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Do Market Segmentation and Preferred Habitat Theories Hold in Japan? : Quantifying Stock and Flow Effects of Bond Purchases[*]

Nao Sudo[†] and Masaki Tanaka[‡]

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Abstract

While major central banks confronting the global financial crisis conducted government bond purchases on an unprecedented scale, macroeconomists began re-examining carefully the once-accepted wisdom that long-term government bond purchases by the central bank reduce long-term yields. This paper follows this shift in economic thought and examines if the wisdom holds in Japan by estimating a dynamic stochastic general equilibrium model that features imperfect substitutability of bonds with different maturities, due to market segmentation and preferred habitats, using Japan's data from the 1980s to 2017. We focus specifically on the transmission mechanism, to determine which matters most: the size of the bond purchases at each period (flow effects), or the total amount of bonds taken away from the private sectors (stock effects). We find that, (i) Japan's data accords well with market segmentation and preferred habitat theories, which implies that government bond purchases conducted by the Bank of Japan have compressed the term premium, exerting an expansionary effect on economic activity and prices; (ii) the effect of bond purchases has been most pronounced since Quantitative and Qualitative Monetary Easing was introduced, compressing the term premium about 50 to 100 basis points as of the end of 2017; and (iii) the compression of the term premium has been mainly driven by stock effects, which underscores the importance of the amount outstanding of the Bank's government bond holdings in determining the term premium.

JEL Classification: C54; E43; E44; E52

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1 Introduction

Over the course of history, it has been difficult to answer the question whether or not purchases of long-term government bonds by the central bank compress long-term yields. This is partly because the consensus among macroeconomists has changed over time. Up to the early 1960s, there seemed to be a consensus that the purchase of long-term government bonds does lower long-term yields. For example, in his open letter to President Roosevelt in 1933, Keynes wrote, "I see no reason why you should not reduce the rate of interest on your long-term Government Bonds to 2.5 per cent or less with favorable repercussions on the whole bond market, if only the Federal Reserve System would replace its present holdings of short-dated Treasury issues by purchasing long-dated issues in exchange." His view accords well with the ideas later provided by Tobin (1961, 1969) and Modigliani and Sutch (1966), who argued that government bonds with different maturities are imperfect substitutes for each other and are held for various reasons, and that bond prices therefore change in response to changes in the demand and supply conditions as well as changes in expected returns. These ideas had drifted into decline after the controversy over the effectiveness of Operation Twist – the attempt by the Federal Reserve to compress long-term interest rates by selling short-term bonds and buying long-term bonds in the 1960s,[1] and had been overshadowed by the alternative argument that short-term and long-term bonds are perfect substitutes, and that long-term interest rates are independent of demand and supply conditions, including the purchase of long-term government bonds by central banks.[2] Views along these lines of thought had been commonly accepted until the outbreak of the global financial crisis (GFC). For example, in the standard dynamic stochastic general equilibrium (DSGE) model, such as the one used in Eggertsson and Woodford (2003),

[1]Modigliani and Sutch (1966) express a pessimistic view about the effectiveness of Operation Twist, stating "there is no evidence that the maturity structure of the federal debt, or changes in this structure, exert a significant, lasting or transient, influence on the relation between the two rates." The effectiveness of this policy was later studied by Swanson (2011). In contrast to what Modigliani and Sutch (1966) concluded, Swanson (2011) argued, based on an analysis of daily data, that announcements about the purchase of long-term bonds had significantly compressed long-term rates, though the effects were quantitatively limited.

[2]The pioneering paper by Wallace (1981) shows theoretically that under some premises including that the asset market is complete, the composition of the government sector balance sheet is neutral to macroeconomic variables. See Borio and Zabai (2016) for a related discussion.

quantitative easing does not affect long-term yields unless it affects the expected future short-term rates.

The GFC was the turning point at which this powerful idea started to receive another careful examination by macroeconomists. This is because major central banks have conducted the purchase of long-term government bonds on a large scale, as a part of unconventional monetary policy implementations, aiming to compress interest rates with long maturities, by adjusting the size and composition of their balance sheets. Macroeconomists have once more turned their attention in this direction, because long-term interest rates have indeed declined while these programs progressed.[3] Through the Large Scale Asset Purchase (LSAP) programs in the U.S., the Public Sector Purchase Programme in the euro area, and the Asset Purchase Facilities in the U.K., long-term government bonds worth 2.35 trillion dollars, 1.99 trillion euros, and 435 billion pounds have been taken away from the private sector, expanding the central banks' assets and reserves.[4] A good number of empirical studies regarding the effects of these programs have already accumulated so far, and as surveyed by Borio and Zabai (2016), the view that long-term government bond purchases influence long-term yields has gained increasing acceptance.

The Bank of Japan was the first among the major central banks to adopt unconventional monetary policy measures. In 2001, the Bank launched Quantitative Easing (QE), which targeted bank reserves to counter the recession following the collapse of IT bubble in the U.S., and continued this policy until 2006. In the aftermath of the GFC, in order to overcome prolonged deflation, the Bank started Comprehensive Monetary Easing (CME) in October 2010 and Quantitative and Qualitative Monetary Easing (QQE) in April 2013,[5] expanding its balance sheet, trying to push down longer-term interest rates. Developments in the Bank's balance sheet and long-term interest rates are shown in Figure 1. Under QQE, in particular, the Bank has purchased an unprecedented amount of long-term bonds,

[3] See, for instance, the work by Joyce et al. (2012).

[4] The amount of bonds purchased reported here is as of the end of October 2014 for the LSAP programs, and as of the end of May 2018 for the other two programs.

[5] In this paper, QQE includes both QQE with a Negative Interest Rate and QQE with Yield Curve Control.

boosting the share of the Bank's holdings in the total amount of Japanese Government Bonds (JGBs) from 11.5% at the end of 2012, to 43.2% at the end of 2017. Meanwhile, long-term yields have declined by about 70 bps over the same period, suggesting that QQE may have affected long-term yields. In fact, as summarized in Table 1, a good number of empirical studies on the effects of JGB purchases by the Bank on long-term JGB yields conclude that, by and large, QQE has indeed reduced long-term interest rates.[6]

Admittedly, however, the transmission mechanisms of the government bond purchases have yet to be fully uncovered; as aptly summarized in the words of former Chair of the Federal Reserve, Ben Bernanke, "the problem with QE is it works in practice but it doesn't work in theory" (Bernanke, 2014). In particular, the key question of the relative importance of stock effects versus flow effects remains unsolved. While the policy implications of the two effects are starkly different, there is little understanding and even less consensus on the quantitative importance of stock effects – to what extent the total amount outstanding of government bonds taken away from the private sector affects yields, compared to that of flow effects – the impact of the total amount of government bond purchases. On the one hand, theories that highlight the role of imperfect substitutability across assets argue that it is the level of the amount of bonds available to the private sector that affects the term premium, and that the growth rate of the bonds does not have independent implications. On the other hand, existing empirical studies, such as D'Amico and King (2013), often identify flow effects separately from stock effects. The Bank for International Settlements (2017) states that "The prevailing view among economists is that stocks matter most for asset prices, ..., At the same time, it is also possible that flows matter," suggesting the possibility that flow effects are operating as well.[7]

[6]In contrast to current empirical studies that examine specifically QQE, earlier empirical studies on the effectiveness of QE in Japan often conclude that the causality from bond purchases to yields was weak if not absent. In our analysis, for the purpose of obtaining robust estimates, we choose a sample period that covers not only the period when QQE was in place, but also when QE was in place. See, for example, Oda and Ueda (2007) and Ugai (2006) for empirical studies of QE in Japan.

[7]One other transmission channel considered important in existing empirical studies is the signaling channel, a transmission channel through whitch government bond purchases induce a change in the expectations of market participants about future short-term interest rates. Based on dynamic term structure models, Christensen and Rudebusch (2012) show that a decline in interest rates following bond purchases in the U.S. is mainly attributed to the signaling effect, a decline in expected short-term interest rates. By constrast, D'Amico and King (2013) and Gagnon et al. (2011) show that a decline in the long-term interest in the

In this paper, we quantitatively assess how the purchase of long-term government bonds by the Bank has been translated to long-term interest rates, economic activity, and prices, focusing specifically on the relative significance of stock effects and flow effects. To do this, we construct a DSGE model and estimate the model using Japan's data from the 1980s to 2017. Because our model consists of households and firms that are both forward looking, and markets of short-term and long-term government bonds as well as goods markets, it can serve not only to isolate stock and flow effects or effects arising from actual bond purchases and those arising from commitments on future bond purchases, but also to study the interdependence of bond and goods markets. To the best of our knowledge, there is only a limited number of studies that employ an estimated DSGE model to explore the effects of government bond purchases by the central bank on the term premium, economic activity, and prices, except for studies of the U.S. economy by Andrés, López-Salido, and Nelson (2004) (ALSN) and Chen, Cúrdia, and Ferrero (2012) (CCF). Our paper is the first attempt to explore Japan's economy along these lines.[8]

Our DSGE model is built upon the models of ALSN (2004) and CCF (2012). The model differs from the standard model, such as Smets and Wouters (2007), in that it explicitly incorporates ideas that reflect two influential thoughts about imperfect substitutability across assets. The first idea is the bond market segmentation hypothesis.[9] In the model, this idea emerges as costs arise when participants arbitrage between short-term and long-term bond markets, leaving the premium not being arbitraged away. The second idea is the concept of bond market participants' "preferred habitats".[10] In the model, households

U.S. was driven by compressed term premiums. For Japan, Fukunaga, Kato, and Koeda (2015) estimate the term structure model and show that term premiums were indeed influenced by a change in the quantity of the government bond circulating in the market.

[8] There are some works that study the effects of government bond purchases on the term premium and economic activities, using a calibrated DSGE model. These include Alpanda and Kabaca (2015), Burlon et al. (2016), Harrison (2012, 2017), and Kolasa and Wesołowskiz (2017). Katagiri and Takahashi (2017) estimate a small open DSGE model that is built upon CCF (2012) using the data of Japan and U.S., forcusing on how the exogenous changes in term premium is translated to the economy.

[9] The market segmentation hypothesis is a theory that is given in Modigliani and Sutch (1966) as a potential explaination of the actual yield curve structure. Based on the theory, participants in short and long bond markets stick to their respective markets and do not take arbitrage across the two. In other words, short-term and long-term interest rates are determined independently, and shocks to each of the bond markets are translated to the corresponding participants disproportionately.

[10] Preferred habitat theory was advocated by Modigliani and Sutch (1966) as a theory to explain the

gain utility from holding long-term bonds, allowing the size and composition of households' assets to affect the term premium. In theory, if preferred habitats exist, the central bank's purchase of long-term government bonds influences long-term interest rates, and if bond market segmentation exists, a change in long-term interest rates affects economic activity and prices on top of the effects due to changes in short-term interest rates. It is important to note that our strategy is not to assume a priori the presence of preferred habitats and bond market segmentation in Japan. Instead, by examining the data from the 1980s to 2017 for evidence of the significance of model parameters that are tied to these theories, we test their relevance and the degree of imperfect substitutability of bonds in Japan.

The findings of the current paper are summarized by the following three points. First, both market segmentation and the preferred habitat theory accord well with Japan's data. This is consistent with the empirical study by Fukunaga, Kato, and Koeda (2015) that examines the net supply effects of bonds on the term structure of interest rates in Japan.[11] Using disaggregated data of JGB holdings by financial sectors, such as banks, insurance companies, and pension funds, and by maturities of bonds, they document that the maturity structure of JGB holdings have been persistently different across financial sectors over time, and show that net supply effects are present. As described above, in our model, the existence of preferred habitats suggests that JGB purchases by the Bank have reduced long-term yields by compressing the term premium, and the existence of bond market segmentation suggests that reduced long-term yields have had an added accommodative effect on economic activity and prices. Second, as of the end of 2017, JGB purchases by

yield curve structure. According to this theory, the long-term interest rate is expressed as the sum of the component that reflects expectations about future short-term interest rates and the term premium component that is susceptible to supply-demand effects because of imperfect substitutability across bonds due to the heterogeneous preferences of bond market participants.

[11] Figure 2 shows the government bond holding by remaining maturities for "banks and others" and "pension funds and insurance companies," and the proportion of privately-held government bonds held by "banks and others," that are borrowed from Fukunaga, Kato, and Koeda (2015), and the proportion of deposit over total financial assets owned by the household sector that is constructed from *Flow of Funds Accounts*. As shown in the upper panels, "banks and others" tends to hold bonds with shorter maturities while "pension and insurance companies" tends to hold bonds with longer maturities, and such a pattern has been persistently observed throughout the period. The lower panel aims to capture proportion of assets whose returns are closely related to short-term interest rates. The proportion of the government bonds held by "banks and others" has been on average 50% and the proportion of the deposit has been on average 60%, and both series have been stable over time.

the Bank have reduced long-term bond yields by 50 to 100 bps. When measured by the metric of effects of JGB purchases worth 10% of GDP, the quantitative impact of the JGB purchases based on our model is 14 bps and this estimate falls within the range of existing estimates, from 3 to 35 bps. Third, stock effects have accounted for more than 90% of the reduction in long-term interest rates due to bond purchases during the sample period, and the contribution of flow effects has been minor. This finding is robust to alternative specifications of flow effects in the model.

Our study is built upon both theoretical and empirical studies about the implications of imperfect substitutability for bonds to bond yields, economic activity, and prices, in particular those studies that focus on the segmented market or preferred habitat theory. Theoretical studies include Tobin (1961, 1969), Modigliani and Sutch (1966), ALSN (2004), and Vayanos and Vila (2009). Empirical studies have accumulated rapidly since the GFC, and they include Gagnon et al. (2011), Krishnamurthy and Vissing-Jorgensen (2011), D'Amico and King (2013), Li and Wei (2013), CCF (2012) for the U.S., De Santis and Holm-Hadulla (2017) for the euro area, Joyce and Tong (2012) for the U.K., and Fukunaga, Kato, and Koeda (2015) for Japan. The focus of our analysis brings our paper close to D'Amico and King (2013) and Pelizzon et al. (2018), which estimate stock and flow effects using high frequency data. The key difference is that our paper estimates parameters of both bond and goods market simultaneously so as to explicitly address the interaction between the two markets. Methodologically, our paper is close to CCF (2012). In contrast to their work, our model addresses not only stock effects but flow effects that are not considered in CCF (2012). In addition, when estimating the model, we exploit expected future short-term interest rates for the purpose of separately identifying fluctuations in the term premium and those in the expected future interest rates, following Del Negro et al. (2017).

The remainder of this paper is organized as follows. Section 2 provides an overview of our model. Section 3 describes our estimation strategy and reports the estimation results. Section 4 is devoted to the robustness check regarding the quantitative importance of flow effects. Section 5 concludes.

2 Model Overview

Our model is built up on ALSN (2004) and CCF (2012). The economy consists of the household sector, the firm sector, and the government sector. The firm sector is standard, while the household and government sectors differ notably from standard New Keynesian models such as Smets and Wouters (2007), particularly in regard to the role of the central bank in the model. More precisely, we introduce the following five elements to an otherwise standard New Keynesian model.

1. The government bond market consists of short-term and long-term bond markets. The long-term bond yield is given as the sum of the term premium and the expected future short-term interest rate. Even at the steady state, the term premium takes a positive value.[12]

2. The household sector consists of two types of households, unrestricted households and restricted households. Unrestricted households can trade both of the two bonds while restricted households can trade only long-term bonds. The former type has to pay transaction costs whenever they trade long-term bonds, while the latter type does not need to pay such costs. The proportion of the two types of household in the economy are denoted as $\omega \in (0, 1)$ and $1 - \omega \in (0, 1)$, respectively.

3. The size of the term premium is determined by the size of the transaction cost that unrestricted households pay when they trade long-term bonds. The size of the cost varies with the stock and flow of households' assets.

4. The central bank conducts government bond purchases as well as nominal interest rate adjustments following the Taylor rule.

5. Some of the shocks to the short-term nominal interest rate adjustments are predicted in advance, in a way similar to the specification of Laseen and Svensson (2011) and

[12] In contrast to CCF (2012), which assumes the steady state term premium is zero, we assume that the steady state term premium is positive, given the fact that the spread between long-term and short-term yields is on average positive during the sample period, and some portions are considered as the term premium in Japan.

Del Negro et al. (2017).

The first three elements reflect the market segmentation and the preferred habitat hypothesis. The fifth element aims to capture the effect of commitments by the central bank to keep future short-term nominal interest rates low. As we discuss below, this is primarily because the sample period of the estimation covers the period when the Bank implemented such a commitment, and in assessing the quantitative impact of bond purchases it is important to quantitatively decompose variations in long-term yields into those associated with commitments and those associated with changes in the term premium. Our model differs from CCF (2012) in terms of the third element, since the transaction cost in our model is affected by not only stocks but also flows of households' assets. Our model also differs in terms of fifth element, since predicted shocks to the short-term interest rate are absent in their model.

