overline{\omega}_{F,t+1}\right) \equiv \int_{\overline{\omega}_{F,t+1}}^{\infty} \overline{\omega}_{F,t+1} dF_F(\omega_F) + \int_0^{\overline{\omega}_{F,t+1}} \omega_F dF_F(\omega_F)$$

$$\Gamma_E\left(\overline{\omega}_{E,t+1}\right) \equiv \int_{\overline{\omega}_{E,t+1}}^{\infty} \overline{\omega}_{E,t+1} dF_E(\omega_E) + \int_0^{\overline{\omega}_{E,t+1}} \omega_E dF_E(\omega_E)$$

Here, P_t denotes the nominal price of consumption goods. Note that the model assumes that FIs and entrepreneurs survive into the next period with a probability γ_F and γ_E, and those who are in business in period t and fail to survive into $t+1$ consume $(1-\gamma_F)V_{F,t+1}$ and $(1-\gamma_E)V_{E,t+1}$ and exit from the economy.

A.2 Households

There is a continuum of households indexed by $h \in [0,1]$, and each household is composed of H_t identical workers. Denoting total consumption and labor inputs and variables divided by the household's size as $C(h)$, $L(h)$, $c(h)$, and $l(h)$, respectively, the household's expected utility $U_t(h)$ is given by the following equation.

$$U_t(h) \equiv \mathrm{E}_t\left[\sum_{q=0}^{\infty} \beta^q d_{t+q} H_{t+q} \left\{\ln\left(c_{t+q}(h) - \theta_h c_{t+q-1}(h)\right) - \varphi \frac{l_{t+q}(h)^{1+\upsilon}}{1+\upsilon}\right\}\right] \tag{21}$$

where $\beta \in (0,1)$ is the discount factor, $\theta_h \in (0,1)$ is the degree of internal habit persistence in consumption preferences, $\upsilon > 0$ is the inverse of Frisch labor-supply elasticity, and φ is the weighting assigned to leisure. The variable d_t is a discount factor shock.

The budget constraint for household h is given by

[39] Following BGG (1999), $\Gamma_F\left(\overline{\omega}_{F,t+1}\right)$ and $\Gamma_E\left(\overline{\omega}_{E,t+1}\right)$ respectively represent the share of investors in IF contracts and that of FIs in FE contracts, measured before excluding monitoring costs.

$$c_t(h)H_t + s_t(h)H_t \leq \begin{bmatrix} \dfrac{W_t(h)l_t(h)H_t}{P_t} - \dfrac{\kappa_w}{2}\left(\dfrac{W_t(h)}{W_{t-1}(h)} - \bar{\pi}\bar{\gamma}\right)^2 \dfrac{W_t L_t}{P_t} \\ +R_{t-1}s_{t-1}(h)H_{t-1} + \dfrac{\Omega_t(h) - \tau_t(h)}{P_t} \end{bmatrix} \tag{22}$$

where $s_t(h)$ is the real savings per household member, R_t is the real interest rate on deposit, $\Omega_t(h)$ is the nominal profit paid to the household, and τ_t is the lump-sum nominal tax taken by the government. $W_t(h)$ is the nominal wage set by a household h and W_t is the aggregate index of the nominal wage. The second term on the right-hand side of the equation is the nominal cost the household needs to pay when it adjusts nominal wage $W_t(h)$, where κ_w is the parameter associated with the adjustment cost, $\bar{\pi}$ is the steady-state inflation rate, and $\bar{\gamma}$ is steady-state growth rate of the output on a per capita basis defined as below[40].

$$\bar{\gamma} = g_{Z_{a,SS}}^{\frac{1}{(1-\gamma)(\alpha+\alpha_E+\alpha_F)}} g_{Z_{d,SS}}^{\frac{(1-\alpha-\alpha_E-\alpha_F)}{\alpha+\alpha_E+\alpha_F}}$$

where $g_{Z_{a,SS}}$ and $g_{Z_{d,SS}}$ are growth rates of neutral technology and investment-specific technology, respectively.

A household h has monopolistic power in its differentiated labor input $L_t(h)$. The demand for differentiated labor is given by

$$L_t(h) = \left(\frac{W_t(h)}{W_t}\right)^{-\theta_{W,t}} L_t \tag{23}$$

where L_t is the aggregate index of labor inputs defined as

$$L_t = \left[\int_0^1 L_t(h)^{\frac{\theta_{W,t}-1}{\theta_{W,t}}} dh\right]^{\frac{\theta_{W,t}}{\theta_{W,t}-1}}$$

where $\theta_{W,t} \in (1, \infty)$ is the time-varying elasticity of labor demand for differentiated labor input concerning wages.

[40] The functional form of the nominal wage adjustment costs implies that the costs are zero at the steady-state where household adjust their wages by the rate equal to $\bar{\pi}\bar{\gamma}$.

A.3 Goods producers

The goods-producing sector comprises entrepreneurs, capital goods producers, a continuum of intermediate goods producers, which are indexed by $l \in [0,1]$, as $\{Y_{g,t}(l)\}_{l\in[0,1]}$, and the aggregators. The capital goods producers purchase capital stock from the investment capital market, transform it into capital goods, and sell them to entrepreneurs. The intermediate goods producers (henceforth firms), each producing differentiated products, behave as price-takers in input markets but have a monopolistic power in the intermediate goods market. The aggregators purchase the differentiated intermediate goods in a perfectly competitive market and construct the composite of the goods $Y_{g,t}$.

Capital Goods Producers

The capital goods producers purchase final goods $I_t/(Z_{d,t}A_{d,t})$, convert them into capital goods K_t with technology $F_{I,t}$, and sell the goods to entrepreneurs at the price Q_t. Here, I_t, $Z_{d,t}$, and $A_{d,t}$ respectively represent investment, the non-stationary component, and the stationary component of the investment-specific technology, respectively. Their maximization problem can be drawn as below:

$$\max_{i_t} \mathrm{E_t}\left[\sum_{q=0}^{\infty} \beta^{t+q}\frac{\Lambda_{t+q}}{\Lambda_t}\left[Q_{t+q}\left(K_{t+q}-(1-\delta)\left(1-fdr_{t+q}\right)K_{t+q-1}\right)-\frac{I_{t+q}}{Z_{d,t}A_{d,t}}\right]\right]$$

where capital accumulation dynamics is defined in Equation (2).

Production Function

The aggregators produce the composite of the differentiated goods $Y_{g,t}$ using the technology described below:

$$Y_{g,t} = \left[\int_0^1 Y_{g,t}(l)^{\frac{\theta_{P_{Y,t}}-1}{\theta_{P_{Y,t}}}}\,dl\right]^{\frac{\theta_{P_{Y,t}}}{\theta_{P_{Y,t}}-1}}$$

where $\theta_{P_{Y,t}} \in (1,\infty)$ denotes the elasticity of substitution between differentiated products. Note also that the demand for each of the differentiated products produced by firm l is derived from the optimization behavior of the aggregator and is represented by

$$Y_{g,t}(l)=\left[\frac{P_t(l)}{P_t}\right]^{-\theta_{P_{Y,t}}} Y_{g,t} \tag{24}$$

where $\{P_t(l)\}_{l\in[0,1]}$ is the nominal price of the differentiated products. These prices are related to the nominal price of the final goods by

$$P_t=\left[\int_0^1 P_t(l)^{1-\theta_{P_{Y,t}}}dl\right]^{\frac{1}{1-\theta_{P_{Y,t}}}}$$

The production function of a differentiated firm l is given by

$$Y_{g,t}(l)=\frac{Z_{a,t}A_{a,t}}{\Omega_t\left(e_{fdr_t}\right)}\Psi_t(l)^{\gamma}[L_t(l)^{\alpha}]^{1-\gamma}\left[\left((1-fdr_t)K_{t-1}(l)U_t(l)\right)^{1-\alpha-\alpha_E-\alpha_F}\right]^{1-\gamma}-F_t \tag{25}$$

where $Z_{a,t}$ and $A_{a,t}$ are non-stationary and stationary components of neutral technology that are not due to flood shock, respectively. $L_t(l)$, $(1-fdr_t)K_{t-1}(l)$, $U_t(l)$ are labor inputs, capital stock net of depreciation by flood, and the capacity utilization rate of capital stock in firm l.[41] Parameters γ and α are the cost share of intermediate inputs and labor inputs, respectively, and F_t is a fixed cost that is exogenous to firms.[42] Note that a firm l is a price-taker in input markets, and its cost-minimization problem yields the following marginal cost function $MC_t(l)$:

[41] The model assumes that the capacity utilization rate U_t is determined by entrepreneurs, and a firm l determines only the product $(1-fdr_t)K_{t-1}(l)U(l)$. The model also assumes that entrepreneurs need to pay the real cost of

$$\frac{\kappa_U\left(U_t^{\Upsilon_U+1}-1\right)}{\Upsilon_U+1}$$

in choosing the capacity utilization rate of capital U_t. Here, κ_U and Υ_U are parameters. The real net return of capital K_{t-1} received by the entrepreneurs can then be expressed by the following equation.

$$R_{E,t}=\left[\frac{U_t\tilde{R}_{E,t}}{P_t}-\frac{\kappa_U\left(U_t^{\Upsilon_U+1}-1\right)}{\Upsilon_U+1}+(1-\delta)Q_t\right]\frac{(1-fdr_t)}{Q_{t-1}}$$

where $\tilde{R}_{E,t}$ is nominal gross return to capital inputs net of depreciation by flood, $(1-fdr_t)K_{t-1}(l)U(l)$.

[42] Following CMR (2010, 2014), the size of the fixed cost F_t is set so that the profits from operating in the goods-producing sector are zero at the steady-state. The model also assumes that the cost exogenously grows at the same rate as does the non-stationary component of $Y_{g,t}(l)$, that is $Z_{a,t}^{\frac{1}{(1-\gamma)(\alpha+\alpha_E+\alpha_F)}}Z_{d,t}^{\frac{(1-\alpha-\alpha_E-\alpha_F)}{\alpha+\alpha_E+\alpha_F}}H_t$, and that firms stop producing goods if the cost exceeds the first term of Equation (25).

$$MC_t(l)=\frac{\Omega_t\left(e_{fdr_t}\right)\bar{\phi}P_t^{\gamma}}{Z_{a,t}A_{a,t}}\left[W_t^{\alpha}W_{E,t}^{\alpha_E}W_{F,t}^{\alpha_F}\tilde{R}_{E,t}^{1-\alpha-\alpha_E-\alpha_F}\right]^{1-\gamma} \tag{26}$$

where $\bar{\phi}$ is a constant.

Price Setting

A differentiated firm l is a monopolistic competitor in the product market, and it confronts Rotemberg-type nominal rigidity. Its optimization problem is formalized as choosing its product price $P_t(l)$ so as to maximize the profits given by equation (24) and the price adjustment costs as described below:

$$\max_{P_t(l)} \mathrm{E}_t\left[\sum_{q=0}^{\infty}\beta^{t+q}\frac{\Lambda_{t+q}}{\Lambda_t}\frac{\Pi_{t+q}(l)}{P_{t+q}}\right] \tag{27}$$

$$s.t.\quad \Pi_{t+q}(l)=P_{t+q}(l)Y_{g,t+q}(l)-MC_{t+q}(l)\left(Y_{g,t+q}(l)+F_{t+q}\right)$$

$$-\frac{\kappa_p}{2}\left(\frac{P_{t+q}(l)}{P_{t+q-1}(l)}-\bar{\pi}\right)^2 P_{t+q}Y_{g,t+q} \tag{28}$$

where Λ_{t+q} is the Lagrange multiplier associated with budget constraint (22) in period $t+q$, and κ_p is the parameter that governs the price adjustment costs.

Goods Market Equilibrium

The composite $Y_{g,t}$ serves either as final goods, e.g. consumption goods and investment goods, as intermediate production inputs, or as goods that are used for financial intermediation activity—namely, monitoring costs. The allocation of the gross output is given by:

$$\begin{aligned}Y_{g,t}=&\underbrace{C_t+\frac{I_t}{Z_{d,t}A_{d,t}}+G_t}_{\text{Final Output}}+\underbrace{\int_0^1\Psi_t(l)dl}_{\text{Intermediate Inputs}}+\underbrace{\frac{\kappa_U\left(U_t^{\Upsilon_U+1}-1\right)}{\Upsilon_U+1}(1-fdr_t)K_{t-1}}_{\text{Inputs for Capital Utilization}}\\&\underbrace{+\left[\mu_E\left(\int_0^{\bar{\omega}_{E,t+1}}\omega_E dF_E(\omega_E)\right)+\mu_F\left(\int_0^{\bar{\omega}_{F,t+1}}\omega_F dF_F(\omega_F)\right)\right]R_{E,t}Q_{t-1}K_{t-1}}_{\text{Monitoring Costs}}\\&+\underbrace{(1-\gamma_F)V_{F,t}+(1-\gamma_E)V_{E,t}}_{\text{Consumption by Exiting FIs and Entrepreneurs}}\end{aligned} \tag{29}$$

A.4 Aggregate Variables

As with CMR (2010), the real GDP Y_t in the model is given as follows:

$$Y_t = C_t + \frac{I_t}{Z_{d,t}A_{d,t}} + G_t \tag{30}$$

The CPI π_t is defined by

$$\pi_t = \frac{P_t}{P_{t-1}} \tag{31}$$

The real interest rate R_t is given by the Fisher equation that connects the nominal interest rate $R_{n,t}$ and the expected inflation $\mathrm{E}_t[\pi_{t+1}]$:

$$R_t = \frac{R_{n,t}}{\mathrm{E}_t[\pi_{t+1}]}$$

Also, for the purpose of the estimation exercise below, the model defines the Solow residual as:

$$\lambda_t = \frac{Y_t}{(L_t)^{\psi_L}(K_{t-1}U_t)^{1-\psi_L}} \tag{32}$$

where ψ_L is the steady-state labor share of income.

A.5 Government Sector

The government collects a per capita lump-sum tax τ_t from households to finance government purchase P_tG_t , for which the amount is exogenously given. The model assumes that a balanced budget is maintained in each period t as follows:

$$P_tG_t = \tau_t$$

The central bank adjusts the policy rate according to the Taylor rule.

A.6 Fundamental Shocks

Except for the capital depreciation shock and TFP shock caused by floods, the model equips with the same fundamental shocks as in Okazaki and Sudo (2018).

A.7 Equilibrium

An equilibrium consists of a set of prices and allocations for a given government policy, the realization of exogenous variables, and initial conditions such that for all t, the following conditions are satisfied.

(i) Each household h maximizes its utility given prices

(ii) Each FI i maximizes its profits given prices and its net worth

(iii) Each entrepreneur j_i in the goods-producing sector maximizes its profits given prices and its net worth

(iv) Each firm l in the goods-producing sector maximizes its profits given prices

(v) Each capital goods producer in the goods-producing sector maximizes its profits given prices

(vi) The government budget constraint holds

(vii) The central bank sets the policy rate following the Taylor rule

(viii) Markets clear

B. Estimation

B.1 Estimation Strategy

First, the model variables are divided by the stochastic trend to derive stationary series; the term expressed by the function of the steady-state growth rate of the two technologies and that of the working-age population, $Z_{a,t}^{\frac{1}{(1-\gamma)(\alpha+\alpha_E+\alpha_F)}} Z_{d,t}^{\frac{(1-\alpha-\alpha_E-\alpha_F)}{\alpha+\alpha_E+\alpha_F}} H_t$, is used to de-trend real variables other than capital stock K_t, e.g., output Y_t or net worth N_t; the term $Z_{a,t}^{\frac{1}{(1-\gamma)(\alpha+\alpha_E+\alpha_F)}} Z_{d,t}^{\frac{1}{\alpha+\alpha_E+\alpha_F}} H_t$ is used to de-trend capital stock K_t,. Next, a Bayesian estimation is conducted following existing studies such as CMR (2014). We write the model's equilibrium conditions in a state-space representation and derive the likelihood function of the system of equilibrium conditions using the Kalman filter. We then combine the likelihood function with the priors for the parameters to obtain the posterior density function numerically. In this process, we use the random walk Metropolis-Hastings algorithm.

B.2 Calibration, Prior Distribution, and Posterior Distribution

Calibrated Parameters

Some parameter values are calibrated following Okazaki and Sudo (2018). These include the discount factor β, the elasticity of substitution between differentiated products θ_{P_Y}, the elasticity of substitution between differentiated labor inputs θ_W, the capital depreciation rate δ, the share of intermediate input, labor input, entrepreneurial labor input and FI labor input in goods production γ, α, α_E, α_F, and the utility weight of leisure φ. See Table 1 for the values of these parameters.

Estimated Parameters

The remaining parameters are estimated: see Table 2 for the values of these parameters. The type, mean, and standard deviation of the prior distribution for the estimated parameters, except for those concerning flood and earthquake shocks, follow Okazaki and Sudo (2018). The prior distribution for parameters regarding flood and earthquake shocks, $\rho_x, \theta_x, \eta_x, x \in \{fdr_t, edr_t\}$, are set in reference to those for other shocks.

Posterior Distribution

This paper employs the Metropolis-Hastings algorithm to calculate the posterior distribution and to evaluate the marginal likelihood of the model. In calculation, a sample of 400,000 draws is created, the initial 200,000 of which are burned in. Estimated posterior distributions of parameters are also shown in Table 2. The last three columns of the table display the posterior mean and the confidence intervals for the estimated parameters.

C. Additional Assumption on Flood Damage

Regression of Flood Damage on the Number of Days of Heavy Rainfall

In order to construct quarterly series of flood damage, we first evaluate the relationship between flood damage and precipitation. Specifically, we examine the relationship between the amount of flood damage and the number of days with more than 100 mm of precipitation per day ("days of heavy rainfall"), assuming that there is a positive correlation between the number of times strong rainfall occurs in a short period and the magnitude of flood damage.

First, the number of days with daily precipitation of 100 mm or more is obtained for each observation point[43] on a monthly basis from the AMeDAS observation data of the Japan Meteorological Agency (JMA), and then the average value is calculated for observation points in each prefecture[44]. This monthly average number of days of heavy rainfall for each prefecture is then summed up for each year and each of the four regions in Japan, following the JMA classification, to produce an annual series of the number of days of heavy rainfall per region[45]. Lastly, this series is regressed on the amount of damage to general assets[46] by region, as described in the following equation. The estimation result shows that a 1% increase in the number of days of heavy rainfall for a year is, on average, associated with a 2% increase in the amount of damage to general assets.

Estimation Equation

$$\Delta \ln\left(y_{i,t}\right) = \beta_0 + \beta_1 \Delta \ln\left(Days_{i,t}\right) + FE_i + TE_t + \epsilon_{i,t}$$

$y_{i,t}$: Amount of flood damage by region (annual, million JPY, actual)

$Days_{i,t}$: Number of days of heavy rainfall by region (year, total of average days by prefecture)

$\Delta \ln\left(x_{i,t}\right)$: First log difference of the variable[47]

t: 1981 – 2019, i: Northern Japan, Eastern Japan, Western Japan, Okinawa/Amami region

FE_i: 4 region fixed effects, and TE_i: Year time effects

[43] Among all AMeDAS observation points in Japan, 911 points with no missing values for the entire period from 1981 to 2019 are used.

[44] For Hokkaido, the average value is calculated for each development bureau and then these values are summed up for obtaining the value of the region.

[45] For details of the classification, please refer to the JMA's website, "Regional names used for general weather information, etc." https://www.jma.go.jp/jma/kishou/know/yougo_hp/tiikimei.html

[46] The amount of damage to general assets in the Flood Statistics includes damage to residential houses and other items that are not considered to fall under the capital stock of the model in this paper. For this reason, private residential buildings are included in the capital stock used as the denominator in the calculation of the capital depreciation rate described below.

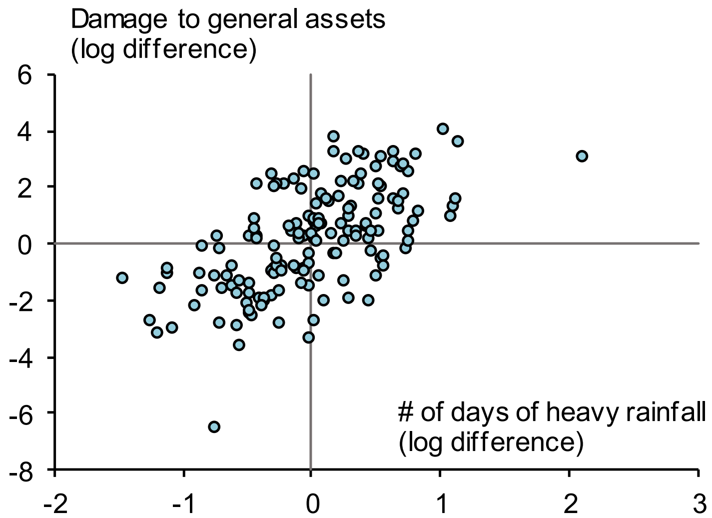
[47] The unit root test is conducted for both the explanatory and dependent variables in the equation above, and the estimation is conducted by taking the first log difference.