In the section below, we describe the model settings regarding the five points above. The full model structures are provided in Appendix A.

2.1 Households

The economy consists of unrestricted households and restricted households, each of which is indexed by h^u and $h^r \in [0,1]$. Denoting a variable X_t associated with the unrestricted (restricted) households as X_t^u (X_t^r), each household in the two types of household supplies labor inputs $N_t^j\left(h^j\right)$, earns labor income $W_t\left(h^j\right)N_t^j\left(h^j\right)$, consumes $C_t^j\left(h^j\right)$, and pays tax $T_t^j\left(h^j\right)$ to the government, for $j \in \{u,r\}$. Following ALSN (2004), we assume that unrestricted households save in the form of deposits $M_t^u\left(h^u\right)$, short-term bonds $B_t\left(h^u\right)$, and long-term bonds $B_t^{L,u}\left(h^u\right)$, and restricted households save in the form of deposits $M_t^r\left(h^r\right)$ and long-term bonds $B_t^{L,r}\left(h^r\right)$. Note also that unrestricted households pay transaction costs $\zeta_t\left(h^u\right)$ when purchasing the long-term bonds. The household sector owns all of the firms existing in the economy, and dividends of firms div_t are distributed equally to all households.

The optimization problem of unrestricted households

Unrestricted households receive utility from consumption $C^u_{t+s}(h^u)$ and deposits $M^u_{t+s}(h^u)/P_{t+s}$, and receive disutility from labor inputs $N^u_{t+s}(h^u)$. They maximize the life-time utility defined below.

$$\mathrm{E}_t \sum_{s=0}^{\infty} \beta^s \left\{ a^u_{t+s} \left[\begin{array}{c} U_{t+s}(h^u) + \phi_m V_{t+s}(h^u) \\ -\frac{\left(N^u_{t+s}(h^u)\right)^{1+\nu_n}}{1+\nu_n} \end{array} \right] - H_{t+s}(h^u) \right\}. \tag{1}$$

Here, E_t is the expectation operator, a^u_t is a time-variant component of the discount factor of the unrestricted households, ϕ_m is the utility weight attached to deposit holding, and ν_n is the inverse elasticity of labor supply. Utilities from consumption, deposits holding, and adjustments in deposits, $U_t(h^u)$, $V_t(h^u)$, and $H_t(h^u)$ are given by the following equations.

$$U_t(h^u) \equiv \frac{1}{1-\sigma_u} \left(\frac{C^u_t(h^u)}{Z_t} - h\frac{C^u_{t-1}(h^u)}{Z_t} \right)^{1-\sigma_u},$$

$$V_t(h^u) \equiv \frac{1}{1-\nu_m} \left(\frac{M^u_t(h^u)}{P_t Z_t} \right)^{1-\nu_m},$$

$$H_t(h^u) \equiv \frac{d}{2} \left\{ \begin{array}{c} \exp\left[c\left\{ \frac{M^u_t(h^u)/(P_t Z_t)}{M^u_{t-1}(h^u)/(P_{t-1}Z_{t-1})} - 1 \right\} \right] \\ + \exp\left[-c\left\{ \frac{M^u_t(h^u)/(P_t Z_t)}{M^u_{t-1}(h^u)/(P_{t-1}Z_{t-1})} - 1 \right\} \right] - 2 \end{array} \right\}.$$

Here, P_t is the aggregate consumption price index, Z_t is the level of the aggregate technology, and σ_u, h, ν_m, c, d are parameters. Their flow budget constraint is

$$\begin{aligned} & P_t C^u_t(h^u) + M^u_t(h^u) + \frac{B_t(h^u)}{1+i_t} + \left(1+\overline{\zeta}\right)(1+\zeta_t) P^L_t B^{L,u}_t(h^u) \\ & \leq \left(1+i^d_t\right) M^u_{t-1}(h^u) + B_{t-1}(h^u) + \left(1+i^L_t\right) P^L_t B^{L,u}_{t-1}(h^u) + W_t(h^u) N^u_t(h^u) - T^u_t(h^u) + div_t, \end{aligned}$$

where i_t is the nominal short-term interest rate, P^L_t is the price of the long-term bond, i^d_t is the nominal interest rate applied to the deposits, and i^L_t is the nominal long-term interest rate.

The optimization problem of restricted households

Similarly, the life-time utility of restricted households is defined as follows.

$$\mathrm{E}_t \sum_{s=0}^{\infty} \beta^s \left\{ a_{t+s}^r \left[\begin{array}{c} U_{t+s}\left(h^r\right) + \phi_m V_{t+s}\left(h^r\right) \\ -\frac{\left(N_{t+s}^r\left(h^r\right)\right)^{1+\nu_n}}{1+\nu_n} \end{array} \right] - H_{t+s}\left(h^r\right) \right\}. \tag{2}$$

Here, a_t^r is a time-variant component of the discount factor of the restricted households. The functional form of each of the three functions, $U\left(\cdot\right)$, $V\left(\cdot\right)$, and $H\left(\cdot\right)$, is assumed to be the same as that of the unrestricted households. Their flow budget constraint is

$$\begin{aligned} & P_t C_t^r\left(h^r\right) + M_t^r\left(h^r\right) + \left(1+\overline{\zeta}\right) P_t^L B_t^{L,r}\left(h^r\right) \\ & \leq \left(1+i_t^d\right) M_{t-1}^r\left(h^r\right) + \left(1+i_t^L\right) P_t^L B_{t-1}^{L,r}\left(h^r\right) + W_t\left(h^r\right) N_t^r\left(h^r\right) - T_t^r\left(h^r\right) + div_t. \end{aligned}$$

Labor supply

Each household h^u and h^r supplies differentiated labor inputs, $N_t^u\left(h^u\right)$ and $N_t^r\left(h^r\right)$, to firms, and determines its nominal wages, $W_t^*\left(h^u\right)$ and $W_t^*\left(h^r\right)$, taking into consideration the demand function towards its labor inputs. Because households are subject to the Calvo type of nominal wage rigidity, only a portion $1-\zeta_w \in (0,1)$ of households is able to determine the nominal wages $W_t^*\left(h^u\right)$ and $W_t^*\left(h^r\right)$. Their maximization problem is given as follows.

$$\max_{W_t^*\left(h^j\right)} \mathrm{E}_t \sum_{s=0}^{\infty} \left(\beta\zeta_w\right)^s \left[MUC_{t+s}^j\left(h^j\right)\ W_t^*\left(h^j\right)\ N_{t+s}^j\left(h^j\right) - a_{t+s}^j \frac{\left(N_{t+s}^j\left(h^j\right)\right)^{1+\nu_n}}{1+\nu_n} \right], \tag{3}$$

$$\text{s.t.}\quad N_{t+s}^j\left(h^j\right) = \left(\frac{W_t^*\left(h^j\right)}{W_{t+s}}\right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} N_{t+s}. \tag{4}$$

Here, $MUC_t^j\left(h^j\right)$ $(j=u,r)$ is the marginal utility of consumption defined below.

$$\begin{aligned} MUC_t^j\left(h^j\right) & \equiv \frac{\partial U_t\left(h^j\right)}{\partial C_t^j\left(h^j\right)} \\ & = \frac{a_t^j}{Z_t}\left(\frac{C_t^j\left(h^j\right)}{Z_t} - h\frac{C_{t-1}^j\left(h^j\right)}{Z_t}\right)^{-\sigma_j} - \beta h \mathrm{E}_t\left[\frac{a_{t+1}^j}{Z_{t+1}}\left(\frac{C_{t+1}^j\left(h^j\right)}{Z_{t+1}} - h\frac{C_t^j\left(h^j\right)}{Z_{t+1}}\right)^{-\sigma_j}\right]. \end{aligned} \tag{5}$$

The remaining households $\zeta_w \in (0,1)$ are unable to optimally set the nominal wage. Their wages mechanically increase with the steady state growth rate of the nominal wage, which is the product of the steady-state inflation rate and technological growth rate.

2.2 Government

The government sector consists of the central bank and the government.

Central bank

Monetary policy implementation in our model is standard, except that it includes anticipated nominal interest rate shocks, and it conducts government bond purchases as well as nominal interest rate adjustments. The central bank adjusts the policy rate i_t according to the following Taylor rule,

$$\frac{1+i_t}{1+i_{ss}} = \left(\frac{1+i_{t-1}}{1+i_{ss}}\right)^{\rho_r} \left[\left(\frac{\Pi_t}{\Pi_{ss}}\right)^{\rho_\Pi}\right]^{1-\rho_r} \exp(\epsilon_{r,t}). \tag{6}$$

Here, i_t is the nominal interest rate, Π_t ($\equiv P_t/P_{t-1}$) is the inflation rate, $\rho_r \in (0,1)$ is the interest rate smoothing parameter of the monetary policy rule, ρ_Π is the policy weight attached to the inflation rate Π_t,[13] i_{ss} is the steady state interest rate, and Π_{ss} is the steady state inflation rate. $\epsilon_{r,t}$ is a shock to the short-term interest rate rule, and it is decomposed into the unanticipated component and anticipated component as follows.

$$\epsilon_{r,t} = \varepsilon_{r,t} + \varepsilon_{r,1,t-1} + \varepsilon_{r,2,t-2} + ... + \varepsilon_{r,\overline{S},t-\overline{S}}.$$

The unanticipated component $\varepsilon_{r,t}$ is an i.i.d. shock. Anticipated policy shocks $\varepsilon_{r,s,t-s}$, $s = 1, 2, ..., \overline{S}$ are known to agents at period $t-s$ in advance, but each of these anticipated shocks materializes in the policy rule (6) with a lag of s quarters, namely at period t. This specification is borrowed from existing studies such as Laseen and Svensson (2011), Del Negro et al. (2017), and Okazaki and Sudo (2018).

[13] In what follows, we denote net inflation rate as $\pi_t \equiv \Pi_t - 1$.

The central bank also purchases long-term government bonds. We assume that bond purchases evolve according to the following law of motion.

$$\log\left(\frac{P_t^L B_t^{L,CB}}{P_t Z_t}\right) = \left(1-\rho_{QE}\right)\log\left(\frac{P_{ss}^L B_{ss}^{L,CB}}{P_{ss} Z_{ss}}\right) + \rho_{QE}\log\left(\frac{P_{t-1}^L B_{t-1}^{L,CB}}{P_{t-1} Z_{t-1}}\right) + \varepsilon_{QE,t} + v_{QE,t}. \tag{7}$$

$$v_{QE,t} = \rho_{u,QE} v_{QE,t-1} + u_{QE,t}.$$

Here, $B_t^{L,CB}$ is the central bank's holdings of long-term government bonds, $\rho_{QE} \in (0,1)$ and $\rho_{u,QE} \in (0,1)$ are the autoregressive parameters associated with bond purchases, $\varepsilon_{QE,t}$ is a short-lived shock to bond purchase, $u_{QE,t}$ is a long-lived shock to bond purchase, and $P_{ss}^L B_{ss}^{L,CB} / \left(P_{ss} Z_{ss}\right)$ is the central bank's holding of real long-term government bonds, detrended by the technology level, at the steady state. We incorporate the persistent shocks $u_{QE,t}$ in order to express the practical nature of long-term government bond purchases by the central bank, including predictability regarding the amount and the length of periods that purchases take place. That is, in the implementation, central banks have often announced in advance the size of the bonds they intend to purchase from the market, and schedules of purchases going forward, and they have purchased the intended amount of the bonds gradually over several quarters, instead of purchasing them at once in a specific quarter. By having persistent shocks $u_{QE,t}$, it is possible to describe in the model the practical features of bond purchases.[14]

We further assume that the central bank supplies deposits to households in exchange for long-term government bonds.[15]

$$P_t^L B_t^{L,CB} = M_t \equiv \omega M_t^u + (1-\omega) M_t^r. \tag{8}$$

[14]Note that once a positive persistent shock $u_{QE,t}$ takes place at period t, households understand that the central bank will continue purchasing bonds at period $t+1$ and beyond, which in turn implies that households' demand for the bonds is affected more than in the case of temporary shocks $\varepsilon_{QE,t}$.

[15]In the current paper, we assume symmetric equilibrium for households who belong to each of the two types of household. This assumption implies that consumption, deposit and so on of households h^u and h^r are equalized within the type. In what follows, therefore, we denote variables X of the two types as follows.

$$X_t^u \equiv X_t^u\left(h^u\right) \text{ and } X_t^r \equiv X_t^r\left(h^r\right).$$

Government

The government finances its expenditure by tax, issuance of both short-term and long-term government bonds, and transfers from the central bank. The budget constraint of the government is given by the following equation.

$$\frac{B_t}{1+i_t} + P_t^L B_t^L + T_t + \xi_t \geq G_t + B_{t-1} + \left(1 + i_t^L\right) P_t^L B_{t-1}^L, \tag{9}$$

where tax T_t is defined as,

$$T_t \equiv \omega T_t^u + (1-\omega) T_t^r,$$

and where transfers from the central bank ξ_t are defined as below.

$$\xi_t \equiv M_t - \left(1 + i_{t-1}^d\right) M_{t-1} - P_t^{L,CB} B_t^{L,CB} + \left(1 + i_t^L\right) P_t^{L,CB} B_{t-1}^{L,CB}.$$

Note that G_t is government expenditure, B_t is short-term government bonds outstanding, and B_t^L is long-term government bonds outstanding.

Government expenditure G_t and issuance of long-term bonds B_t^L evolve according to the following laws of motions.

$$\log\left(\frac{G_t}{P_t Z_t}\right) = \left(1-\rho_g\right)\log\left(\frac{G_{ss}}{P_{ss} Z_{ss}}\right) + \rho_g \log\left(\frac{G_{t-1}}{P_{t-1} Z_{t-1}}\right) + \varepsilon_{g,t}, \tag{10}$$

$$\log\left(\frac{P_t^L B_t^L}{P_t Z_t}\right) = \left(1-\rho_{b^L}\right)\log\left(\frac{P^L B^L}{P_{ss} Z_{ss}}\right) + \rho_{b^L} \log\left(\frac{P_{t-1}^L B_{t-1}^L}{P_{t-1} Z_{t-1}}\right) + \varepsilon_{b^L,t}, \tag{11}$$

where $\rho_g \in (0,1)$ and $\rho_{bL} \in (0,1)$ are the auto-regressive parameters, $\varepsilon_{g,t}$ and $\varepsilon_{b^L,t}$ is a shock to the government expenditure G_t and a shock to issuance of long-term bonds, and $G_{ss}/\left(P_{ss} Z_{ss}\right)$ and $P_{ss}^L B_{ss}^L/\left(P_{ss} Z_{ss}\right)$ are the real government expenditure and long-term bonds outstanding, detrended by the technology level, at the steady state.

2.3 Long-term Government Bonds

Term premium

A standard DSGE model assumes that long-term interest rates are determined by expected short-term interest rates alone. For example, a long-term interest rate with maturity of T quarters, which we denote as i_t^T, is given by the following equation.

$$\hat{\imath}_t^T = \frac{1}{T} \sum_{s=0}^{T-1} \mathrm{E}_t \hat{\imath}_{t+s}.$$

Here, $\hat{\imath}_t^T$ and $\hat{\imath}_t$ denote the deviation of each variable from its steady state value.

By contrast, in the current model and also in the model of ALSN (2004) and CCF (2012), the long-term interest rate i_t^L deviates from the average of expected short-term interest rates, since unrestricted households need to pay transaction costs ζ_t whenever they hold long-term bonds, and the premium is not arbitraged away. Denoting a long-term interest rate in a hypothetical economy where such transaction costs are absent by $i_t^{L,EH}$, the term premium TP_t is expressed as the difference between the actual long-term interest rate and this hypothetical long-term interest rates $i_t^{L,EH}$,[16]

$$TP_t \equiv \hat{\imath}_t^L - \hat{\imath}_t^{L,EH} = \frac{1}{D} \sum_{s=0}^{\infty} \left(\frac{D-1}{D} \right)^s \mathrm{E}_t \hat{\zeta}_{t+s}. \tag{12}$$

$\hat{\imath}_t^L$, $\hat{\imath}_t^{L,EH}$, and $\hat{\zeta}_t$ are the deviation of each variable from its steady state value, and D is the duration of the two long-term bonds at the steady state. This equation indicates that the term premium TP_t at the current period is the weighted sum of the expected size of transaction costs associated with long-term bond transactions from period t to the infinite future.

Transaction cost

Following ALSN (2004) and CCF (2012), we assume that transaction costs ζ_t vary with the size and composition of households' assets. ALSN (2004) consider that the costs represent households' concerns over the loss of liquidity that comes together with the holding of long-term bonds, and assume that transaction costs are small when households hold more liquid assets, which is money in their framework, relative to long-term bonds.

[16] See CCF (2012) for the derivation of the equation below.