Estimation Result

Dep. variable	ΔLn(Damage to general assets)	
Exp. variable	ΔLn(# of days of heavy rainfall)	2.11 *** [0.35]
	Fixed effects	Region x Year
	# of observations	155
	Adjusted R^2	0.21

Note: Numbers in parentheses are standard errors. *** denotes 1% significance.

Relationship between the Number of Days of Heavy Rainfall and Flood Damage



Note: Damage to general assets after the removal of fixed effects.

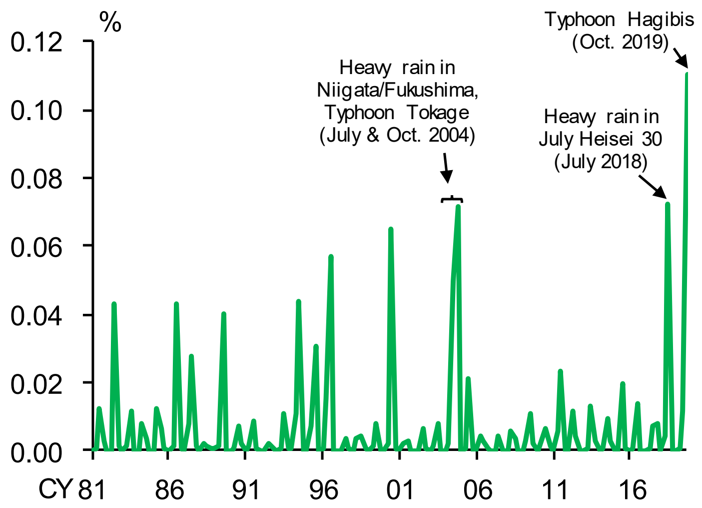
Source: Ministry of Land, Infrastructure, Transport and Tourism “Flood Statistics”; Japan Meteorological Agency; Bank of Japan.

Quarterly Estimates of Flood Damage

Since the time-frequency of the model in this paper is quarterly, it is necessary to transform the annual series of flood damage into the quarterly series for the purpose of estimating the model. Using the estimation results of the relationship between flood damage and the number of days of heavy rainfall obtained above, we divide the amount of flood damage in a year into four quarterly observations based on the quarterly difference of the number of days of heavy rainfall by region and then aggregated for the whole country to obtain the quarterly series of national-level flood damage.

The figure below shows the quarterly series of the flood-induced capital depreciation rate. The rate was particularly high in the fourth quarter of 2019, when Japan was strongly hit by Typhoon Hagibis, and in the second half of 2004, when the torrential rains in Niigata and Fukushima prefectures and Typhoon Tokage occurred.

Capital Depreciation Rate due to Flood Damage (quarterly)



Source: Ministry of Land, Infrastructure, Transport, and Tourism, "Flood Statistics"; Cabinet Office, "Quarterly Estimates of Net Capital stock of Fixed Assets"; Bank of Japan.

Looking at the descriptive statistics of the flood-induced quarterly capital depreciation rate, the average depreciation rate in July-September (the third quarter) is markedly higher than that in other three quarters since the number of heavy rainy days is strongly correlated with the frequency of typhoons, which usually occur in this quarter. In years when typhoons occur in October-December (e.g., 2019), the amount of flood damage in that quarter is larger, and thus the rate for October-December (the fourth quarter) is characterized by a large standard deviation.

Looking by decade, while the average flood-induced depreciation rate temporarily declined from the 1980s to the 1990s as the rapid accumulation of capital stock increased the denominator, the rate has increased since then, indicating that the recent rise in the frequency of heavy rainfall is translated into the amount of flood damage.

Descriptive Statistics of Capital Depreciation Rate

By Quarter basis point

	Average	Median	S.D.	10 percentile	90 percentile
Jan.-Mar.	0.01	0.00	0.01	0.00	0.02
Apr.-June	0.32	0.14	0.38	0.01	0.79
July-Sep.	1.85	0.91	1.91	0.27	4.40
Oct.-Dec.	0.55	0.04	2.02	0.00	0.30
Total	0.68	0.07	1.57	0.00	1.44

By Decade basis point

	Average	Median	S.D.	10 percentile	90 percentile
1980s	0.64	0.07	1.17	0.00	1.39
1990s	0.56	0.06	1.20	0.00	1.11
2000s	0.68	0.09	1.66	0.00	1.19
2010s	0.84	0.06	2.06	0.00	1.43
Total	0.68	0.07	1.57	0.00	1.44

D. Comparison with Hayashi and Prescott (2002)

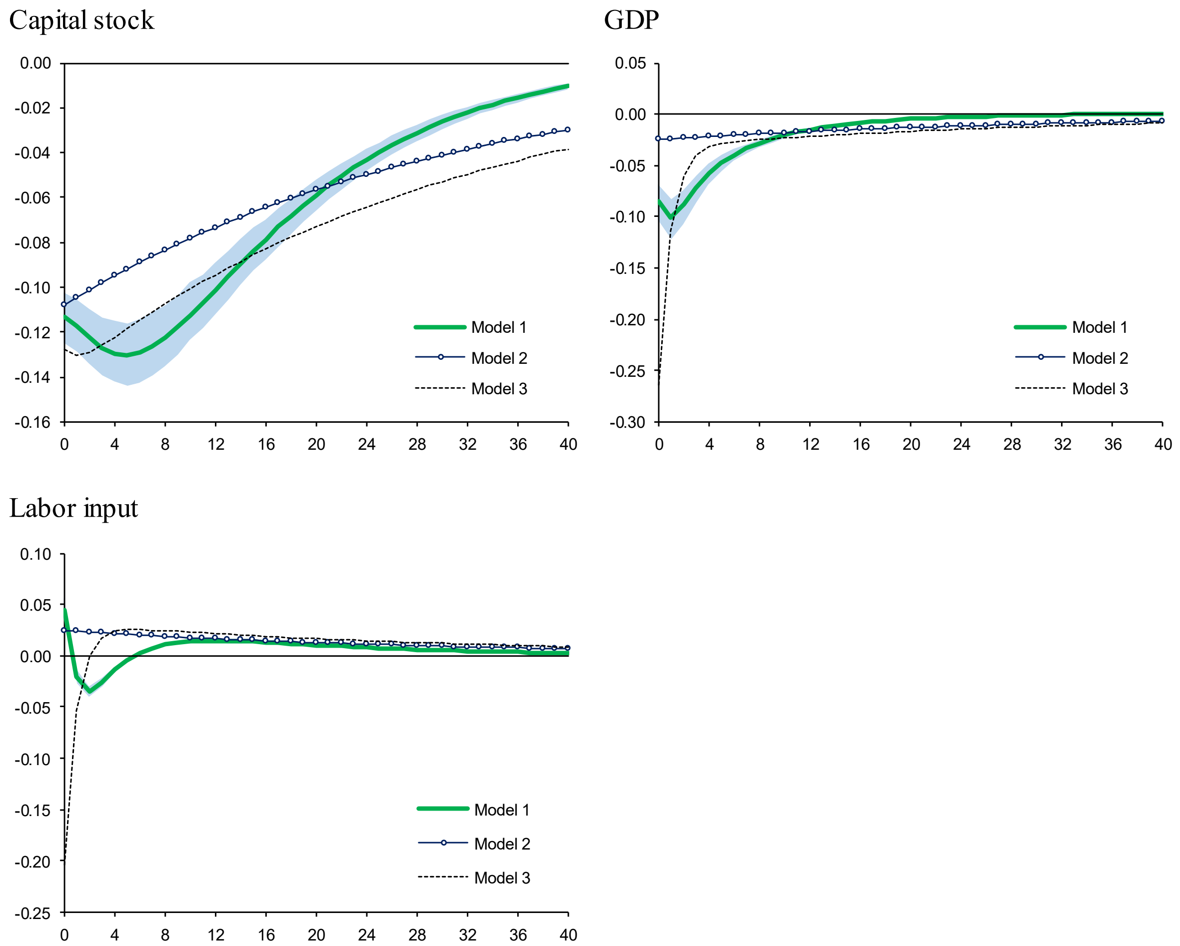
Hayashi and Prescott (2002) is a well-established theoretical analysis of the business cycle fluctuations in Japan using the neoclassical growth model, which is one of the textbook DSGE models. The model used in Hayashi and Prescott (hereinafter the HP model) combined with the time series of the actual TFP reasonably captures the fluctuation in Japan's GDP from the 1960s to the 1980s. Compared to the HP model, the model used in this paper differs in two respects: first, there are nominal rigidities in goods prices and wages; second, there are loan contracts between the household and FI sectors, and between the FI sector and the goods-producing sector. It therefore is considered that differences in simulation results between our model and the HP model can possibly be attributed to these aspects.

In this section, we consider a response of the economy to a flood shock of the same magnitude as that caused by Typhoon Hagibis, as in Section 4.1 above, and compare the responses when the shock occurs in the baseline model and in the HP model. For the purpose of examining the transmission mechanism through both capital stock and TFP, we compare three models: our baseline model (hereafter Model 1); the HP model in which flood shocks do not directly affect TFP at the impact (Model 2); and the HP model in which flood shocks directly affect both capital stock and TFP at the impact (Model 3). In using the HP model, the parameter values of the model are set to be equivalent to those used in Hayashi and Prescott (2002).

First, comparing responses of labor input across models, while the economy sees a large decrease in Model 1 and Model 3, it sees an increase in Model 2. This suggests that the effect of a decline in TFP on the supply of labor input through a decline in wages is quantitatively large. Next, regarding capital stock, in Model 2—in which flood-induced decline in TFP is absent—the economy sees the least decline, which in turn suggests that the absence of a decline in TFP could result in only a minor decline in the rate of return on capital, which in turn weakens the impediment to investment. As for cumulative quantitative impacts on GDP, however, the difference across models is modest, varying only about 0.8 to 1.5 times.

Note that there is a difference in the recovery pace of GDP across models. In Model 3, GDP shows the largest drop at the impact period but recovers at the quickest pace. On the other hand, the initial drop in GDP is limited in Model 1 but the downward pressure is persistent, and therefore the recovery is slow compared to other models. As described above, in addition to the price rigidity, the balance sheet adjustment in Model 1 may have acted to create additional inertia in the dynamics of GDP.

Impulse Response Functions



Note: 1. The vertical axis of each figure shows the deviation of the variable from the steady-state value (%).