Similarly, CCF (2012) assumes that transaction costs are small when their long-term bond holdings are small. In some sense, our model generalizes the settings chosen by the two existing works and assumes that concerns over the loss of liquidity are heterogeneous across the two types of household and that not only the stock of households' assets but changes in their stocks matter to transaction costs ζ_t.[17] The size of the transactions is given by the following equation.

$$1+\zeta_t \equiv \left[\left(\frac{P_t^L B_t^{L,P} / (P_t Z_t)}{P_{ss}^L B_{ss}^{L,P} / (P_{ss} Z_{ss})} \right)^{\tau_1} \left(\frac{M_t^u / (P_t Z_t)}{M_{ss}^u / (P_{ss} Z_{ss})} \right)^{-\tau_2} \left(\frac{M_t^r / (P_t Z_t)}{M_{ss}^r / (P_{ss} Z_{ss})} \right)^{-\tau_3} \right]$$
$$\left[\left(\frac{P_t^L B_t^{L,P} / (P_t Z_t)}{P_{t-1}^L B_{t-1}^{L,P} / (P_{t-1} Z_{t-1})} \right)^{\tau_4} \left(\frac{M_t^u / (P_t Z_t)}{M_{t-1}^u / (P_{t-1} Z_{t-1})} \right)^{-\tau_5} \left(\frac{M_t^r / (P_t Z_t)}{M_{t-1}^r / (P_{t-1} Z_{t-1})} \right)^{-\tau_6} \right] \exp\left(\zeta_t^{ex}\right), \tag{13}$$

where $\tau_i > 0$ for $i \in \{1, 2, \cdots, 6\}$ is the elasticity of transaction costs with respect to each of the variables regarding households' asset holdings. $P_{ss}^L B_{ss}^{L,P} / (P_{ss} Z_{ss})$, $M_{ss}^u / (P_{ss} Z_{ss})$, and $M_{ss}^r / (P_{ss} Z_{ss})$ are, respectively, real long-term bond holdings by the private sector, real deposit holdings of unrestricted households, and real deposit holdings of restricted households, detrended by the technology level, at the steady state. The variable ζ_t^{ex} captures exogenous changes in transaction costs and evolves following the law of motion with an autoregressive parameter ρ_ζ as described below.

$$\zeta_t^{ex} = \rho_\zeta \zeta_{t-1}^{ex} + \varepsilon_{\zeta,t}. \tag{14}$$

In what follows, we refer to the effect on transaction costs of the terms of τ_1, τ_2, and τ_3 as "stock effects," and the effect of the terms of τ_4, τ_5, and τ_6 as "flow effects," respectively. This categorization is generally consistent with the definition provided by D'Amico and King (2013). In their paper, these effects are defined as "persistent changes in prices that result from movements along Treasury demand curves," and "the response of prices to the ongoing purchase operations." Furthermore, they state the latter could reflect, on top of

[17] The functional form of transaction costs is derived from households' optimization problem in ALSN (2004) while it is assumed in CCF (2012). We follow CCF (2012) and assume the functional form of the transaction costs as given.

portfolio rebalancing activity due to the outcome of the purchases, impairments in liquidity and functioning that lead to sluggish price discovery. They estimate the two effects, using U.S. data, as a mapping to the cumulative change in securities' prices during a specific period from the total amount of these securities that the Federal Reserve purchased during the same period, and as a mapping to a percentage change in securities prices on each day that purchase operations occurred and the amount of the securities purchased on those days. Being consistent with the definitions and estimation strategies of D'Amico and King (2013), other things being equal, in our model, stock effects persistently reduce the term premium TP_t, as long as the central bank maintains the purchased long-term bonds on its balance sheet, as equations (12) and (13) indicate. On the other hand, flow effects continue to surface only as long as the size of the stock expands or shrinks, and it dies out once the central bank starts maintaining a constant level of stock outstanding.

Market clearing condition of the long-term bonds

At every period, the long-term bonds market clears.

$$B_t^L = B_t^{L,CB} + B_t^{L,P} = B_t^{L,CB} + \left(\omega B_t^{L,u} + (1-\omega)\, B_t^{L,r}\right).$$

2.4 Transmission of Monetary Policy Shocks

The two types of household are affected in a different manner by each of three types of monetary policy shocks, unanticipated shocks to the short-term rate $\varepsilon_{r,t}$, anticipated shocks to the short-term rate $\varepsilon_{r,s,t}$, and shocks to the long-term government bond purchase $\varepsilon_{QE,t}$ and $u_{QE,t}$. The difference in the effect on the two types of household leads to a different macroeconomic consequences. To see this, we derive the Euler equations shown below for the restricted and unrestricted households. Note that, for the sake of simplicity, we assume that $\rho_r = 0$ and that there have been no anticipated shocks to the short-term rate at periods before $t-1$.

$$\begin{aligned}\widehat{MUC}_t^u &= \sum_{s=0}^{\infty} \mathrm{E}_t\left[\widehat{i}_{t+s}\right] - \sum_{s=1}^{\infty} \mathrm{E}_t\left[\widehat{\pi}_{t+s}\right] \\ &= \sum_{s=0}^{\infty} \mathrm{E}_t\left[\varepsilon_{t+s}\right] + \sum_{s=0}^{\infty}\sum_{k=1}^{\overline{S}} \mathrm{E}_t\left[\varepsilon_{r,k,t+s-k}\right] + \rho_{\Pi}\widehat{\pi}_t + (\rho_{\Pi}-1)\sum_{s=1}^{\infty} \mathrm{E}_t\left[\widehat{\pi}_{t+s}\right] \ , \end{aligned} \tag{15}$$

$$\begin{aligned}\widehat{MUC}_t^r &= \sum_{s=0}^{\infty} \mathrm{E}_t\left[\widehat{i}^L_{t+s}\right] - \sum_{s=1}^{\infty} \mathrm{E}_t\left[\widehat{\pi}_{t+s}\right] \\ &= \sum_{s=0}^{\infty}\left[\frac{1}{D}\sum_{j=0}^{\infty}\left(\frac{D-1}{D}\right)^j \mathrm{E}_t\widehat{i}_{t+s+j} + \mathrm{E}_t\widehat{TP}_{t+s}\right] - \sum_{s=1}^{\infty} \mathrm{E}_t\left[\widehat{\pi}_{t+s}\right] \\ &= \sum_{s=0}^{\infty}\frac{1}{D}\sum_{j=0}^{\infty}\left(\frac{D-1}{D}\right)^j \mathrm{E}_t\left[\varepsilon_{t+s}\right] + \sum_{s=0}^{\infty}\frac{1}{D}\sum_{j=0}^{\infty}\left(\frac{D-1}{D}\right)^j \sum_{k=1}^{\overline{S}} \mathrm{E}_t\left[\varepsilon_{r,k,t+s+j-k}\right] \\ &+ \sum_{s=0}^{\infty} \mathrm{E}_t\left[\widehat{TP}_{t+s}\right] + \sum_{s=0}^{\infty}\left[\frac{1}{D}\sum_{j=0}^{\infty}\left(\frac{D-1}{D}\right)^j \mathrm{E}_t\left(\rho_{\Pi}\widehat{\pi}_{t+s+j}\right)\right] - \sum_{s=1}^{\infty} \mathrm{E}_t\left[\widehat{\pi}_{t+s}\right] \ . \end{aligned} \tag{16}$$

Here, $\widehat{MUC}_t^u$, $\widehat{MUC}_t^r$, $\widehat{\pi}_t$, and $\widehat{TP}_t$ are the marginal utilities of households of the two types, the inflation rate, and the term premium, expressed in the deviation from the steady state value. The first and second terms in equations (15) and (16) represent the effect on the marginal utility of unanticipated shocks and anticipated shocks to the short-term nominal interest rate, and the third term in equation (16) represents the effect on the marginal utility of shocks to government bond purchase by the central bank. With the standard utility function in which marginal utility falls with consumption C_t^u and C_t^r, a positive shock to the right-hand side of the equations reduces the current level of consumption, exerting contractionary effects on the economy. As these equations indicate, shocks to the short-term rate affect both types of household in the similar manner.[18] By contrast, a shock to government bond purchase primarily affects the restricted households exclusively through the third term in equation (16). However, because any change in the spending of restricted households affects macroeconomic variables, these shocks also affect the un-

[18] Note that the same size of a shock to the right hand side of the equation can result in a quantitatively different outcome across households, since, as shown in the equation (5), the intertemporal elasticity of substitution σ_u^{-1} and σ_r^{-1} may be different across the types.

restricted households. This indirect transmission mechanism is seen in the term of the inflation rate $\widehat{\pi}_t$ in both of the equations.

Because the proportion of the two types of household in the economy is ω and $1-\omega$, aggregate consumption C_t is given by the following equation.

$$C_t = \omega C_t^u + (1-\omega)\, C_t^r. \tag{17}$$

This equation indicates that, other things being equal, a change in the term premium TP_t is more likely to be translated to the macroeconomy when ω takes a smaller value.

3 Estimation Strategy and Results

3.1 Estimation Strategy

We employ Bayesian methodology following the standard approach of estimating medium-scale DSGE models, as in Smets and Wouters (2007). We use the time series of 13 variables from 1986:3Q to 2017:4Q[19]: (1) the real GDP, (2) the consumer price index (less fresh food), (3) the real private consumption, (4) the real private non-residential investment, (5) the real wages per unit of labor, (6) the labor inputs, (7) the short-tern nominal interest rate, (8) the long-term nominal interest rate, (9) the real long-term JGB holdings by the Bank, and (10) to (13) the expected short-term nominal interest rates. Some observations are missing for series (9) to (13). The data series used for the estimation are shown in Figure 3.[20]

The data source of the series (1), (3), and (4) is the *System of National Accounts* (SNA) released by the Cabinet Office of Japan. Series (5) is constructed from the compensation of employees based on the SNA, divided by series (6), where series (6) is obtained from the

[19] To convert the nominal series into the quantity series, we employ the series (2). We also divide all of the quantity series by the population aged 15 to 64 years old as reported in the *Labour Force Survey*, to obtain the series on a per-capita basis. The series (2) is adjusted to remove the effects of the introduction of the consumption tax in 1989 and rises in the rate in 1997 and 2014.

[20] All of the series other than series (7), (8) and series (10) to (13) are displayed on a year-on-year basis in Figure 3. Note, however, that we use a quarter-on-quarter change rather than a year-on-year change of these variables in our estimation. We use the quartered values for series (7), (8) and series (10) to (13) in our estimation.

number of employees based on the *Labour Force Survey*, multiplied by hours-worked per employee based on the *Monthly Labour Survey*. Series (7) is the uncollateralized overnight call rate and series (8) is the 10-year government bond yield. Series (9) is constructed from the data released by the Bank.[21,22] Series (10) to (13) are constructed from the overnight index swap (OIS) rates. We use the spot rates of OIS with a maturity of 3 months, 6 months, 1 year, and 2 years, imputing the spot rates for periods that fall in the intervals by linearly interpolating the raw data, and we derive the expected short-term nominal interest rates, as the forward rates using these rates.

We use series (7) to (13) as the observable so as to identify and separately assess the effects of three monetary policy instruments: adjustments of the short-term interest rate, commitments to keep the short-term interest rates at the lower bound, and government bond purchases, because all three instruments were in place simultaneously during our sample period. Specifically, the Bank used the short-term interest rate as the primal policy instrument up to the late 1990s when it cut the rate to a level close to zero, and then started employing commitments on future short-term interest rates as an alternative policy instrument. Since the early 2000s, the Bank has also conducted QE, CME, and QQE, all of which involve the purchase of government bonds. Series (8) and (9), and series (10) to (13) are needed to isolate effects of bond purchases by the central bank on the term premium TP_t, since the term premium itself is not observable and needs to be estimated using the information contained, among other things, in the long-term interest rate, (series (8)), and the expected short-term nominal interest rate, (series (10) to (13)).

When estimating, we first detrend model variables by dividing them by the stochastic trend. We detrend the real variables with the level of technology Z_t, and the nominal variables with the consumer price index P_t and the level of technology Z_t. We then conduct a Bayesian estimation following existing studies such as Smets and Wouters (2007). We first 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

[21] We do not include floating rate bonds and inflation-indexed bonds in our definition of long-term bonds.

[22] ALSN (2004) and CCF (2012) use the domestic monetary base series and the ratio between long-term and short-term U.S. Treasury debt, respectively, as the observable that represents the quantity of assets.

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. To calculate the posterior distribution and to evaluate the marginal likelihood of the model, we employ the Metropolis-Hastings algorithm. In this process, we create a sample of 200,000 draws, disregarding the initial 100,000 draws.

3.2 Calibration and Priors

Calibrated parameters

Some parameter values are calibrated. These include the capital share α, the discount factor β, the depreciation rate of capital stock δ, the duration of long-term government bonds D, the steady state share of government expenditure g_{ss}, the steady state value of the central bank's holdings of long-term government bonds $P^L_{ss}B^{L,CB}_{ss}$, and the steady state value of the central bank's holdings of long-term government bonds relative to the private sector's holdings of long-term government bonds $B^{L,CB}_{ss}/B^{L,P}_{ss}$. Values for α, β, and δ are constructed with reference to existing studies, including CCF (2012), Okazaki and Sudo (2018), and Fueki et al. (2016). The steady state value of the external demand relative to GDP g_{ss} is calibrated to the average of government expenditure over GDP during the sample period. Duration D is set to 10 years (40 quarters). The last two values are set using the historical average of the periods before the introduction of QQE. See Table 2 for the values of these parameters.

Prior distributions

We estimate the remaining parameters. See Table 3 for the values of these parameters. The type, mean, and standard deviation of the prior distribution are mostly taken from existing studies such as CCF (2012), Smets and Wouters (2007), Fueki et al. (2016), Sugo and Ueda (2008), and Justiniano, Primiceri and Tambalotti (2010), and reported in the first three columns of Table 3. The proportion of unrestricted households ω has prior mean 0.5, so that it is roughly consistent with the figure reported by Fukunaga, Kato, and Koeda (2015) that is shown in Figure 2, and has standard deviation 0.2. Parameters associated with preferred habitats $\tau_i,\ i = 1, 2, ..., 6,$ have prior means and standard deviation, so that they are generally consistent with the estimates of existing studies shown in Table 1. Parameters associated with households' utility over deposits, ν_m and δ_m, have prior means 1.82 and 4.36 that are taken from the estimated values of the corresponding parameters in ALSN (2004), and have standard deviation 1.0. Priors of the steady state value for technology growth γ, inflation rate π, and the term premium are taken from the sample period average of the growth rate of real GDP on a per capita basis, that of the consumer price index (less fresh food), and that of the difference between the 10-year government bond yield and the call rate.

3.3 Estimation Results

Posterior distribution

The last three columns of the table show the posterior mean and the credible intervals for the estimated parameters. The posterior mean for the proportion of unrestricted households ω is 0.49, with a 90% interval (0.25, 0.72), which is consistent with the finding by Fukunaga, Kato, and Koeda (2015) that about a half of the long-term government bond outstanding is held by "Banks and others." The estimation result indicates that the market segmentation hypothesis holds in Japanese bond markets, which in turn implies that fluctuations in the term premium TP_t are translated to economic activity and prices independently of fluctuations in the short-term interest rate i_t, as shown in equations (16) and (17). Our estimate for ω falls between the estimates based on the U.S. data. Specifically, CCF (2012) estimates a similar model to ours using the same Bayesian methods, and reports a value for ω that is higher and with a wider interval, namely (0.82, 0.99), while the corresponding value for ω in ALSN (2004), which is estimated using the maximum likelihood method, is 0.29.

The 90% intervals for the parameters associated with preferred habitats $\tau_i, i = 1, 2, ..., 6,$ are positive. This result means that a change in the amount of long-term bonds and deposits held by the households affects the term-premium TP_t. The degree of preferred habitat is roughly the same across the two types of the household. Likewise, there is no difference across both stock effect and flow effect. Note that there is a marked difference in the intertemporal elasticities of substitution of the unrestricted σ_u and the restricted σ_r, for which the 90% intervals are (1.82, 3.43) and (0.76, 1.64) respectively.

The 90% interval of the estimate of the autoregressive parameter for the central bank's long-term government bond purchases ρ_{QE} and that for the persistent long-term government bond purchase shocks $\rho_{u,QE}$ are (0.85, 1.00) and (0.89, 0.98), respectively.[23] Because the estimated parameter values are close to unity, once a shock strikes the government bond purchase rule, bond market participants expect the purchases to continue in the subsequent periods, which in turn has a quantitatively larger impact on the term premium than would otherwise be the case.

Impulse response functions

How does the central bank's purchase of government bonds affect the long-term interest rate i_t^L and macroeconomic variables? Figure 4 shows the impulse response function of the term premium TP_t and other key macroeconomic variables to a positive temporary shock $\varepsilon_{QE,t=0} > 0$ to the rule of the central bank's bond purchases (7) in period 0. The size of the shock is 10% of GDP at the impact period. The central bank's long-term bond holdings $P_t^L B_t^{L,CB}$ are highest at period 0, and gradually revert back to the steady state level at a pace governed by the autoregressive parameter ρ_{QE}. Regarding how the central bank adjusts its policy rate i_t to the shock, we follow CCF (2012) and consider two scenarios. In the first scenario, we assume that the central bank keeps its policy rate i_t at the steady state level in the first eight quarters after the impact period. It then raises the policy rate i_t following the Taylor rule (6), allowing the rate to vary with developments in inflation rates π_t. In the second scenario, we assume that the central bank fully adjusts its policy rate i_t with reference to the Taylor rule (6) in all quarters. The first scenario is useful as it brings the economic states in the simulation exercise closer to the actual economic conditions where QQE was implemented in Japan. The second scenario is useful in separating the effects of bond purchases from the effects of commitments to keep the policy rate at the

[23] Note that ρ_{QE} takes a value that is strictly below unity. We report $\rho_{QE} = 1$ here because the number is rounded.

lower bound. In Figure 4, impulse responses at the posterior median are depicted by the blue solid line under the first scenario, and by the red solid line under the second scenario. The shaded area and the area between red dotted lines are 90% intervals under each of the two scenarios.

As a result of the bond purchase shock $\varepsilon_{QE,t}$, the term premium TP_t declines by a maximum 19 bps at the posterior median. The decline of the term premium TP_t is largest at the impact period, and reverts back monotonically to the steady state in the subsequent quarters.[24] The movement of the term premium TP_t is generally well translated into the movement of the long-term interest rate i_t^L. Transmission of bond purchases to the macroeconomy is larger under the first scenario, boosting output Y_t and inflation rate π_t by 44 bps and 11 bps, compared with 25 bps and 5 bps under the second scenario, at the posterior median. The difference in the responses of macroeconomic variables across the two scenarios is understood as capturing the effect of commitments on future short-term interest rates or as indicating that the degree of offsetting effect resulting from a rise in the short-term interest rate i_t is modest and that a cut in the long-term interest rate i_t^L has a stabilizing effect independent of the short-term interest rate i_t.[25,26]

Historical decomposition of long-term nominal interest rates

Lastly, we explore how much variations in long-term interest rates in the years after 2000 have been attributed to shocks to JGB purchases by the Bank, $\varepsilon_{QE,t}$ and $u_{QE,t}$. The upper panel in Figure 5 shows the estimated contribution of these shocks to variations in term premium TP_t, where the solid line denotes the estimate at the posterior median, and the

[24] Note that the term premium at period t is affected not only by transaction costs that are paid in the same period but also by transaction costs that are expected to be paid in future periods. Consequently, the effect of bond purchases on the term premium TP_t depends on expectations of households about bond purchases that will be conducted in future periods. In Appendix B, we study how the announcements regarding bond purchases or sales in the subsequent period affect long-term yields in a period by conducting simulations with different scenarios about the future time path after the central bank's government bond holdings are announced.

[25] Our estimation results are in a stark contrast to the estimates by CCF (2012), which quantitatively decompose the expansionary effects of the LSAP II into those stemming from a change in expected future short-term interest rates and those stemming from a change in the term premium, finding that the latter effects have been minimal. One possible reason for the difference may be that the estimated value for ω is relatively large in CCF (2012) compared with the value estimated in this paper.

[26] Though not reported here to save space, similarly to a positive temporary shock $\varepsilon_{QE,t}$, a positive persistent shock $u_{QE,t}$ reduces the term premium TP_t, boosting GDP Y_t and inflation rate π_t.

shaded area denotes the 95% interval of the estimate.[27] Before QQE was launched, during the periods when QE and CME were in place, shocks $\varepsilon_{QE,t}$ and $u_{QE,t}$ reduced the term premium on average about 10 bps, fluctuating slightly as a reflection of changes in monetary policy and economic conditions. Since the start of QQE, the negative contribution has become prominent, reaching 75 bps at the posterior median and 49 to 108 at the 95% interval, as of the end of 2017.[28] Using a metric of effects of JGB purchases worth 10% of GDP, our estimate of the effects of bond purchases on long-term interest rates is 14 bps, which falls somewhere in the middle of existing estimates that range from 3 to 35 bps, as documented in Table 1.

The relative quantitative importance of stock effects and flow effects in the total contributions is illustrated in the bottom panel of Figure 5.[29] Nearly all of the downward movement in the long-term rates i_t^L was the result of stock effects, while flow effects were minor throughout the sample period. For example, as of the end of 2017, at the posterior median, shocks to bond purchases $\varepsilon_{QE,t}$ and $u_{QE,t}$ were compressing the long-term rates about 75 bps in total, with 72 bps of the decline stemming from the stock effect and only about 3 bps decline stemming from the flow effect. On average, stock effects have been the dominant channel accounting for more than 90% of the compression of long-term rates induced by shocks to the Bank's JGB purchases $\varepsilon_{QE,t}$ and $u_{QE,t}$. The relative importance of the two effects has been unchanged over time. This observation suggests that, other things being equal, the prevailing downward pressure on long-term interest rates i_t^L

[27] Note that the term-premium TP_t in our model varies endogenously in response to shocks not only to the central bank's bond purchases $\varepsilon_{QE,t}$ and $u_{QE,t}$, but also to other parameters such as discount factors of households. What is shown in Figure 5(1) is the portion of variations in the long-term interest rate i_t^L that are accounted for by shocks $\varepsilon_{QE,t}$ and $u_{QE,t}$.

[28] Note also that, in our specifications, the effects of other policy measures launched since the outset of QQE, including the introduction of a price stability target of 2%, forward guidance, the negative short-term interest rate i_t, and purchases of ETFs, are caught by the contribution of other shocks, including predicted shocks to short-term rates, unpredicted shocks to short-term rates, or other exogenous shocks to the term premium TP_t, and these are included in "Others" in Figure 5.

[29] As Figure 4 shows, shocks to the central bank's bond purchases $\varepsilon_{QE,t}$ and $u_{QE,t}$ affect not only the term premium TP_t but also expected future short-term rates by inducing inflationary pressure on the economy in these two channels. In the panels in Figure 5, we show the contribution of these shocks $\varepsilon_{QE,t}$ and $u_{QE,t}$ to variations in the long-term interest rate i_t^L through the term premium TP_t exclusively and not to those in the inflation rate π_t. This is because the primary focus of our analysis is to quantify the impact of bond purchases through the term premium TP_t.

is likely to be maintained as long as the Bank's stock of JGB holdings is maintained. In the following section, we analyze the robustness of this quantitative finding by estimating three alternative models that employ different specifications of flow effects.

4 Assessing Flow Effects using Alternative Models

Compared with stock effects, the nature of flow effects, including their causes, is less well-understood, and there are potentially various approaches in modeling and assessing flow effects in a DSGE framework. In this section, we develop three alternative DSGE models that differ from each other, and also from the baseline model, only in the way that flow effects are incorporated into the model. We then estimate these models and study if their quantitative implications deviate substantially from those obtained from the baseline model.

4.1 Alternative Approaches to Capture Flow Effects

Here, we provide a description of the three alternative models. These models differ from the baseline model in how transaction costs ζ_t are formulated in equation (13), while the rest of the model remains the same as the baseline model.

1. Model I: a model without flow effects. In this model, transaction costs ζ_t are specified as follows.

$$\begin{aligned} 1+\zeta_{\mathrm{I},t} \equiv & \left[\left(\frac{P_t^L B_t^{L,P} / \left(P_t Z_t\right)}{P_{ss}^L B_{ss}^{L,P} / \left(P_{ss} Z_{ss}\right)} \right)^{\tau_{\mathrm{I},1}} \left(\frac{M_t^u / \left(P_t Z_t\right)}{M_{ss}^u / \left(P_{ss} Z_{ss}\right)} \right)^{-\tau_{\mathrm{I},2}} \left(\frac{M_t^r / \left(P_t Z_t\right)}{M_{ss}^r / \left(P_{ss} Z_{ss}\right)} \right)^{-\tau_{\mathrm{I},3}} \right] \\ & \times \exp\left(\zeta_t^{ex}\right), \qquad (18) \\ \zeta_t^{ex} = & \ \rho_{\zeta_{\mathrm{I}}} \zeta_{t-1}^{ex} + \varepsilon_{\zeta,t}, \end{aligned}$$

   where $\tau_{\mathrm{I},i} > 0$, $i \in \{1, 2, 3\}$ and $\rho_{\zeta_{\mathrm{I}}}$ are parameters to be estimated.

2. Model II: a model where flow effects emerge only in response to shocks to the gov-

ernment bond purchases, namely $\varepsilon_{QE,t}$ and $u_{QE,t}$.

$$1+\zeta_{\mathrm{II},t} \equiv \left[\left(\frac{P_t^L B_t^{L,P}/\left(P_t Z_t\right)}{P_{ss}^L B_{ss}^{L,P}/\left(P_{ss} Z_{ss}\right)}\right)^{\tau_{\mathrm{II},1}}\left(\frac{M_t^u/\left(P_t Z_t\right)}{M_{ss}^u/\left(P_{ss} Z_{ss}\right)}\right)^{-\tau_{\mathrm{II},2}}\left(\frac{M_t^r/\left(P_t Z_t\right)}{M_{ss}^r/\left(P_{ss} Z_{ss}\right)}\right)^{-\tau_{\mathrm{II},3}}\right]$$
$$\times \exp\left(-\tau_{\mathrm{II},4}\varepsilon_{QE,t}\right)\times \exp(-\tau_{\mathrm{II},5}u_{QE,t})\times \exp\left(\zeta_t^{ex}\right), \tag{19}$$
$$\zeta_t^{ex}=\rho_{\zeta_{\mathrm{II}}}\zeta_{t-1}^{ex}+\varepsilon_{\zeta,t}$$

where $\tau_{\mathrm{II},i}>0$, $i\in\{1,2,3,4,5\}$ and $\rho_{\zeta_{\mathrm{II}}}$ are parameters to be estimated.

3. Model III: a model where flow effects emerge only in response to contemporaneous government bond purchases, which we denote as $\varepsilon_{QEGross,t}$, and not to expected government bond purchases in future periods. In this model, the term premium TP_t is given as

$$TP_t=\frac{1}{D}\sum_{s=0}^{\infty}\left(\frac{D-1}{D}\right)^s \mathrm{E}_t\hat{\zeta}_{\mathrm{III},t+s},$$

where transaction cost at t, namely $1+\zeta_{\mathrm{III},t}$, is given as

$$\left[\left(\frac{P_t^L B_t^{L,P}/\left(P_t Z_t\right)}{P_{ss}^L B_{ss}^{L,P}/\left(P_{ss} Z_{ss}\right)}\right)^{\tau_{\mathrm{III},1}}\left(\frac{M_t^u/\left(P_t Z_t\right)}{M_{ss}^u/\left(P_{ss} Z_{ss}\right)}\right)^{-\tau_{\mathrm{III},2}}\left(\frac{M_t^r/\left(P_t Z_t\right)}{M_{ss}^r/\left(P_{ss} Z_{ss}\right)}\right)^{-\tau_{\mathrm{III},3}}\right]$$
$$\times \exp\left(-\tau_{\mathrm{III},4}\varepsilon_{QEGross,t}\right)\times \exp\left(\zeta_t^{ex}\right), \tag{20}$$
$$\zeta_t^{ex}=\rho_{\zeta_{\mathrm{III}}}\zeta_{t-1}^{ex}+\varepsilon_{\zeta,t},$$

and expected transaction costs going forward, namely $\mathrm{E}_t\left[\zeta_{\mathrm{III},t+s}\right]$ for $s>0$, is given as

$$\left[\left(\frac{P_{t+s}^L B_{t+s}^{L,P}/\left(P_{t+s} Z_{t+s}\right)}{P_{ss}^L B_{ss}^{L,P}/\left(P_{ss} Z_{ss}\right)}\right)^{\tau_{\mathrm{III},1}}\left(\frac{M_{t+s}^u/\left(P_{t+s} Z_{t+s}\right)}{M_{ss}^u/\left(P_{ss} Z_{ss}\right)}\right)^{-\tau_{\mathrm{III},2}}\left(\frac{M_{t+s}^r/\left(P_{t+s} Z_{t+s}\right)}{M_{ss}^r/\left(P_{ss} Z_{ss}\right)}\right)^{-\tau_{\mathrm{III},3}}\right]$$
$$\times \exp\left(\zeta_{t+s}^{ex}\right),$$
$$\zeta_{t+s}^{ex}=\rho_{\zeta_{\mathrm{III}}}\zeta_{t+s-1}^{ex}+\varepsilon_{\zeta,t+s},$$

where $\tau_{\mathrm{III},i}>0$, $i\in\{1,2,3,4\}$ and $\rho_{\zeta_{\mathrm{III}}}$ are parameters to be estimated. Note that the series $\varepsilon_{QEGross,t}$ is measured as the deviation from the steady state value of government bond purchases by the central bank.[30]

Model I is in line with the setting chosen by ALSN (2004) and CCF (2012) in which flow effects are absent. Models II and III incorporate flow effects, but in a different manner from the baseline model. These two alternative models reflect the view that flow effects do not arise from anticipated flows of government bond purchases in the future, and arise only from changes in flows of the ongoing purchases of government bonds. Models II and III differ from each other, however, in terms of how the ongoing purchases affect the current term premium TP_t. In Model II, only the unanticipated components of the ongoing purchases, $\varepsilon_{QE,t}$ and $u_{QE,t}$, affect the current term premium TP_t, and anticipated flows of future purchases do not affect the term premium TP_t. In Model III, the current flow of government bond purchases all affect the current term premium TP_t, regardless of whether they are anticipated or not. Similar to Model II, however, expected flows in periods beyond period t do not affect the term premium TP_t.

4.2 Estimation Results of the Alternative Models

We estimate Models I and II, using the 13 observables that are used in the baseline model. In estimating Model III, we construct the series for $\varepsilon_{QEGross,t}$ and use this series as well as the 13 observables. The estimation period runs from 1986:3Q to 2017:4Q, being the same as the baseline model.

Posterior distribution of the key parameters

Table 4 shows the posterior distribution of a subset of model parameters in Models I, II, and III that are related to bond market segmentation and preferred habitats. These include ω, $\tau_{\mathrm{I},i}$ $(i = 1, 2, 3)$, $\tau_{\mathrm{II},i}$ $(i = 1, 2, 3, 4, 5)$, and $\tau_{\mathrm{III},i}$ $(i = 1, 2, 3, 4)$. Although the estimated parameter values vary somewhat across the three models, they all indicate that

[30] We assume in the model that the amount of long-term government bonds held by the central bank relative to the size of GDP is constant at the steady state, which implies that the central bank keeps purchasing the bonds at the rate of the steady state GDP growth rate. Based on this assumption, we construct the data counterpart of the series $\varepsilon_{QEGross,t}$ from the actual purchases of long-term government bonds by the Bank minus the steady state GDP growth rate.

bond market segmentation is present and that the term premium TP_t is not independent of the size of the long-term government bond and deposit holdings of the households.

Response of the long-term interest rate in alternative models

To illustrate the nature of each of the alternative models, we conduct a simulation exercise that is similar to those shown in Figure 4 using the three models. We assume that a temporary positive shock to the purchase of long-term bonds, that is worth 10% of GDP takes place at period 0 ($\varepsilon_{QE,t} > 0$), and in the subsequent periods the central bank adjusts the size of its long-term bond holdings following the autoregressive rule specified by equation (7).[31] In the figure, the responses of the term premium TP_t are decomposed into two components, the component originating from flow effects and that originating from stock effects, where the former effect is computed as the sum of contributions by the terms that appear in $\tau_{\mathrm{I},i}$, $\tau_{\mathrm{II},i}$, and $\tau_{\mathrm{III},i}$, ($i \in \{1, 2, 3\}$) in the equation of the transaction cost ζ_t, and the latter effect is computed as the remaining component.

The flow effect manifests itself differently across the models. In the baseline model, flow effects lower the term premium at period 0, but raise the term premium in the following quarters, reflecting the fact that the level of long-term government bond holdings by the central bank $P_t^L B_t^{L,CB}$ gradually reverts back to the steady state level and the flow of the central bank's bond purchases accordingly turns negative. It is also notable that an anticipated decline in the flow of bond purchases at period 1 and beyond partly offset the expansionary influence of stock effects on the term premium. By contrast, in Model II, for example, flow effects only emerge at period 0 and the expected decline in flows of long-term bond purchases has no role to play.

The models all agree, however, that flow effects play a minor role in the transmission mechanism of bond purchases by the central bank to term premium, while stock effects play the dominant role. When comparing the size of the two effects by how much of the term premium these effects reduce on average from period 0 to 20 quarters, the estimated stock and flow effects are -7 bps and 1 bps, respectively under the baseline model, -6 bps

[31] Though not reported here to save space, impulse responses of long-term bonds held by the central bank to the bond purchase shock in the alternative models are similar to those in the baseline model.

and -0 bps under Model II, and -7 bps and -0 bps under Model III.