2. The horizontal axis of each figure represents the quarter after the shock.

3. The legend for each graph is as follows

Model 1 - Solid line (green): Baseline (90% confidence interval for shadows)

Model 2 - Solid line with a marker: Hayashi and Prescott (2002) + capital depreciation shock

Model 3 - Dashed line: Model 2 + TFP shock

E. Robustness Check: News Shock

Forecasting Extreme Weather Events

The baseline model assumes that flood shocks are not anticipated in advance. However, forecasts regarding future possible floods and heavy rains that may cause floods are normally released. For example, the Japan Meteorological Agency (JMA) publishes an index of ocean and weather conditions of the Indian Ocean and the equatorial Pacific Ocean from the viewpoint of studying the El Niño phenomenon, which could affect Japan's medium- to long-term weather[48]. In addition, it releases monthly forecasts for the next three months regarding how weather conditions such as temperature and precipitation will change compared to the average year. In light of this, in this section, we check the robustness of the model implications when flood shocks are assumed to be predictable to some extent[49].

Validity and Setting of News Shock

First, in order to examine the extent to which exogenous damage to the capital stock can be anticipated in advance on average, we analyze the relationship between sea surface temperatures (SSTs) at period t in the tropical Indian Ocean and the eastern equatorial Pacific Ocean[50] and the amount of flood damage at period $t+1$. When the SST in the tropical Indian Ocean is higher than usual, the amount of precipitation in Japan tends to be higher on average. When the SST in the eastern equatorial Pacific Ocean is lower than usual (La Niña phenomenon), precipitation in the Okinawa-Amami region tends to be higher than usual from June to August. Given this relationship, we regress flood damage on the SSTs in the two oceans as follows[51].

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[48] The El Niño (La Niña) phenomenon is one in which the sea surface temperatures rise above (fall below) the normal in the equatorial Pacific Ocean from near the date line to the coast of South America. This phenomenon has a significant impact on Japan's weather, as the rise or fall of sea surface temperatures in the Indian and Pacific Oceans changes the location where cumulonimbus clouds occur.

[49] Under the assumption that climate change continues in the long run, economic agents may conduct capital investment or pursue technological innovation from a long-term perspective, trying to potentially limit the direct effects and subsequent indirect effects on the economy. In this section, we focus only on the short-run dynamics as a result of the change in short-term expectations of flood shocks, and do not consider a long-term dynamic relationship between the expected flood shocks and the indirect effects.

[50] The definition of sea areas follows the Japan Meteorological Agency. Specifically, the tropical Indian Ocean corresponds to IOBW (the rectangle from 20° N to 20° S and 40° E to 100° E), and the eastern equatorial Pacific Ocean corresponds to NINO.3 (the rectangle from 5° N to 5° S and 150° W to 90° W).

[51] Among the explanatory variables, IOBW and NINO are converted to the deviation from the average of each month in the last 30 years, and for IOBW, the trend was removed by the Japan Meteorological Agency. In addition, based on the results of unit root tests conducted for both explanatory and dependent variables, explanatory and the dependent variables are transformed into the log difference from the same quarter of the previous year and first log difference, respectively.

Estimation Equation

$$\Delta \ln(y_{i,t+1}) = \beta_0 + \beta_1 \Delta IOBW_t + \beta_2 \Delta NINO_t + FE_i + TE_t + \epsilon_{i,t}$$

$y_{i,t+1}$: Amount of flood damage by region (quarterly, million JPY, estimated by Appendix C)

$IOBW_t, NINO_t$: Deviation in the SSTs in the two regions from the reference value (°C, 5-month MA)[52]

t: Q1 1990 to Q4 2019, i: Northern Japan, Eastern Japan, Western Japan, Okinawa/Amami region

FE_i: 4 regions x quarterly fixed effects, and TE_t: Year time effect

The estimation result is shown below. All of the coefficients are statistically significant (at the 5% level), and the signs of the coefficients are as expected. In other words, higher SSTs in the tropical Indian Ocean can be associated with greater damage from floods through increased precipitation in the following season (and vice versa in the eastern equatorial Pacific Ocean). This result implies that it is possible to predict flood damage in the following quarter based on SSTs in the two oceans.

Estimation result

Dep. variable	ΔLn(Damages to general assets)	
Exp. variables	SST in tropical Indian Ocean (y/y dif)	4.61 ***
		[1.13]
	SST in equatorial Pacific Ocean (y/y dif)	-0.53 **
		[0.22]
	Fixed effects	Region x quarter
	# of observations	480
	Adjusted R^2	0.10

Note: Numbers in parentheses are standard errors.

*** indicates 1% significance, ** indicates 5% significance.

Next, based on this result, we add the assumption that some of the direct damage caused by the occurrence of floods is predicted in advance by the baseline model and analyze how the impact of flood shocks on economic variables changes in the model with this assumption. Specifically, we assume the following equation holds for the amount of damage to capital stock associated with a flood shock that occurs in period t.

$$fdr_t = \epsilon_{fdr,t} + \varepsilon_{fdr_{1,t-1}}$$

[52] $IOBW_t$ and $NINO_t$ are both released on a monthly basis, but in this estimation, we use the value published three months earlier, i.e. the value published in January in the case of the April-June quarter.

where $\varepsilon_{fdr_{1,t-1}}$ is the portion of the flood shock that occurs in period t that was anticipated one period earlier. We assume that the economic agents know at time $t-1$, through weather forecasts and other means, that this shock will occur at t and also the magnitude of the shock. However, this forecast does not accurately predict the amount of damage to the capital stock that will occur in period t. Rather, the realized amount of damage to capital stock in period t deviates from the expected amount of damage to capital stock. In other words, in period t, an unanticipated capital depreciation shock $\epsilon_{fdr,t}$ occurs, and the total amount of realized damage to capital stock in period t is the sum of these two shocks. Both shocks are assumed to follow i.i.d.

Simulation Result

The result of the simulation is presented in Figure 8, which compares the dynamics of key economic variables when a flood shock similar to that by Typhoon Hagibis is anticipated to hit the economy in period -1, one quarter before the arrival of the shock, and when the flood shock is not anticipated and occurs suddenly in period 0 (baseline model). Similar to the theoretical analysis of news shocks cited in Beaudry and Portier (2014), in our model, the anticipation of flood damage incentivizes economic agents to change their behavior from the time they anticipate the damage to their capital stock in period -1.

The simulation result under the news shock is qualitatively similar to that obtained in the baseline model, i.e. the news shock leads to impairment of the balance sheets of the goods-producing and FI sectors and persistent depression of capital stock and GDP. In other words, the result confirms that the transmission channels and effects of flood shocks on the real economy do not change significantly even when some of the shocks are anticipated beforehand.

However, when the responses for the two models are compared in detail, there are some differences between them. For example, while capital stock is expected to be depreciated in period 0, in period -1, the goods-producing sector refrains from investment and the household sector reduces labor supply, resulting in downward pressure on GDP even before the realization of flood-induced capital depreciation. As a result, the balance sheets of the goods-producing and the FI sectors will be damaged and lending rates will rise, albeit only slightly.

Table 1: Calibrated Parameters

α	Labor share (households)	0.600
α_E	Labor share (entrepreneurs)	0.020
α_F	Labor share (FIs)	0.020
γ	Share of intermediate goods	0.583
κ_U	Scaling parameter of capital utilization adjustment cost	0.050
φ	Weight on labor disutility	0.200
β	Households' discount factor at the steady-state (quarterly)	0.998
δ	Capital depreciation rate (quarterly)	0.028
θ_{P_Y}	Elasticity of substitution between differentiated products at the steady-state	7.000
θ_W	Elasticity of substitution between differentiated labor inputs at the steady-state	7.000

Table 2: Estimated Parameters (Prior and Posterior Distributions)

	Prior distribution			Posterior distribution		
	Distribution	Mean	S.D.	Mean	5th percentiles	95th percentiles
Elasticity of labor supply	gamma	0.8	0.075	1.0206	0.9874	1.0503
Capital stock adjustment cost	gamma	2	0.25	2.2047	2.1233	2.2847
Price adjustment cost	gamma	12	1	7.8092	7.4593	8.1402
Nominal wage adjustment cost	gamma	2.5	0.5	0.7009	0.5845	0.8445
Policy weight on inflation in Taylor rule	normal	2.75	0.05	2.7197	2.7033	2.7363
Monetary policy smoothing	beta	0.5	0.01	0.5337	0.5286	0.5383
Inverse elasticity of capital utilization rate	gamma	5	1	2.3873	2.1554	2.5930
Riskiness of idiosyncratic productivities (FIs)	gamma	0.104	0.002	0.1029	0.1022	0.1035
Riskiness of idiosyncratic productivities (entrepreneurs)	gamma	0.309	0.002	0.3087	0.3083	0.3090
Monitoring cost (IF contract)	gamma	0.539	0.01	0.5500	0.5421	0.5564
Monitoring cost (FE contract)	gamma	0.02	0.01	0.0459	0.0375	0.0524
Survival rates (FIs)	beta	0.86	0.001	0.8634	0.8631	0.8638
Survival rates (entrepreneurs)	beta	0.96	0.001	0.9598	0.9592	0.9604
Steady-state value of technology (neutral)	gamma	1.001	0.001	0.9995	0.9992	0.9998
Steady-state value of technology (investment-specific)	gamma	1.002	0.001	1.0016	1.0011	1.0021
Staedy state value of target inflation rate	normal	1.002	0.001	1.0025	1.0020	1.0030
Degree of internal habit persistence	beta	0.6	0.15	0.5245	0.4705	0.6071
Scaling parameter of flood-related TFP shock	beta	0.5	0.15	0.8425	0.7605	0.9321
Scaling parameter of earthquake-related TFP shock	beta	0.5	0.15	0.4092	0.3084	0.5060
Non-stationary technology shock (neutral) AR	beta	0.5	0.15	0.3186	0.2532	0.3906
Stationary technology shock (neutral) AR	beta	0.5	0.15	0.9494	0.9364	0.9618
Non-stationary technology shock (investment-specific) AR	beta	0.5	0.15	0.2351	0.1895	0.2780
Stationary technology shock (investment-specific) AR	beta	0.5	0.15	0.9878	0.9812	0.9946
Net worth shock (FIs) AR	beta	0.5	0.15	0.2415	0.1819	0.2995
Net worth shock (entrepreneurs) AR	beta	0.5	0.15	0.7212	0.6707	0.7648
External demand shock AR	beta	0.5	0.15	0.9863	0.9782	0.9951
Investment adjustment shock AR	beta	0.5	0.15	0.4938	0.4164	0.5721
Price markup shock AR	beta	0.5	0.15	0.9402	0.9130	0.9673
Nominal wage markup shock AR	beta	0.5	0.15	0.5769	0.4969	0.6844
Discount factor shock AR	beta	0.5	0.15	0.6561	0.6009	0.7080
Target inflation rate shock AR	beta	0.5	0.15	0.3472	0.2918	0.4051
Flood-related capital depreciation shock AR	beta	0.5	0.15	0.3597	0.3090	0.4098
Earthquake-related capital depreciation shock AR	beta	0.5	0.15	0.7016	0.6680	0.7286
Non-stationary technology shock (neutral) SD	invg	0.01	5	0.0022	0.0017	0.0027
Stationary technology shock (neutral) SD	invg	0.05	5	0.0060	0.0059	0.0061
Non-stationary technology shock (investment-specific) SD	invg	0.01	5	0.0153	0.0137	0.0169
Stationary technology shock (investment-specific) SD	invg	0.05	5	0.0174	0.0155	0.0192
Monetary policy shock (SD)	invg	0.01	5	0.0020	0.0015	0.0024
Net worth shock (FIs) SD	invg	0.02	5	0.0032	0.0026	0.0037
Net worth shock (entrepreneurs) SD	invg	0.02	5	0.0046	0.0037	0.0055
External demand shock SD	invg	0.01	5	0.0659	0.0585	0.0729
Investment adjustment shock SD	invg	0.01	5	0.0389	0.0333	0.0445
Price markup shock SD	invg	0.01	5	0.0292	0.0258	0.0326
Nominal wage markup shock SD	invg	0.01	5	0.0476	0.0321	0.0667
Discount factor shock SD	invg	0.015	5	0.0050	0.0033	0.0067
Target inflation rate shock SD	invg	0.01	5	0.0035	0.0031	0.0039
Flood-related capital depreciation shock SD	invg	0.0001	5	0.0002	0.0002	0.0002
Earthquake-related capital depreciation shock SD	invg	0.0009	5	0.0010	0.0009	0.0011

Table 3: GDP Variance Decomposition

(%)

	Period at shock	5 years later	10 years later
Technology factors	75.4	76.6	76.4
Demand factors	2.8	4.7	6.5
Flood factors	0.3	0.1	0.1
Others	21.6	18.6	17.1

Note: 1. The contribution of technology factors is the sum of the contribution of both non-stationary and stationary shocks for neutral and investment-specific technologies.

2. The contribution of demand factors is the sum of the contribution of shocks to the external demand and discount factor.

Figure 1: Outline of the Model

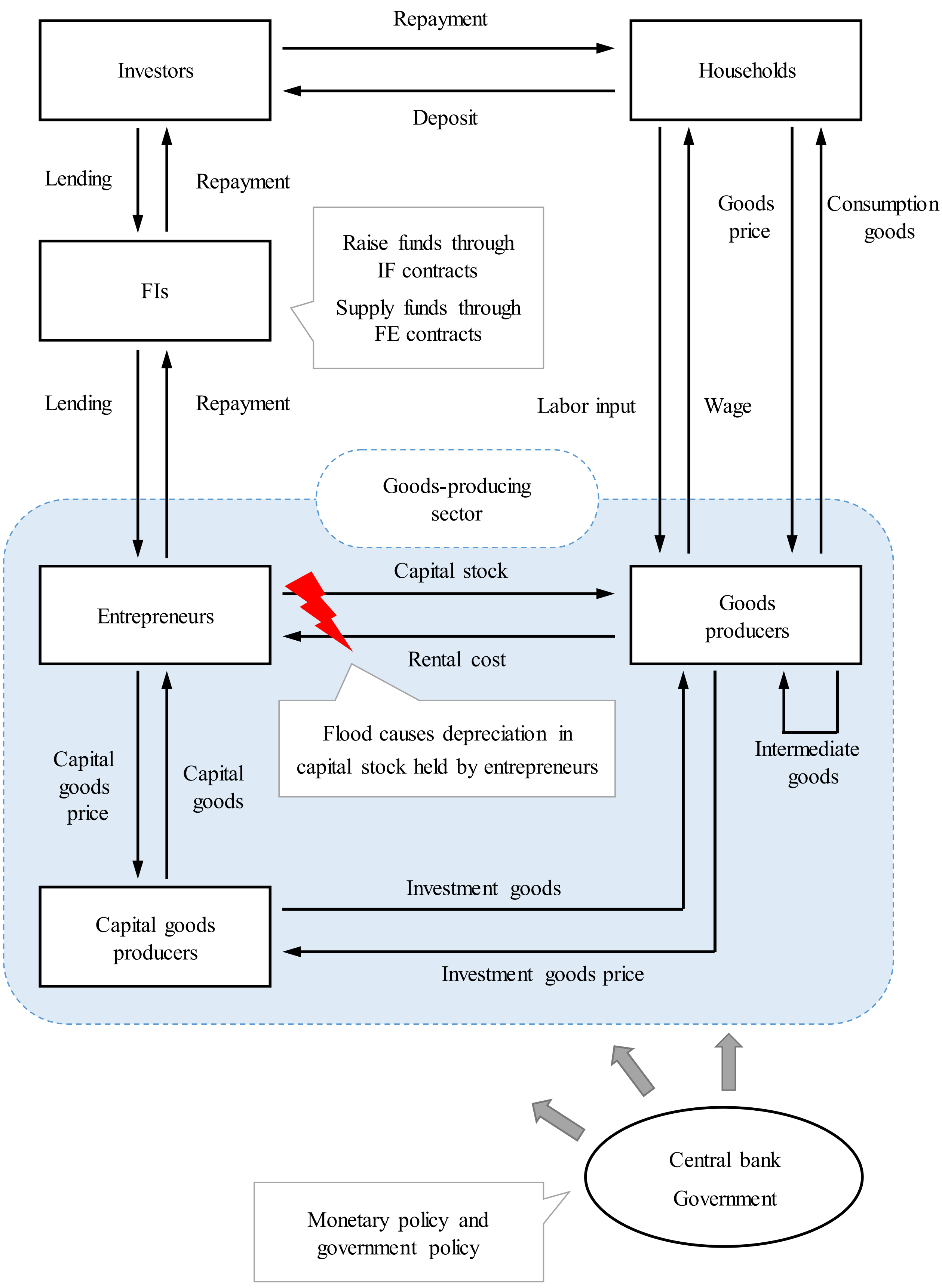


Figure 2: Flow of Capital Stock

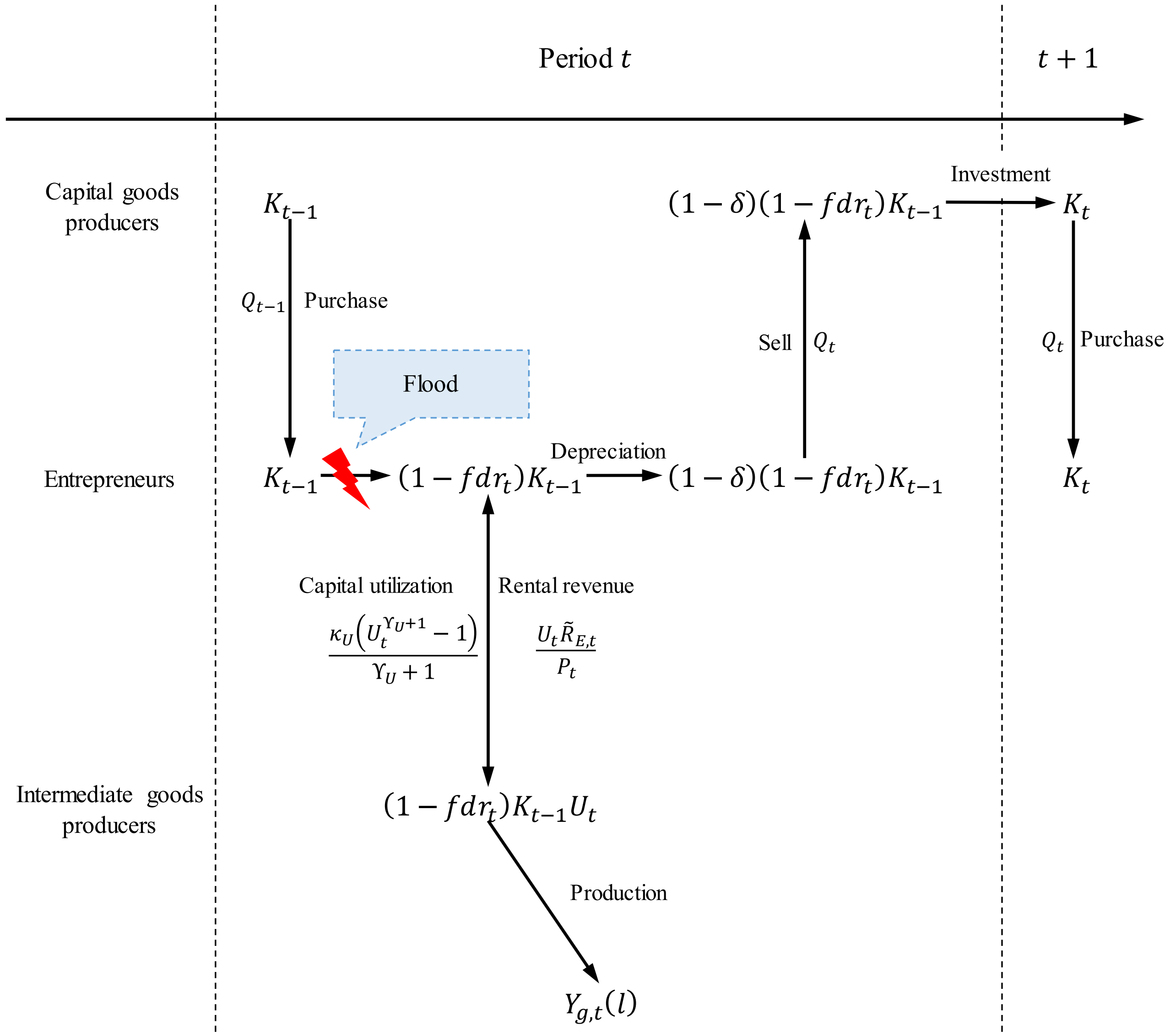
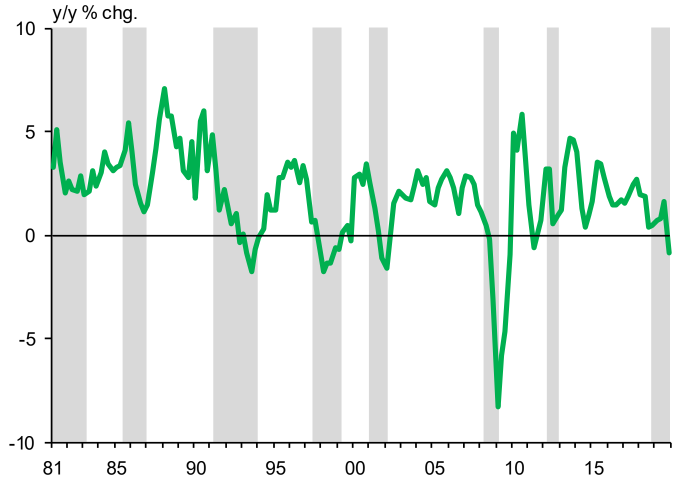
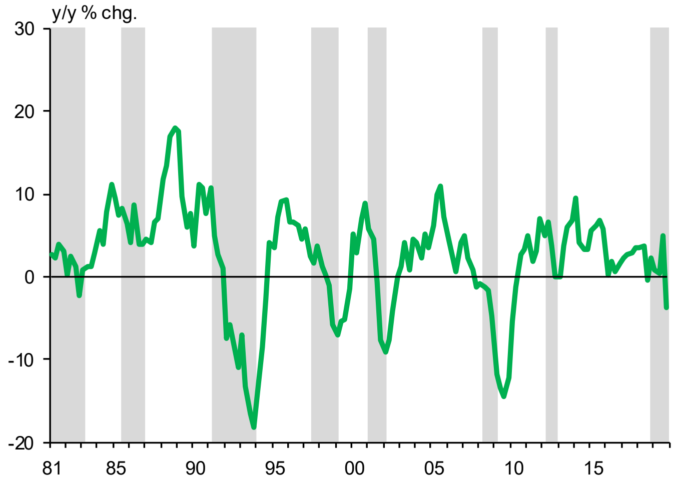