Effects of bond purchases in the alternative models

Figure 7 shows the contribution of long-term bond purchases by the Bank to a decline in the term premium TP_t estimated under each of the alternative models, together with an outline of these models. All of the contributions estimated by the alternative models that are shown in the middle and lower panel are expressed in terms of the difference from the corresponding series estimated using the baseline model. Note also that the contribution of bond purchases is the sum of the contributions of shocks $\varepsilon_{QE,t}$ and $u_{QE,t}$ for Models I and II, and the sum of the contributions of shocks $\varepsilon_{QE,t}$, $u_{QE,t}$, and $\varepsilon_{QEGorss,t}$ for Model III.

The models deliver slightly different pictures, particularly during the period after 2013. For example, in that year, Model I starts to exhibit more negative contributions to the term premium TP_t through stock effects, while Model III starts to exhibit less negative contributions to the term premium TP_t through both stock and flow effects. It is important to note, however, that the quantitative difference from the baseline model is about 8 bps at most, implying that the estimates of the contributions of bond purchases based on the baseline model are robust to the choice of specifications about flow effects.

5 Concluding Remarks

In this paper, we have estimated a DSGE model that incorporates bond market segmentation and preferred habitats of bond market participants, using Japanese data from the 1980s to 2017 to explore how purchases of JGBs by the Bank have been translated to long-term interest rates, economic activity, and prices. In particular, we have focused on comparing the quantitative importance of stock effects and flow effects in the transmission mechanism.

Our findings are summarized as follows: (1) Market segmentation and preferred habitat theories are both consistent with Japanese experience in the estimation period, which in turn indicates that the Bank's JGB purchases have reduced the term premium and have had an accommodative impact on economic activity and prices. (2) A reduction in the term premium due to JGB purchases by the Bank became prominent, particularly during the QQE period, when the Bank's JGB holdings reached an unprecedentedly high level, and as of the end of 2017, bond purchases by the Bank accounted for about 50 to 100 bps of the compression of the term premium. (3) While flow effects have been at work, their quantitative role has been minor: that is, based on our estimation, more than 90% of the reduction in the term premium due to the purchase of JGBs has been through stock effects rather than flow effects. This finding suggests that the amount outstanding of JGB held by the Bank is disproportionately important in the relationship between JGB purchases and long-term yields. It is also notable that the third finding is robust to various alternative specifications regarding how flow effects are incorporated in our DSGE model.

Three caveats are noteworthy regarding our analysis. The first point is about the degree of bond market segmentation and/or preferred habitats that are reflected in parameters ω and τ_i, for $i = 1, 2, ..., 6$. While the quantitative influence of JGB purchases relies heavily on the values of these parameters, this is not to say that these parameters will be unaffected by changes in economic and regulatory environments, such as the introduction of tighter financial regulations or advances in financial technology. The second point relates to the definition of short-term and long-term bonds. Following CCF (2012), this paper categorizes bonds with maturities of less than a year as short-term bonds, and the rest as long-term bonds, which implies that financial institutions or households conducting intertemporal decisions based on bond yields of 5, 10, and 20 years, and beyond are assumed to be the same in nature and to behave identically. However, given that some banks hold bonds with maturities longer than a year, it is possible that more accurate estimates may be obtained under an alternative model in which bond markets are split into three or four groups, such as short, medium, long, and super-long bond markets, instead of just two groups. The third caveat concerns potential drivers of long-term interest rates. This paper focuses on the transmission of changes in the quantity of long-term JGB to long-term interest rates exclusively, and therefore abstracts from other drivers, including external factors or risk aspects that are often considers in existing studies.[32] Elaborating the current framework in these directions, and providing a larger and more detailed picture of the effects of bond purchases is left as a future research agenda.

[32] For example, as shown in Bank of Japan (2016), the Comprehensive Assessment conducted by the Bank in 2016 employs an econometric model of 10-year JGBs in which U.S. government bond yield is treated as one of the driving forces. See also Van Binsbergen et al. (2012) where a DSGE model is constructed in which the term premium is addressed using a recursive preference.

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A Model

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

- The household sector consists of two types of households, unrestricted households and restricted households, each of which contains a continuum of households. Each household supplies labor inputs to the goods-producing sector, earns wages, stores its assets in the form of deposits and government bonds, and receives repayments in return from these assets. Unrestricted households can hold both short-term and long-term bonds but need to pay transaction costs when holding long-term bonds. Restricted households can hold only long-term bonds but do not have to pay transaction costs.
- The goods-producing sector consists of intermediate goods producers, final goods producers, and capital goods producers. The intermediate goods producers hire capital goods from capital goods producers and labor inputs from households to produce intermediate goods. Final goods producers produce final goods from intermediate goods. The capital goods producer purchases final goods and convert them into capital goods.
- The government sector consists of the central bank and the government. The central bank adjusts the nominal interest rate so as to stabilize the inflation rate, and conducts government bond purchases. The government collects taxes from households and spends it on government purchases. The deficit is financed by the issuance of short-term and long-term bonds.

Most of the settings of our model are borrowed from CCF (2012). What mainly differentiates our model from CCF (2012) is that our model explicitly addresses flow effects in addition to stock effects, and incorporates terms for deposits M_t^u and M_t^r in transaction costs ζ_t. The remaining part of the model, in particular settings relating to the household sector and the government sector, are changed from the settings of CCF (2012) so as to be consistent with the changes in the form of transaction costs ζ_t. Because we have already explained about the household sector and the government sector in Section 2, we provide only the unexplained settings in this appendix.

A.1 Long-term Bonds

In this section, we describe how long-term bonds are specified in the model, and how their prices and yields are derived from the setting. We follow Woodford (2001) in considering long-term government bonds as perpetuities with coupons that decay exponentially by a factor of κ. In other words, a long-term bond issued in period t pays κ^k yen $k+1$ quarters later. Denoting the price of long-term bonds that were issued k quarters ago as $P_t^L(k)$, the price of bonds issued today $P_t^L(0)$ and the long-term interest rates i_t^L today are expressed by the following equations.

$$P_t^L(0) \equiv \mathrm{E}_t\left[\frac{1}{1+i_t} + \frac{\kappa}{(1+i_t)(1+i_{t+1})} + \frac{\kappa^2}{(1+i_t)(1+i_{t+1})(1+i_{t+2})} + \cdots\right], \tag{A.1}$$

$$P_t^L(0) = \mathrm{E}_t\left[\frac{1}{1+i_t^L} + \frac{\kappa}{\left(1+i_t^L\right)^2} + \cdots\right] \text{ or } i_t^L = \frac{1}{P_t^L(0)} + \kappa. \tag{A.2}$$

Denoting the quantity of the decaying bonds issued k quarters ago as $B_t^L(k)$, the total amount of interest payment from the government at period t is given by the equation below.

$$\sum_{k=1}^{\infty} \kappa^{k-1} B_t^L(k).$$

Here we denote by B_{t-1}^L the quantity of long-term bonds issued at $t-1$ $B_t^L(1)$ that yields the interest payment that equals the amount of interest payment above; hence we have

$$B_{t-1}^L \equiv \sum_{k=1}^{\infty} \kappa^{k-1} B_t^L(k).$$

Using this expression, the value of long-term bonds in total and the yield are expressed by the following equations.

$$\sum_{k=1}^{\infty} P_t^L(k) B_t^L(k) = \kappa P_t^L \sum_{k=1}^{\infty} \kappa^{k-1} B_t^L(k) = \kappa P_t^L B_{t-1}^L, \tag{A.3}$$

$$\begin{aligned} \sum_{k=1}^{\infty} \kappa^{k-1} B_t^L(k) + \sum_{k=1}^{\infty} P_t^L(k) B_t^L(k) &= B_{t-1}^L + \kappa P_t^L B_{t-1}^L \\ &= \left(1 + i_t^L\right) P_t^L B_{t-1}^L, \end{aligned} \tag{A.4}$$

where $P_t^L \equiv P_t^L(0)$. Note that we use the following equations when deriving the equations above.

$$B_t^L(k) = \kappa^{k-1} B_t^L(1),$$

$$P_t^L(k) = \mathrm{E}_t\left[\frac{\kappa^k}{1+i_t} + \frac{\kappa^{k+1}}{(1+i_t)(1+i_{t+1})} + \cdots\right] = \kappa^k P_t^L(0).$$

A.2 Goods-producing Sector

A.2.1 Final Goods Producers

Final goods producers purchase differentiated intermediate goods $Y_t(i)$ from each intermediate goods producer i, and produce the final goods Y_t using the production technology shown below.

$$Y_t = \left[\int_o^1 Y_t(i)^{\frac{1}{1+\lambda_p}} dj\right]^{1+\lambda_p}, \tag{A.5}$$

where λ_p is the parameter that governs the substitutability of differentiated intermediate goods.

Final goods producers maximize their profits taking as given prices in their input markets and the product market. From the first order conditions of these producers, the demand for each of the differentiated goods $Y_t(i)$ and the consumer price index P_t are given as follows.

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\frac{1+\lambda_p}{\lambda_p}} Y_t \ , \tag{A.6}$$

$$P_t = \left[\int_o^1 P_t(i)^{-\frac{1}{\lambda_p}} \, di\right]^{-\lambda_p} , \tag{A.7}$$

where $P_t(i)$ is the price of intermediate goods produced by an intermediate goods producer i.

A.2.2 Intermediate Goods Producers

Each intermediate goods producer is indexed by $i \in [0,1]$, and produces differentiated products $\{Y_t(i)\}_{\ i \in [0,1]}$ by hiring effective capital stock K_t from capital goods producers and labor inputs N_t from households, using the production technology below

$$Y_t(i) = K_t(i)^{\alpha} \left(Z_t N_t(i)\right)^{1-\alpha} , \tag{A.8}$$

where $K_t(i)$ and $N(i)$ are effective capital stock and labor inputs hired by an intermediate goods producer i, and α is the capital share. Z_t is the level of the labor-augmented technology, and it grows at the rate γ plus two innovations, long-lived shocks $z_{l,t}$ and short-lived shocks $\varepsilon_{z,t}$, as described below.

$$\log\left(\frac{Z_t}{Z_{t-1}}\right) = \log(1+\gamma) + z_{l,t} + \varepsilon_{z,t} \ ,$$

The former shocks $z_{l,t}$ are assumed to follow the law of motion specified below.

$$z_{l,t} = \rho_z z_{l,t-1} + \varepsilon_{zl,t} \ . \tag{A.9}$$

Each intermediate goods producer i takes input prices W_t and R_t^k as given, but it behaves monopolistically in the intermediate goods market. That is to say, each firm takes as given the demand function towards its products $Y_t(i)$ that is shown in the equation (A.6), and sets its product price $P_t(i)$ so as to maximize its profits. Because of the nominal rigidity à la Calvo, only $1-\zeta_p \in (0,1)$ of these intermediate goods producers are able to set their optimal prices, and the remaining firms mechanically increase their prices by the steady state inflation rate Π_{ss}.

A.2.3 Capital Goods Producers

Capital goods producers purchase investment goods I_t from the final goods producers and convert them to capital stock $\overline{K}_t$. They set the optimal utilization rate u_t of the capital stock and rent an amount of effective capital $u_t\overline{K}_t$ to the intermediate goods producers and earn its return R_t^k. Formally, the optimization problem of capital goods producers is given by the equations below.

$$\max_{\left\{\overline{K}_{t+s},\ u_{t+s},\ I_{t+s}\right\}} \mathrm{E}_t \sum_{s=0}^{\infty} \Lambda_{t,t+s} \left[R_{t+s}^k u_{t+s}\overline{K}_{t+s} - P_{t+s}a\left(u_{t+s}\right)\overline{K}_{t+s} - P_{t+s}I_{t+s}\right],$$

$$\text{s.t.}\quad \overline{K}_t = (1-\delta)\,\overline{K}_{t-1} + \mu_t\left(1 - \frac{\eta}{2}\left(\frac{I_t}{I_{t-1}} - \exp(\gamma)\right)^2\right) I_t. \tag{A.10}$$

Here, $a\left(u_t\right)$ is the cost that capital goods producers have to pay whenever they set the utilization rate u_t of the capital stock, and $\Lambda_{t,t+s}$ is the discount factor from period t to $t+s$, each of which is defined as follows.

$$a\left(u_t\right) \equiv \mu \frac{u_t^{1+\psi^{-1}} - 1}{1+\psi^{-1}}, \tag{A.11}$$

$$\Lambda_{t,t+s} \equiv \frac{\omega MUC_{t+s}^u + (1-\omega)\,MUC_{t+s}^r}{\omega MUC_t^u + (1-\omega)\,MUC_t^r}, \tag{A.12}$$

where μ and ψ are parameters that govern the size of the costs associated with specifying utilization rate u_t. Equation (A.10) is the law of motion of the capital stock $\overline{K}_t$, μ_t is the time-varying parameter that governs the efficiency of investments, δ is the depreciation rate of the capital stock, and η is the parameter that governs the size of costs incurred when the capital stock is adjusted.

A.3 Resource Constraint

The resource constraint of final goods is given by the following equation.

$$Y_t = \omega C_t^u + (1-\omega) C_t^r + I_t + G_t + a(u_t) \overline{K}_t. \tag{A.13}$$

A.4 Fundamental Shocks

The model consists of twelve fundamental shocks and $\overline{S}$ number of anticipated monetary policy shocks. They are categorized into the following four groups.

1. Shocks to technology: these are shocks that directly affect the neutral production technology of the intermediate goods production Z_t. There are both long-lived and short-lived shocks, denoted as $\varepsilon_{zl,t}$ and $\varepsilon_{z,t}$, respectively.

2. Shocks to the quantity of long-term bonds supplied into the economy: these are shocks to the rule about the issuance of bonds by the government $\varepsilon_{b^L,t}$, and shocks to the rule about purchases by the central bank, $\varepsilon_{QE,t}$ and $u_{QE,t}$.

3. Shocks to demand factors: these are shocks to the discount factor of each of the two types of household and shocks to government expenditures, denoted as $\varepsilon_{a_u,t}$, $\varepsilon_{a_r,t}$, and $\varepsilon_{g,t}$, respectively.

4. Other shocks: these are shocks that are not categorized above, including shocks to investment efficiency μ_t, price markups $\lambda_{p,t}$, wage markups $\lambda_{w,t}$, the exogenous component of the term premium ζ_t^{ex}, and both unanticipated and anticipated monetary policy shocks $\varepsilon_{r,t}$ and $\{\varepsilon_{r,s,t-s}\}_{s=1}^{\overline{S}}$.

The law of motion for each fundamental shock is given as follows.

$$
\begin{aligned}
z_t &= \varepsilon_{z,t} + z_{l,t},\ \ z_{l,t} = \rho_z z_{l,t-1} + \varepsilon_{zl,t}, \\
\log P_t^L b_t^L &= \rho_{b^L} \log P_{t-1}^L b_{t-1}^L + \varepsilon_{b^L,t}, \\
\log P_t^L b_t^{L,CB} &= \rho_{QE} \log P_{t-1}^L b_{t-1}^{L,CB} + \varepsilon_{QE,t}, \\
v_{QE,t} &= \rho_{u,QE} v_{QE,t-1} + u_{QE,t}, \\
\log a_t^j &= \rho_{a_j} \log a_{t-1}^j + \varepsilon_{a_j,t}, \quad j = u, r, \\
\log g_t &= \rho_g \log g_{t-1} + \varepsilon_{g,t}, \\
\log \mu_t &= \rho_\mu \log \mu_{t-1} + \varepsilon_{\mu,t}, \\
\lambda_{p,t} &= \rho_{\lambda_p} \lambda_{p,t-1} + \varepsilon_{\lambda_p,t}, \\
\lambda_{w,t} &= \rho_{\lambda_w} \lambda_{w,t-1} + \varepsilon_{\lambda_w,t}, \\
\zeta_t^{ex} &= \rho_\zeta \zeta_{t-1}^{ex} + \varepsilon_{\zeta,t},
\end{aligned}
$$

where ρ_z, ρ_{a_u}, ρ_{a_r}, ρ_μ, ρ_g, ρ_{b^L}, ρ_{QE}, $\rho_{u,QE}$, ρ_ζ, ρ_{λ_p}, and $\rho_{\lambda_w} \in (0,1)$ are the autoregressive roots of the corresponding shocks, and $\varepsilon_{z,t}$, $\varepsilon_{zl,t}$, $\varepsilon_{a_u,t}$, $\varepsilon_{a_r,t}$, $\varepsilon_{\mu,t}$, $\varepsilon_{g,t}$, $\varepsilon_{b^L,t}$, $\varepsilon_{QE,t}$, $u_{QE,t}$, $\varepsilon_{\zeta,t}$, $\varepsilon_{\lambda_p,t}$,$\varepsilon_{\lambda_w,t}$, $\varepsilon_{r,t}$ and $\{\varepsilon_{r,s,t-s}\}_{s=1}^{\overline{S}}$ are the exogenous i.i.d. shocks that are normally distributed with mean zero.