Figure 3-1: Data Used in Estimation (1)

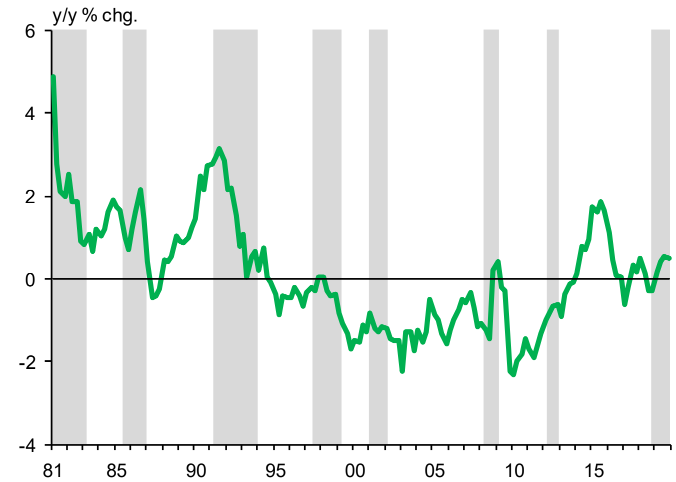
(1) Real GDP



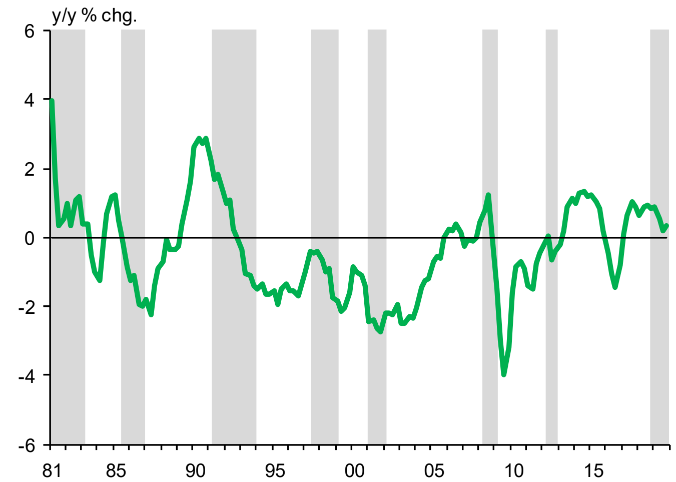
(2) Real investment



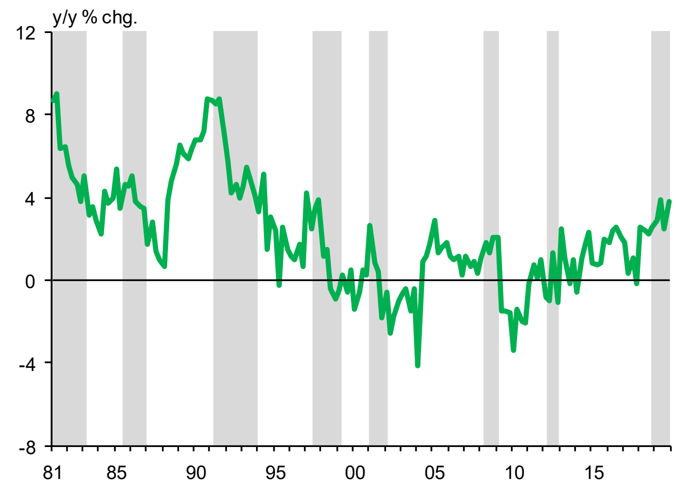
(3) GDP deflator



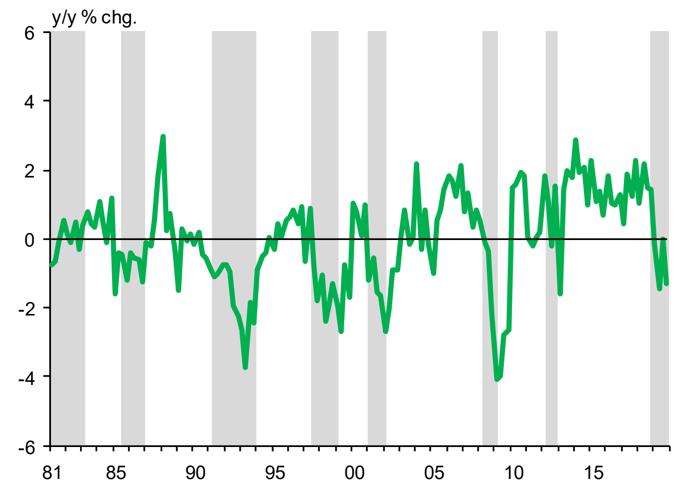
(4) Investment deflator



(5) Nominal wage



(6) Working hours

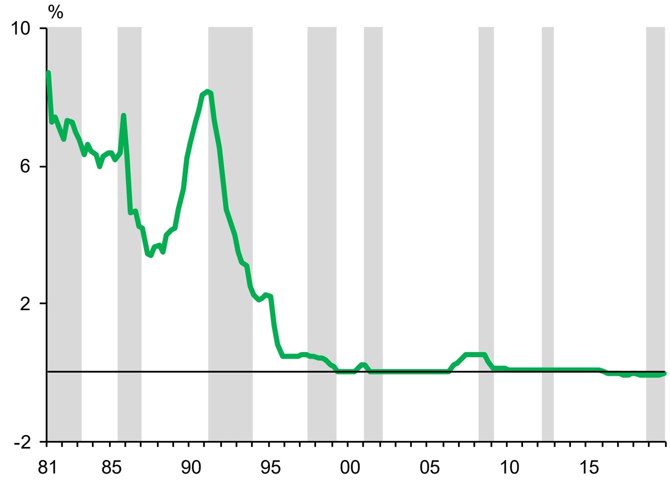


Note: 1. Series (1), (2), and (6) are on a per capita basis. For all variables, we use a quarter-on-quarter % change of the variable rather than a year-on-year % change.
2. The shaded areas show the period of business cycle peak-to-trough determined by the Cabinet Office.

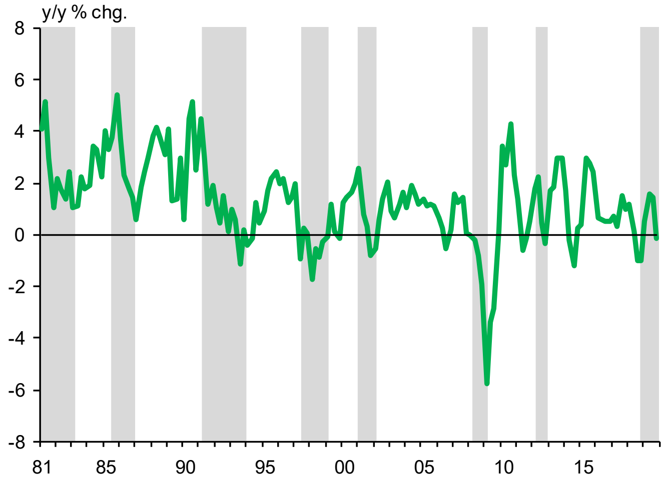
Source: Cabinet Office, "National Accounts"; Ministry of Health, Labour, and Welfare, "Monthly Labour Survey"; Ministry of Internal Affairs and Communications, "Labour Force Survey"

Figure 3-2: Data Used in Estimation (2)

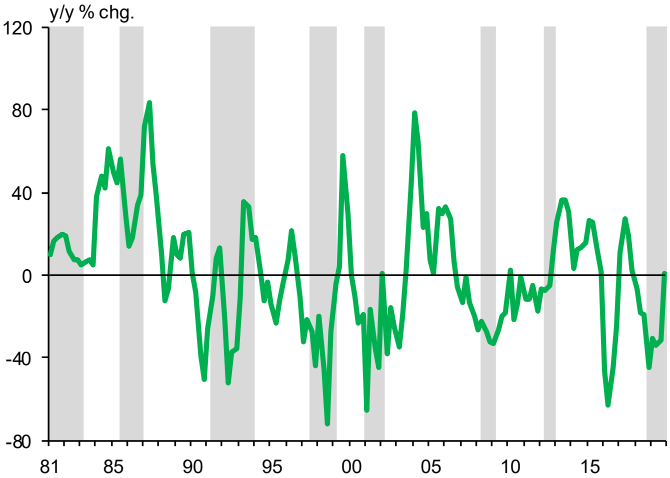
(7) Policy rate



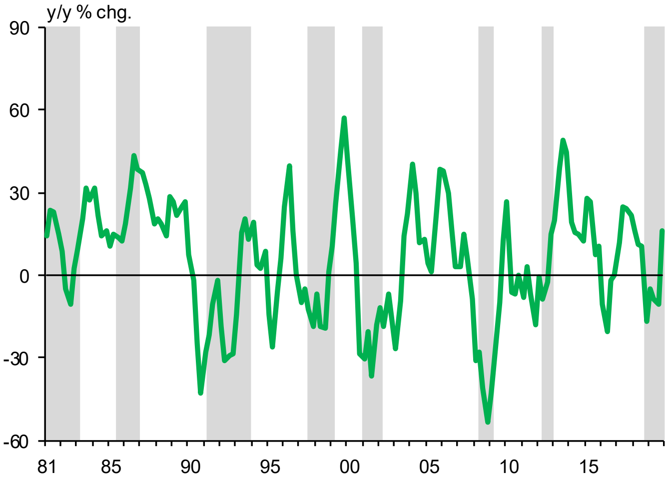
(8) Measured TFP (Solow residuals)