A.5 Equilibrium

An equilibrium consists of a set of prices, $\{P_t,\ W_t,\ i_t^L,\ \zeta_t,\ i_t^d,\ R_t^k\}_{t=0}^\infty$, and the allocations $\{Y_t,\ C_t^u,\ C_t^r,\ I_t,\ Y_t(i),\ N_t(i),\ K_t(i)\}_{t=0}^\infty$, for all $i \in [0,1]$, for given government policy $\{G_t$, T_t, i_t, $\{i_{t+s}\}_{s=1}^{\overline{S}}\}_{t=0}^\infty$, realization of exogenous variables $\{\varepsilon_{z,t}$, $\varepsilon_{zl,t}$, $\varepsilon_{a_u,t}$, $\varepsilon_{a_r,t}$, $\varepsilon_{\mu,t}$, $\varepsilon_{g,t}$, $\varepsilon_{b^L,t}$ $\varepsilon_{QE,t}$, $u_{QE,t}$, $\varepsilon_{\zeta,t}$, $\varepsilon_{\lambda_p,t}$, $\varepsilon_{\lambda_w,t}$, $\varepsilon_{r,t}$, $\{\varepsilon_{r,s,t-s}\}_{s=1}^{\overline{S}}\}_{t=0}^\infty$, and initial conditions such that for all t , the following conditions are satisfied.

(i) each unrestricted household h^r maximizes its utility given prices;

(ii) each restricted household h^r maximizes its utility given prices;

(iii) each final goods producer maximizes its profits given prices;

(iv) each intermediate goods producer i maximizes its profits given input prices;

(v) each capital goods producer maximizes its profits given prices;

(vi) the government budget constraint holds;

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

(viii) markets clear.

B Announcement Effects

In this appendix, we study the effects of the central bank's current bond purchases and those of anticipated bond purchases by conducting a set of simulation exercises where the pattern of bond holdings by the central bank, such as the length of time that the central bank maintains the increased size of the balance sheet, is different from each other. In the simulations below, at period 0, the central bank announces the exact time path of its long-term bond holdings from period 0 and beyond, and in subsequent period conducts the purchase and sale of bonds as announced. The responses of long-term yields are affected not only by the size of the ongoing purchase or sale of bonds during the period, but also by the announcements because of the forward-looking nature of the model.[33]

The upper panel of the Appendix Figure shows the response of long-term rates i_t^L when the central bank announces that it will purchase long-term bonds worth 10% of GDP in total, over four quarters, and will hold these bonds for two years, before gradually reducing the long-term bond holdings in the subsequent quarters. While the central bank's holding of long-term bonds $P_t^L B_t^{L,CB}$ reaches its peak in 4 quarters after the announcement, the long-term interest rate i_t^L falls at the most when the announcement is made. This is because households adjust their demands towards long-term bonds at period 0, knowing they will shortly witness a shortage of long-term bonds supply due to the central bank's purchases.[34]

The middle panel shows simulation results under four different scenarios where the central bank continues to hold long-term bonds over different periods of 2, 3, 4, and 5

[33] In principle, announcements about future government bond purchases reduce the current long-term interest rate in a similar way to how commitments to maintaining future short-term interest rates at a low rate reduce the current long-term interest rates. There are, however, two significant differences. First, announcements about future government bond purchases reduce the term premium component rather than the expectation component of the long-term interest rate, thus primarily affecting restricted households, while announcements about future short-term interest rates in theory do not reduce the term premium but lower the expectation component, affecting both unrestricted and restricted households. Second, because the central bank has no direct control over the term premium, there are uncertainties, as shown in the 90% intervals in Table 3, regarding how much announcements about government bond purchases are translated to changes in the term premium.

[34] Mathematically, this mechanism is straightforward since the term premium TP_t is a function of the sum of the expected future bond holdings by the central bank at period t and beyond as indicated by equations (12) and (13). The long-term interest rate i_t^L returns to the steady state in the quarters after the announcement, since as time goes by the sum of the expected central bank's bond holding at period t and beyond falls.

years, respectively, after it finishes purchasing the intended amount of long-term bonds. The total amount of long-term bonds purchased and held by the central bank is all set 10% of GDP across all four scenarios, for the purpose of comparison. It is seen that while the impact on long-term interest rate i_t^L is largest at period 0 in all of the cases, the quantitative impact on the interest rate i_t^L is different, being larger as the central bank holds the purchased bonds for a longer period. For example, at period 0, the long-term interest rate i_t^L falls by 23 bps when the central bank announces that it will hold the bonds for two years, while it falls by 30 bps when it will hold them for three years.

The last panel shows three simulation results under the scenario in which the central bank reduces its long-term bond holdings $P_t^L B_t^{L,CB}$ at a difference pace, once it finishes purchasing the intended amount of long-term bonds. For the purpose of comparison, the accumulated sum of the central bank's long-term bond holdings over time, $\mathrm{E}_0 \left[\sum_{s=0}^{\infty} P_s^L B_s^{L,CB}\right]$, is the same across these simulations. It is seen that the responses of the long-term interest rate i_t^L at period 0 are all about 23 bps. The responses of the rates in the subsequent periods are, however, different from each other, returning slowly to the steady state rate when the central bank reduces its long-term bond holdings at a slower pace, and returning quickly to the steady state rate and exhibiting a small overshoot when the opposite is the case.

Table 1: Empirical Studies on Long-Term Bond Purchases by the Bank of Japan

	Period	Estimated Reduction in Long-term Rate (bps)	Frequency of the Samples
Lam (2011)*	2010	14	Daily
Ueda (2012)*	2010	14	Daily
Hausman and Wieland (2014)*	2013	6	Daily
Fukunaga, Kato, and Koeda (2015)**	1992-2014	24	Monthly
	2013-14	18	Monthly
Monetary Affairs Department, the Bank of Japan (2015)	2013-15	15	Quarterly
The Bank of Japan (2016)	2013-14	35	Monthly
<Comprehensive Assessment of Monetary Easing>	2014-16	3	Monthly
Katagiri and Takahashi (2017)**	1987-2016	11	Quarterly
This Paper**	1986-2017	14	Quarterly

Notes: 1. Purchases are normalized to 10% of GDP.
2. The GDP used for the normalization is as of the final year of the sample period.
3. * denotes studies that estimate the announcement effects of long-term bond purchases.
4. ** denotes studies that estimate the term premium component of movements in long-term rates.
5. In normalizing the estimates by Lam (2011) and Ueda (2012), the size of the announced asset purchase (35 trillion yen) is used. Changing the scale to the announced amount of assets newly purchased (5 trillion yen), the values increase to 100 bps and 99 bps respectively.

Table 2: Calibrated Parameters

	Parameter	Value
α	Capital share	0.33
β	Discount factor (quarterly)	0.998
δ	Depreciation rate of the capital stock (quarterly)	0.02
D	Duration of long-term bonds (quarters)	40
g_{ss}	Steady state share of government expenditure	0.24
$P_{ss}^{L} B_{ss}^{L,CB}$	Steady state value of the central bank's holdings of long-term government bonds	0.08
$B_{ss}^{L,CB} / B_{ss}^{L,P}$	Steady state value of the central bank's holdings of long-term government bonds relative to the private sector's holdings of long-term government bonds	0.17

Note: Decaying rate of coupons, κ, is set to whatever makes $D = 40$.

Table 3: Estimated Parameters

	Parameter	Dist.	Prior		Posterior		
			Mean	S.D.	Mean	5%	95%
Structural Parameters							
σ_u	Inverse elasticity of substitution: Unrestricted	G	2.00	(0.50)	2.66	1.82	3.43
σ_r	Inverse elasticity of substitution: Restricted	G	2.00	(0.50)	1.20	0.76	1.64
ν_n	Inverse elasticity of labor supply	G	2.00	(0.50)	1.19	0.63	1.76
h	Consumption habit	B	0.70	(0.05)	0.58	0.48	0.69
ω	Proportion of unrestricted households	B	0.50	(0.20)	0.49	0.25	0.72
ν_m	Inverse elasticity of deposit demand	G	1.82	(1.00)	0.16	0.04	0.30
δ_m	A parameter in deposit demand functions	G	4.36	(1.00)	4.34	2.71	5.79
C_u/C_r	Consumption ratio between 2 types of the households	G	1.00	(0.05)	0.99	0.91	1.07
η	Investment adjustment cost	G	4.00	(1.00)	4.78	3.15	6.34
ψ	Inverse elasticity of capital utilization	G	1.00	(0.50)	1.87	0.87	2.89
ζ_p	Probability of no price revision	B	0.50	(0.10)	0.90	0.87	0.92
ζ_w	Probability of no wage revision	B	0.50	(0.10)	0.63	0.52	0.76
λ_p	Price markup at the steady state	G	0.15	(0.02)	0.19	0.15	0.23
λ_w	Wage markup at the steady state	G	0.15	(0.02)	0.15	0.12	0.18
$1000\tau_1$	A parameter related to elasticity of term premium	N	1.50	(0.50)	1.48	0.62	2.28
$1000\tau_2$	A parameter related to elasticity of term premium	N	1.50	(0.50)	1.54	0.78	2.30
$1000\tau_3$	A parameter related to elasticity of term premium	N	1.50	(0.50)	1.14	0.28	2.00
$1000\tau_4$	A parameter related to elasticity of term premium	N	1.50	(0.50)	1.48	0.71	2.27
$1000\tau_5$	A parameter related to elasticity of term premium	N	1.50	(0.50)	1.46	0.66	2.26
$1000\tau_6$	A parameter related to elasticity of term premium	N	1.50	(0.50)	1.47	0.59	2.33
$400\pi_{ss}$	Steady state inflation rate (ann., %)	G	0.30	(0.20)	0.86	0.52	1.20
400γ	Steady state growth rate of productivity (ann., %)	G	1.30	(0.20)	1.06	0.79	1.29
$400\bar{\zeta}$	Steady state term premium (ann., %)	G	1.00	(0.20)	0.91	0.63	1.19
Policy Parameters							
ρ_r	Lagged short-term interest rate	B	0.75	(0.05)	0.83	0.80	0.87
ρ_π	Inflation	G	1.50	(0.20)	2.21	1.96	2.45
ρ_{QE}	Persistence of the central bank's long-tem bond holdings	B	0.80	(0.15)	0.95	0.85	1.00*
Persistence of shocks							
ρ_{b_u}	Preference shock: Unrestricted	B	0.80	(0.15)	0.99	0.98	1.00*
ρ_{b_r}	Preference shock: Restricted	B	0.80	(0.15)	0.19	0.07	0.31
ρ_{z_l}	Persistent productivity growth shock	B	0.98	(0.01)	0.99	0.98	0.99
ρ_g	Government expenditure shock	B	0.50	(0.15)	0.90	0.85	0.95
ρ_μ	Investment adjustment cost shock	B	0.70	(0.15)	0.51	0.38	0.63
ρ_{λ_p}	Price markup shock	B	0.50	(0.15)	0.81	0.75	0.86
ρ_{λ_w}	Wage markup shock	B	0.50	(0.15)	0.50	0.24	0.77
ρ_{b^L}	Issuance of long-term bonds shock	B	0.70	(0.15)	0.71	0.48	0.95
$\rho_{u,QE}$	Persistent long-term bond purchase shock	B	0.70	(0.15)	0.92	0.89	0.98
ρ_ζ	Exogenous term premium shock	B	0.70	(0.15)	0.93	0.88	0.97
S.D. of shocks							
σ_{b_u}	Preference shock: Unrestricted	invG	5.00	(Inf)	5.93	2.01	10.54
σ_{b_r}	Preference shock: Restricted	invG	5.00	(Inf)	6.55	2.32	11.11
σ_z	Temporary productivity growth shock	invG	5.00	(Inf)	1.65	1.49	1.83
σ_{z_l}	Persistent productivity growth shock	invG	0.10	(Inf)	0.11	0.08	0.14
σ_g	Government expenditure shock	invG	1.00	(Inf)	3.01	2.67	3.33
σ_μ	Investment adjustment cost shock	invG	3.00	(Inf)	7.37	4.22	10.70
σ_{λ_p}	Price markup shock	invG	1.00	(Inf)	2.07	1.23	2.89
σ_{λ_w}	Wage markup shock	invG	1.00	(Inf)	0.72	0.24	1.29
σ_{b^L}	Issuance of long-term bonds shock	invG	0.50	(Inf)	0.49	0.12	1.11
σ_{QE}	Temporary long-term bond purchase shock	invG	5.00	(Inf)	0.63	0.59	0.68
$\sigma_{u,QE}$	Persistent long-term bond purchase shock	invG	5.00	(Inf)	3.27	2.91	3.64
σ_ζ	Exogenous term premium shock	invG	0.50	(Inf)	0.31	0.15	0.48
σ_r	Short-term interest rate shock	invG	0.10	(Inf)	0.02	0.02	0.03
$\sigma_{r,1}$	1 Q ahead anticipated short-term interest rate shock	invG	0.10	(Inf)	0.02	0.02	0.02
$\sigma_{r,2}$	2 Q ahead anticipated short-term interest rate shock	invG	0.10	(Inf)	0.01	0.01	0.02
$\sigma_{r,3}$	3 Q ahead anticipated short-term interest rate shock	invG	0.10	(Inf)	0.02	0.01	0.02
$\sigma_{r,4}$	4 Q ahead anticipated short-term interest rate shock	invG	0.10	(Inf)	0.01	0.01	0.02
$\sigma_{\pi,obs}$	Measurement error: Inflation	invG	0.30	(Inf)	0.24	0.21	0.27
$\sigma_{w,obs}$	Measurement error: Real wage	invG	0.30	(Inf)	1.19	1.07	1.32

Notes: 1. N represents normal distribution, G gamma distribution, B beta distribution, invG inverse gamma distribution.
2. Without rounding, the values with * are strictly below unity.

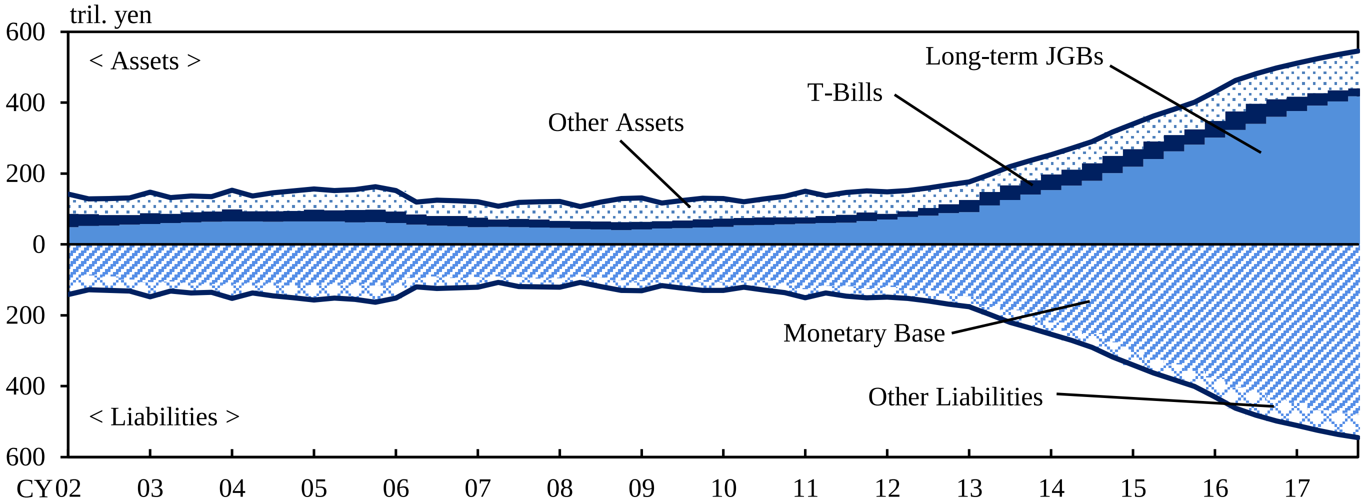
Table 4: Major Estimated Parameters in the Alternative Models

	Baseline Model	Alternative (I)	Alternative (II)	Alternative (III)
ω	0.49 (0.25 , 0.72)	0.43 (0.22 , 0.63)	0.44 (0.23 , 0.65)	0.43 (0.23 , 0.62)
τ_1	1.48 (0.62 , 2.28)	1.44 (0.59 , 2.29)	1.46 (0.62 , 2.27)	1.47 (0.66 , 2.31)
τ_2	1.54 (0.78 , 2.30)	1.53 (0.69 , 2.34)	1.51 (0.65 , 2.33)	1.55 (0.73 , 2.37)
τ_3	1.14 (0.28 , 2.00)	1.13 (0.23 , 2.00)	1.08 (0.14 , 2.04)	1.18 (0.31 , 2.03)
τ_4	1.48 (0.71 , 2.27)			
τ_5	1.46 (0.66 , 2.26)			
τ_6	1.47 (0.59 , 2.33)			
$\tau_{\mathrm{II},4}$			2.46 (1.64 , 3.26)	
$\tau_{\mathrm{II},5}$			2.48 (1.65 , 3.29)	
$\tau_{\mathrm{III},4}$				2.48 (1.66 , 3.32)

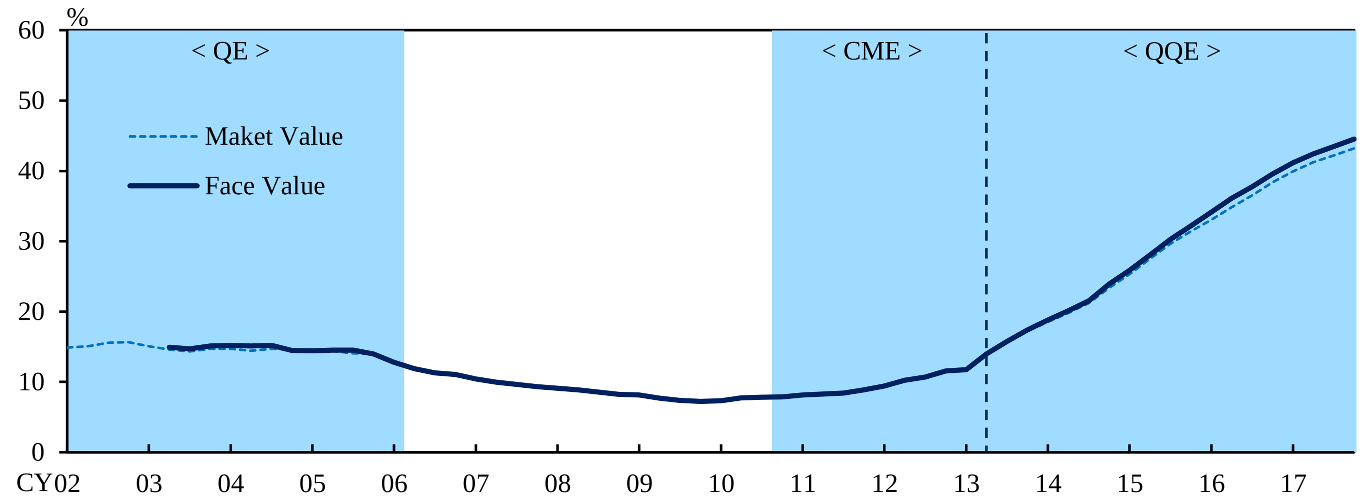
Note: The figures are posterior means, and the figures in ( ) are 90% intervals.

Figure 1: JGBs Held by the Bank of Japan and Long-Term Interest Rates

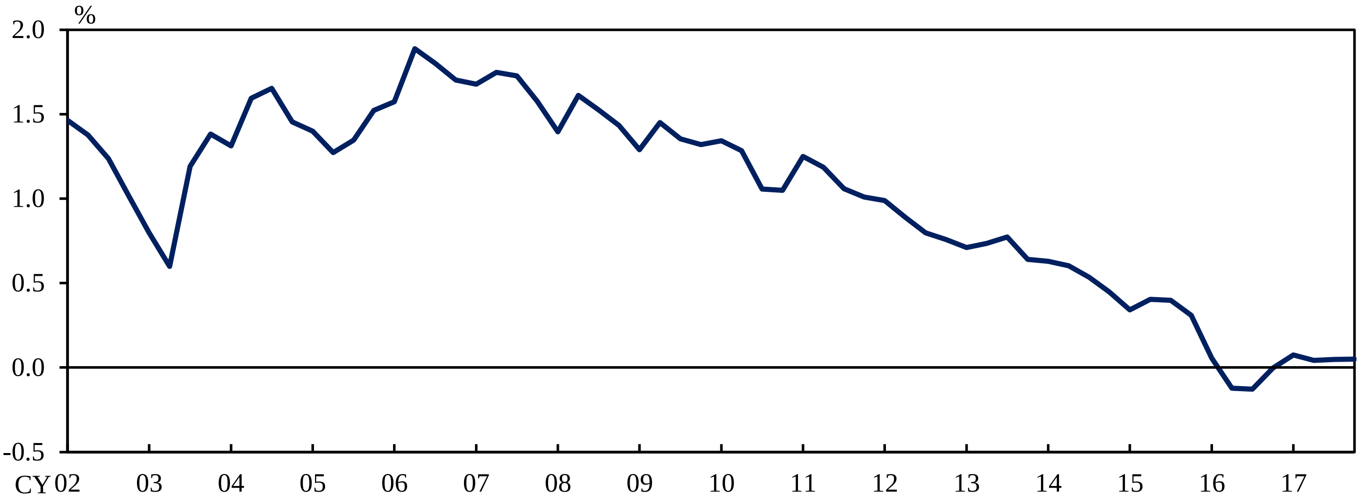
(1) Balance Sheet of the Bank of Japan



(2) Share of the Bank of Japan's JGBs Holdings



(3) Long-Term Nominal Interest Rate (10-Year JGB Yields)



Notes: 1. In (1), the series for long-term JGBs includes JGBs with all remaining maturities.
2. The series in (2) excludes T-Bills and Financing Bills.

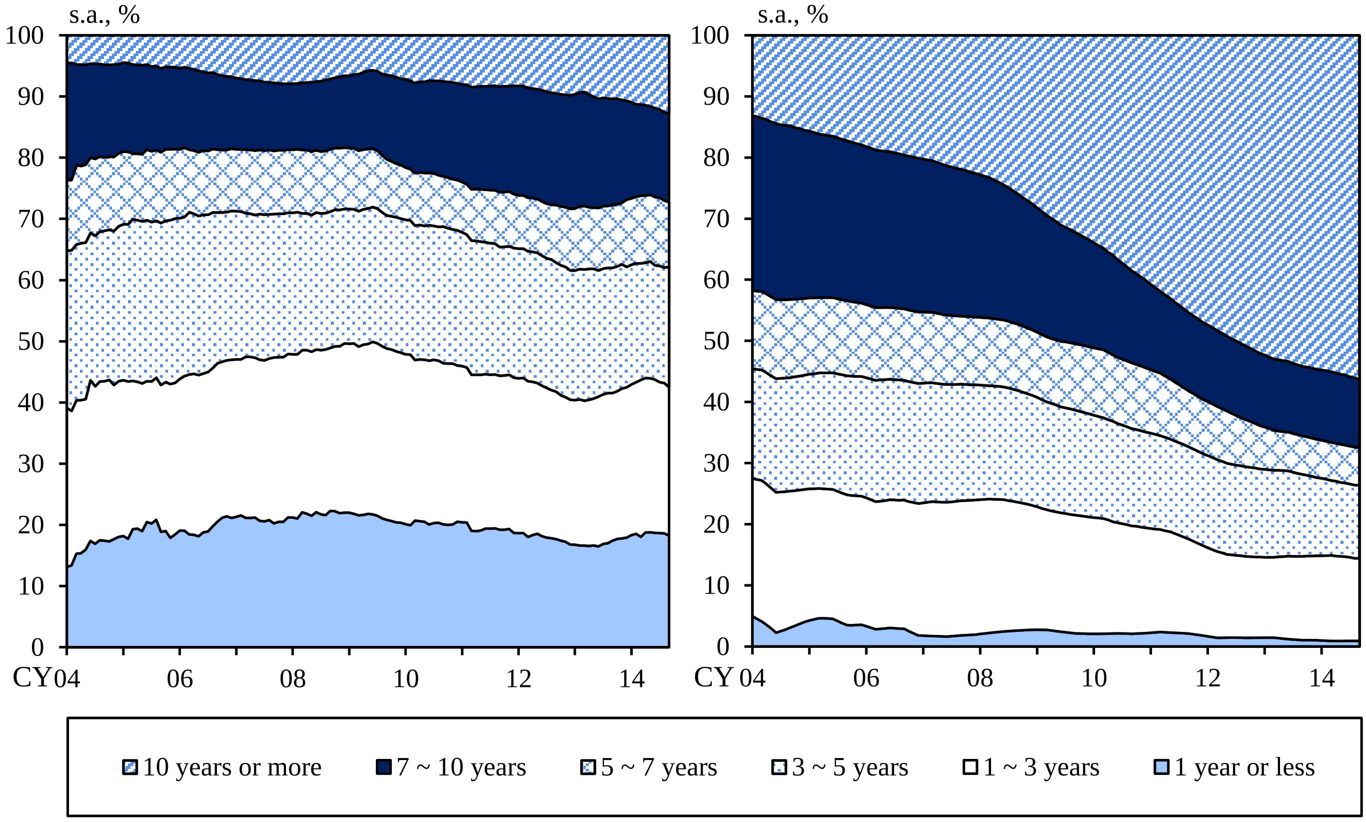
Sources: Ministry of Finance, "Interest Rate"; Bank of Japan, "Monetary Base and the Bank of Japan's Transactions," "Flow of Funds Accounts," "JGBs held by the Bank of Japan," "T-Bills Purchased by the Bank of Japan," "Bank of Japan's Transactions with the Government," "Issuance, Redemption, and Outstanding of Public and Corporate Bonds."

Figure 2: JGB Holding by Each Sector

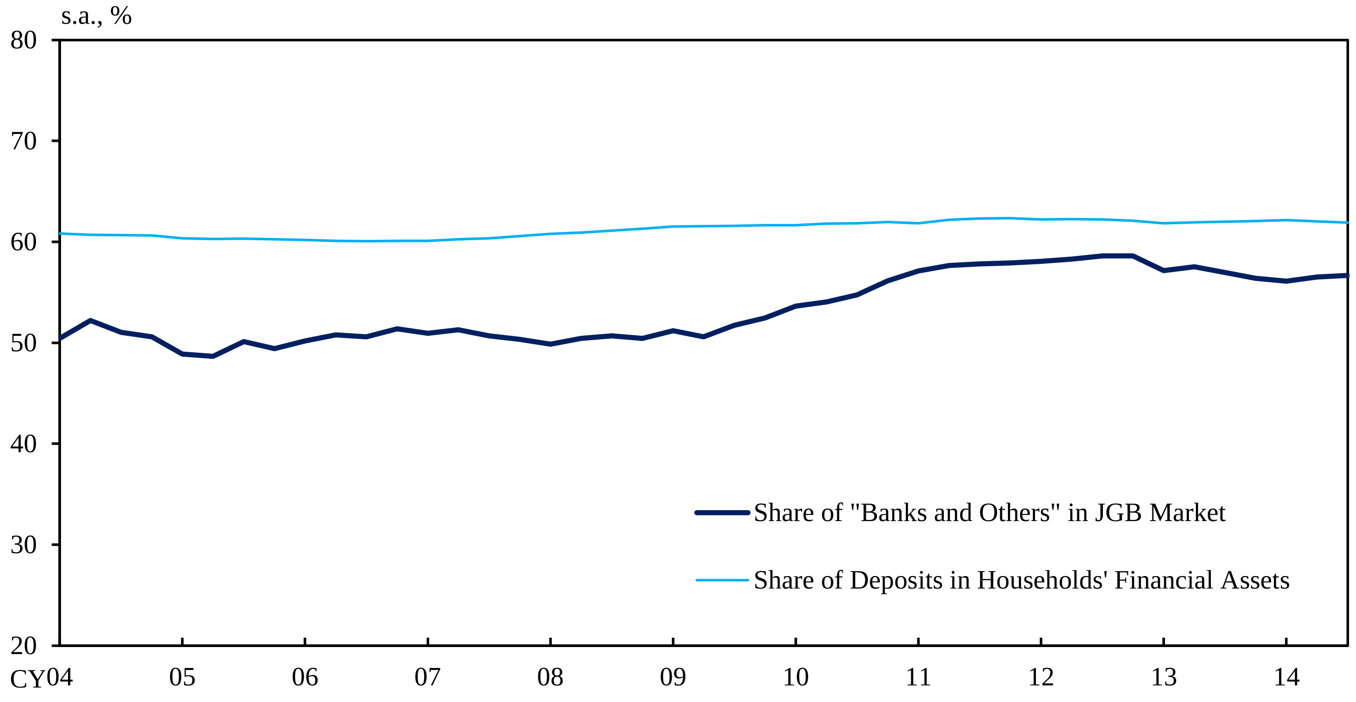
(1) Maturity Structure of JGBs Held by Each Sector

(a) Banks and Others

(b) Pension Funds and Insurance Companies



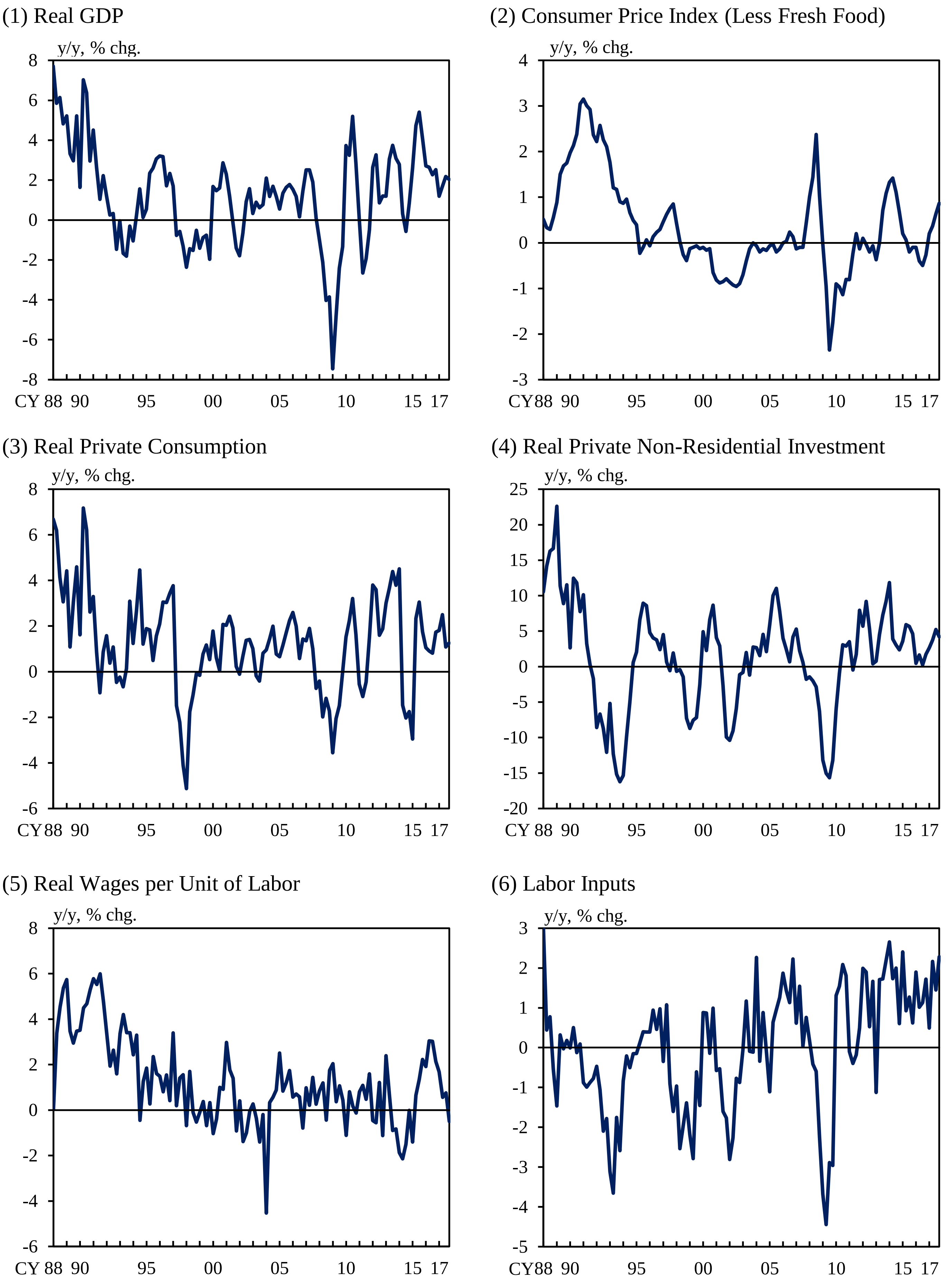
(2) Share of "Banks and Others" in JGB Market and of Deposits in Households' Financial Assets



Notes: 1. The data for (1) and the bold line in (2) are taken from Fukunaga, Kato, and Koeda (2015).
2. "Banks and Others" is defined as private participants in the JGB market except for pension funds and insurance companies.
3. Series for share of deposits in households' financial assets is calculated as Deposits /(Deposits + Insurance and Pension). A discontinuity due to a revision of Flow of Funds Accounts is adjusted.

Sources: Fukunaga, Kato, and Koeda (2015), "Maturity Structure and Supply Factors in Japanese Government Bond Markets"; Bank of Japan, "Flow of Funds Accounts."