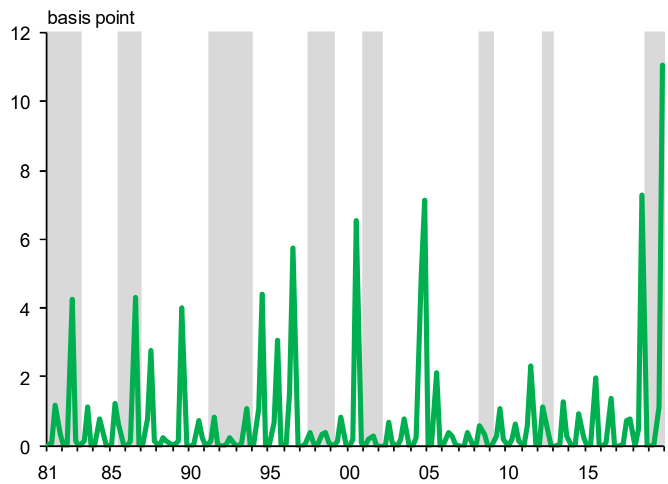
(9) Real net worth in FI sector



(10) Real net worth in goods-producing sector



(11) Flood-related capital depreciation rate

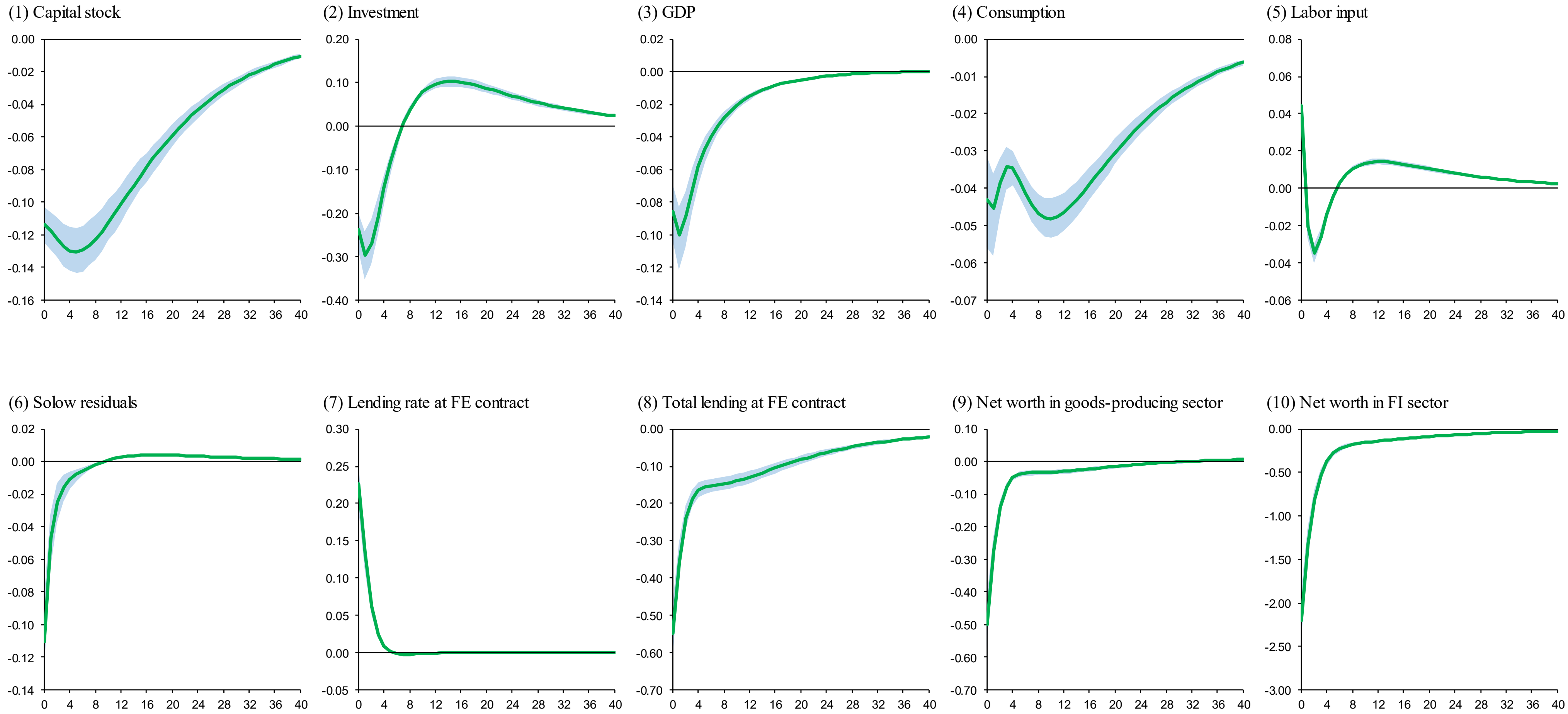


Note: 1. Series (9) and (10) are on a per capita basis. For series (8) ~ (10), we use a quarter-on-quarter % change of the variable rather than a year-on-year % change.

2. The shaded areas show the period of business cycle peak-to-trough determined by the Cabinet Office.

Source: Cabinet Office, "National Accounts"; Japan Exchange Group, Inc., "Market Capitalization"; Ministry of Land, Infrastructure, Transport, and Tourism, "Flood Statistics"; Japan Meteorological Agency; Bank of Japan, "Flow of Funds Accounts"

Figure 4: Impulse Response Functions for Flood Shocks

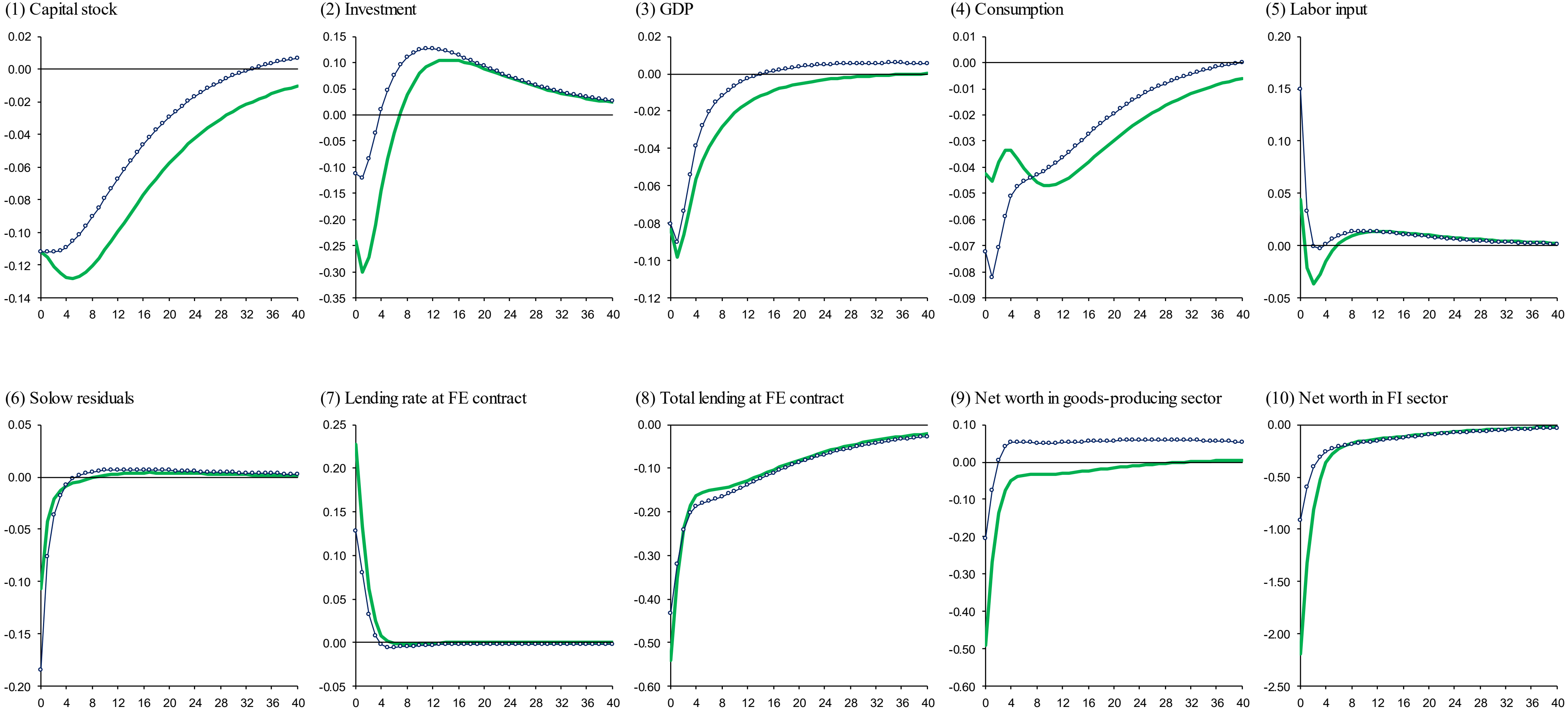


Note: 1. The series shown in (7) is the deviation from the non-stochastic steady-state, on an annual basis. Others are the percentage deviation from the non-stochastic steady-state. The size of flood shock in this simulation is set to a value equivalent to that of Typhoon Hagibis in terms of the size of the capital stock depreciation.

2. The horizontal axis denotes quarters after the shock.

3. The solid line and the shaded areas represent the point estimate of the impulse response and the 90% confidence intervals of the estimate, respectively.

Figure 5: Impulse Response Functions: When Insurance Covers the Damage to Capital Stock held by Entrepreneurs

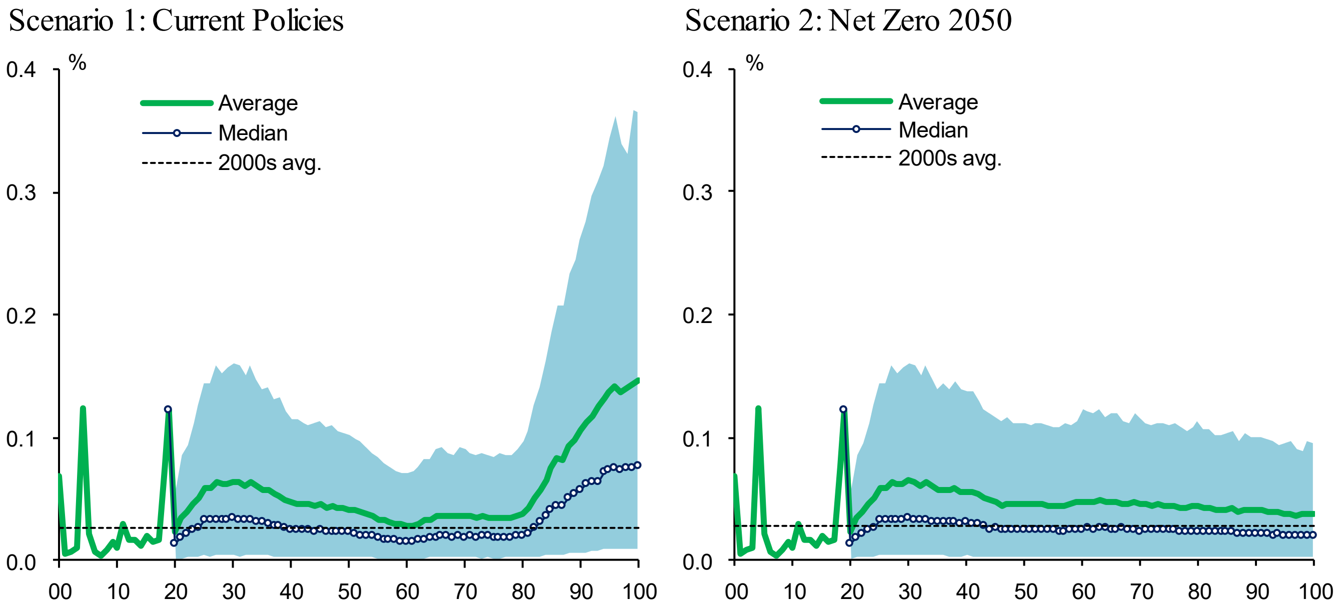


Note: 1. The series shown in (7) is the deviation from the non-stochastic steady-state, on an annual basis. Others are the percentage deviation from the non-stochastic steady-state.

2. The horizontal axis denotes quarters after the shock.

3. The solid line and the dotted line represent the impulse response in the baseline model and that of the model in which capital stock held by the goods-producing sector is fully insured against damage from a flood shock, respectively.

Figure 6: Flood-induced Capital Depreciation Rates in Climate Change Scenarios

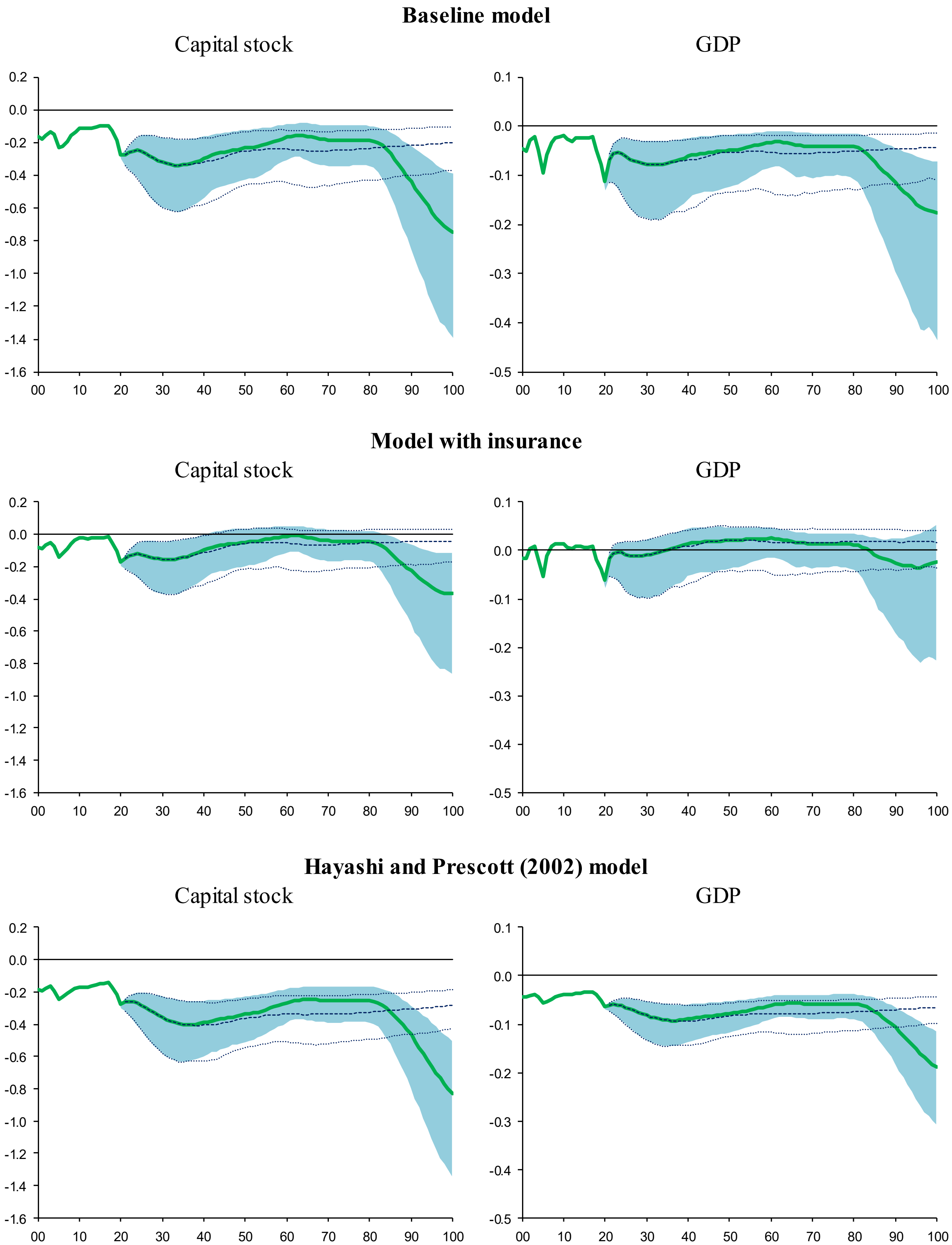


Note: 1. The horizontal axis denotes years up to 2100.

2. Capital depreciation rates are the sum of quarterly rates per year. The figures up to 2019 are the actual values, while those after 2020 are based on the 5000 sets of flood-induced capital depreciation rate series assumed in the scenario.

3. The shaded areas represent 90% confidence intervals for the shock series.

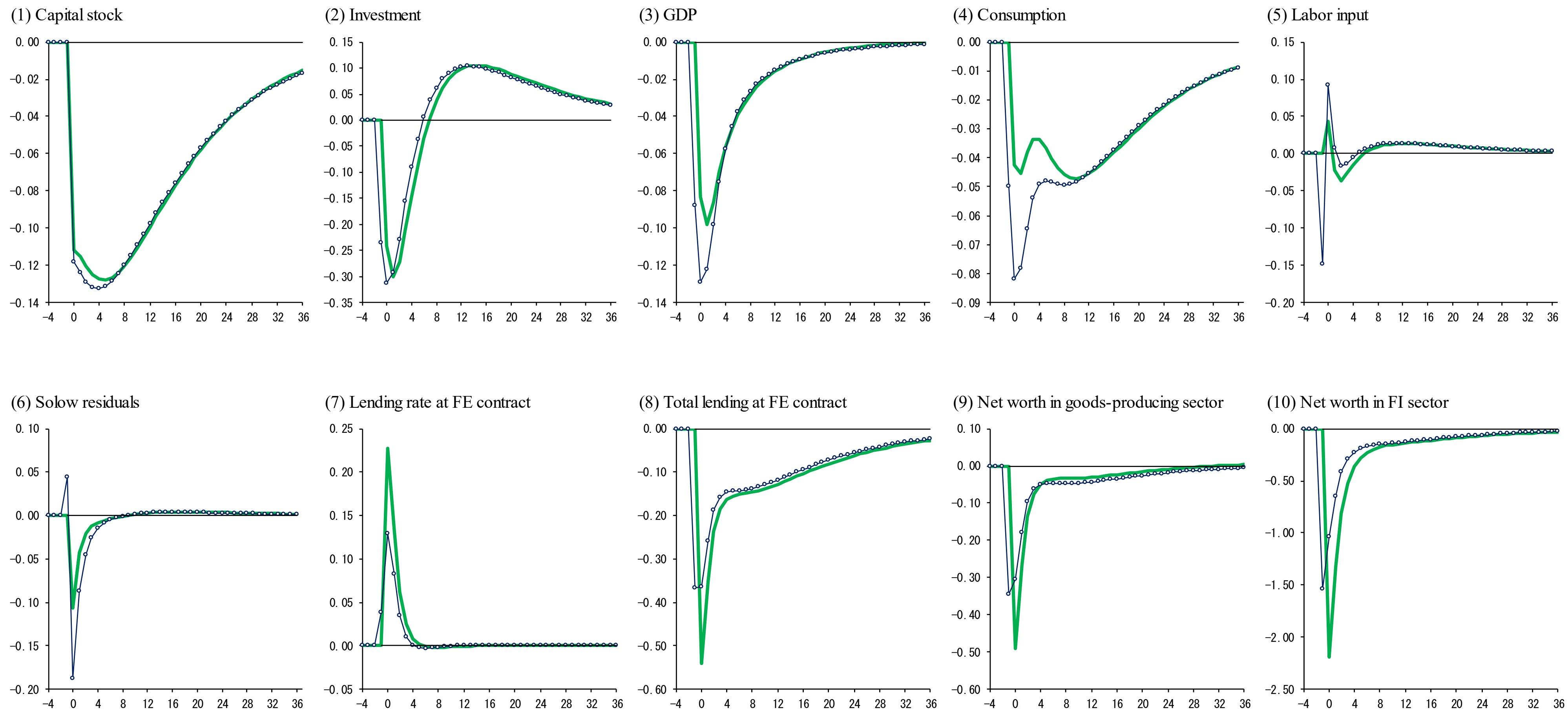
Figure 7: Economic Projections up to 2100



Note: 1. The horizontal and vertical axes denote years up to 2100 and percentage deviation from the non-stochastic steady-states.

2. The solid line and the shaded areas represent the median estimate and the 10th-90th percentile ranges of the impulse response in Scenario 1: Current Policies, respectively, while the thin dotted lines show those in Scenario 2: Net Zero 2050.

Figure 8: Impulse Response Functions: News Shocks



Note: 1. The series shown in (7) is the deviation from the non-stochastic steady-state, on an annual basis. Others are the percentage deviation from the non-stochastic steady-state.

2. The horizontal axis denotes quarters after the shock.

3. The solid line and the dotted line represent the impulse responses for the unanticipated and the anticipated (news) shocks, respectively.