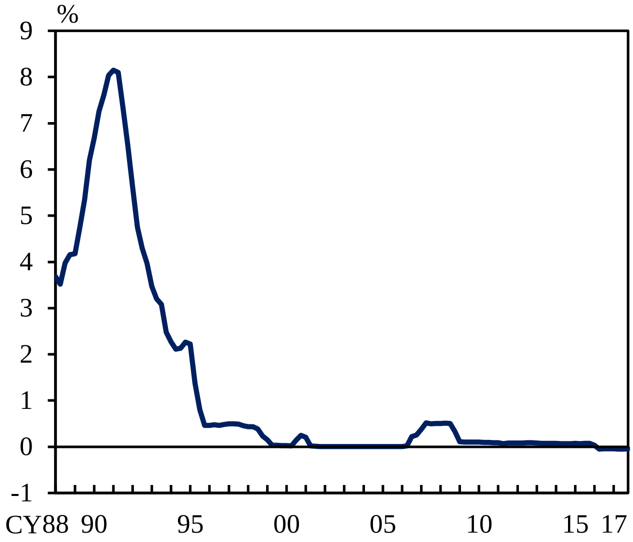
Figure 3: Data Used for Estimation (1)



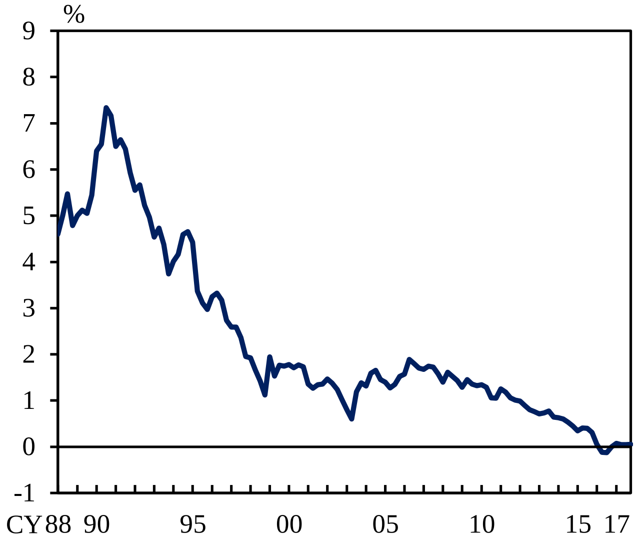
Notes and Sources: See the next page.

Figure 3: Data Used for Estimation (2)

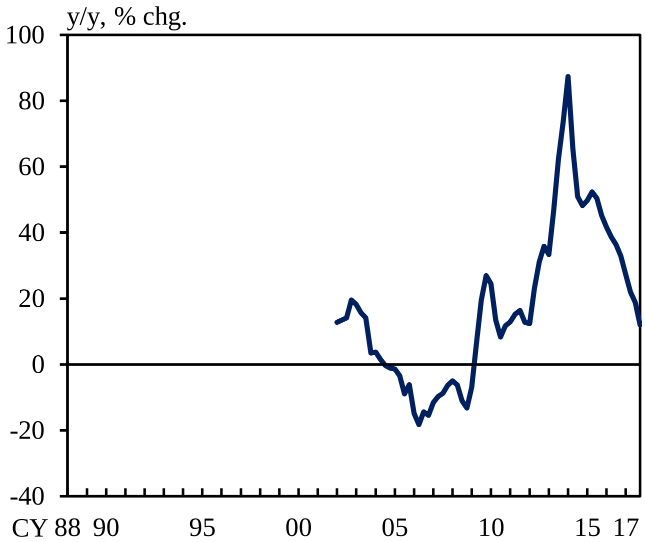
(7) Short-Term Nominal Interest Rate (Call Rate)



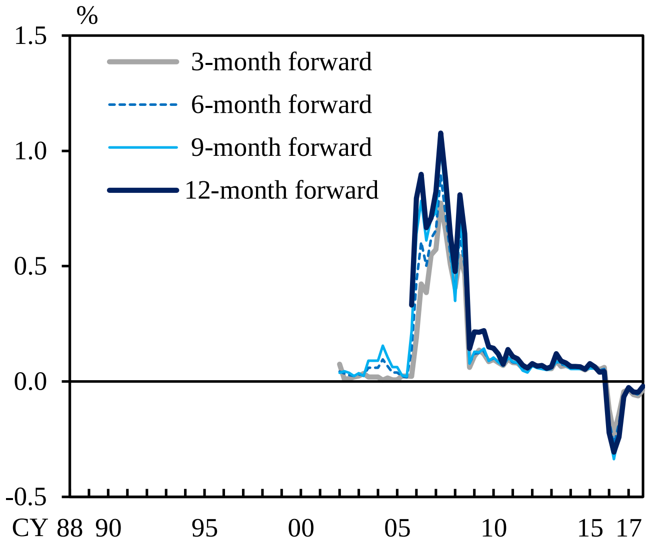
(8) Long-Term Nominal Yield (10-year JGB Yield)



(9) Real Long-Term JGBs Held by the Bank of Japan



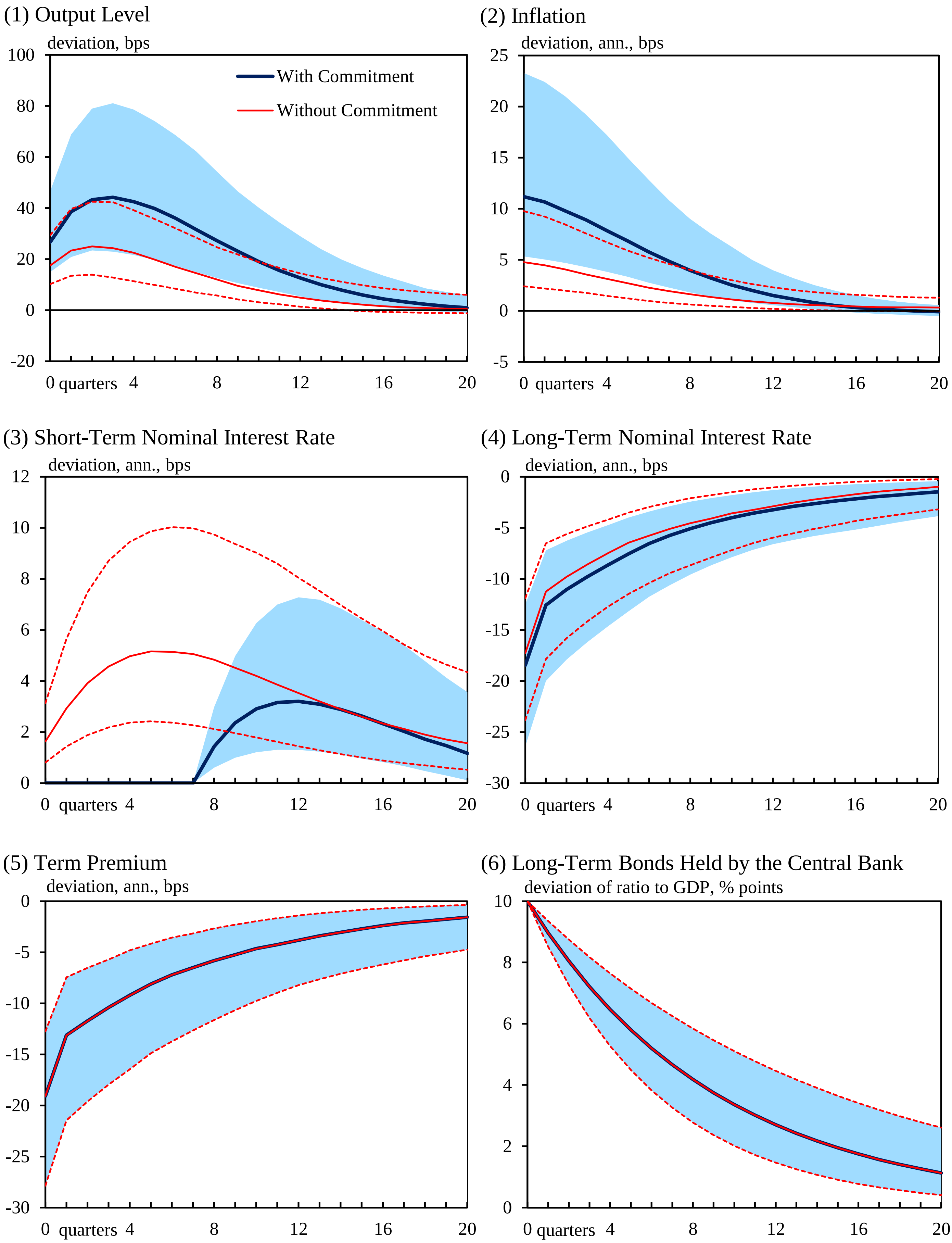
(10) ~ (13) Expected Short-Term Nominal Interest Rates



Notes: 1. For series (1) ~ (6) and (9), quarter-on-quarter % changes of the variables are used rather than year-on-year % changes in our estimation. For series (7), (8) and series (10) ~ (13), the quartered values are used in our estimation.
2. Series (1), (3), (4), (6) and (9) are on a per capita basis.
3. Series (1), (3), (4), (5) and (9) are deflated by the consumer price index (less fresh food).
4. Series (2) is adjusted for the introduction of the consumption tax and changes in the rates.
5. Series (3) includes private residential investment.
6. Series (9) are calculated as the Bank of Japan's holding amount of JGBs with remaining maturities more than 1 year. The information on JGBs held by the Bank of Japan is obtained from "Japanese Government Bonds Held by the Bank of Japan." Data on floating-rate bonds and inflation-linked bonds are not included.
7. Series (10) ~ (13) are forward rates implied in overnight index swaps (OIS).

Sources: Cabinet Office, "National Accounts"; Ministry of Health, Labour and Welfare, "Monthly Labour Survey"; Ministry of Internal Affairs and Communications, "Labour Force Survey," "Consumer Price Index"; Ministry of Finance, "Interest Rate"; Bank of Japan, "Call Money Market Data," "Japanese Government Bonds Held by the Bank of Japan"; Bloomberg.

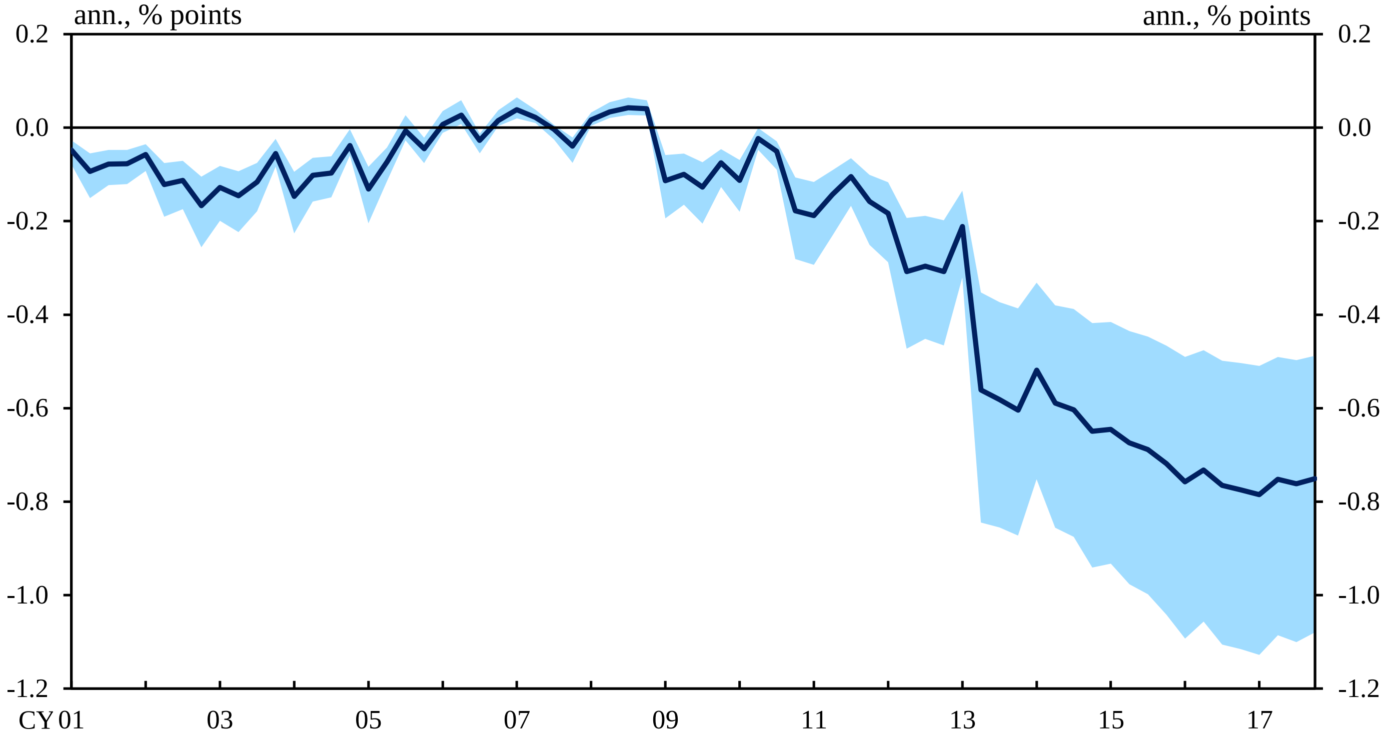
Figure 4: Impulse Response Functions to Long-Term Bond Purchases



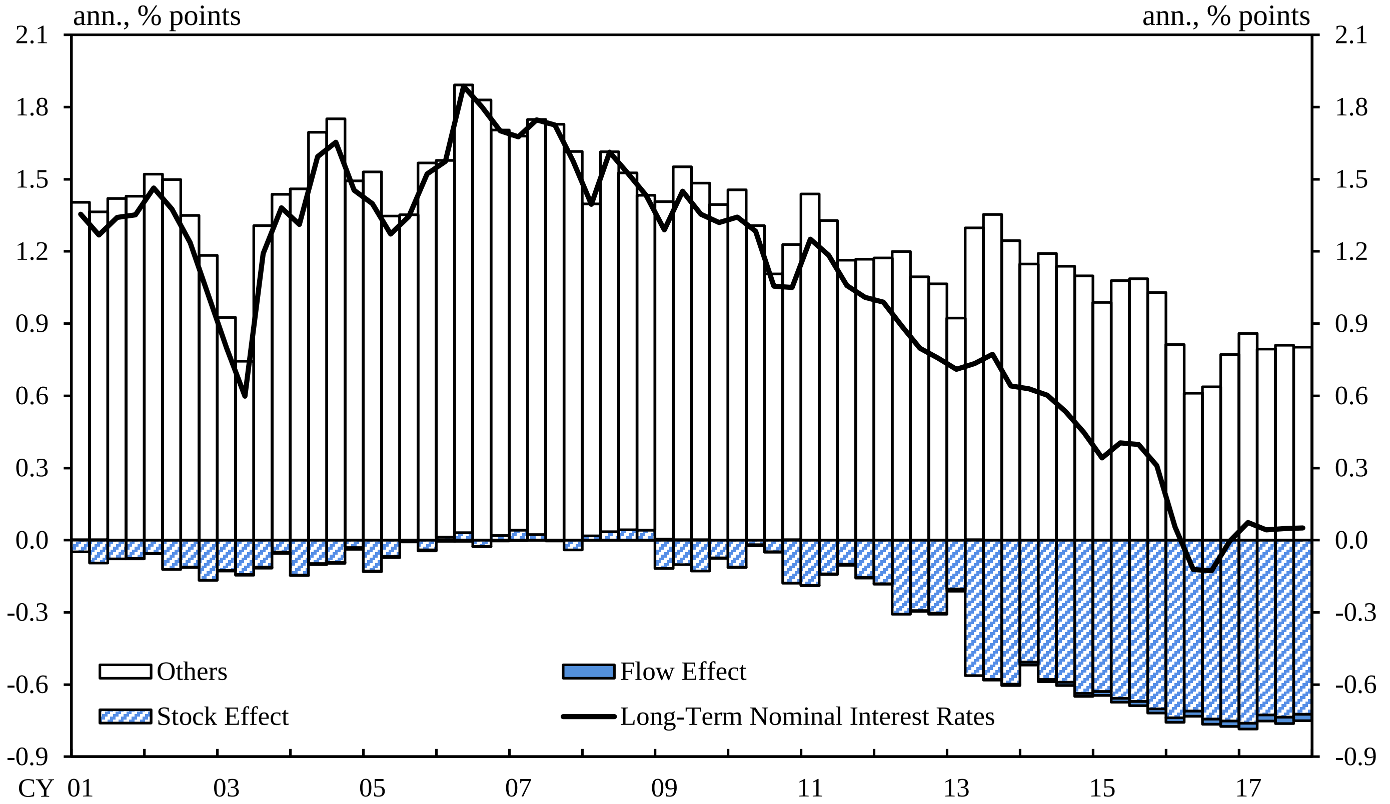
Notes: 1. The size of the shock is equal to 10% of GDP. The series are deviations from the non-stochastic steady state.
2. Each solid line represents the median of the impulse response, and the shaded areas and the dotted lines represent the 90% intervals of the estimate.

Figure 5: Term Premium Reduction Due to Long-Term Bond Purchases

(1) Term Premium Reduction Due to Long-Term Bond Purchases



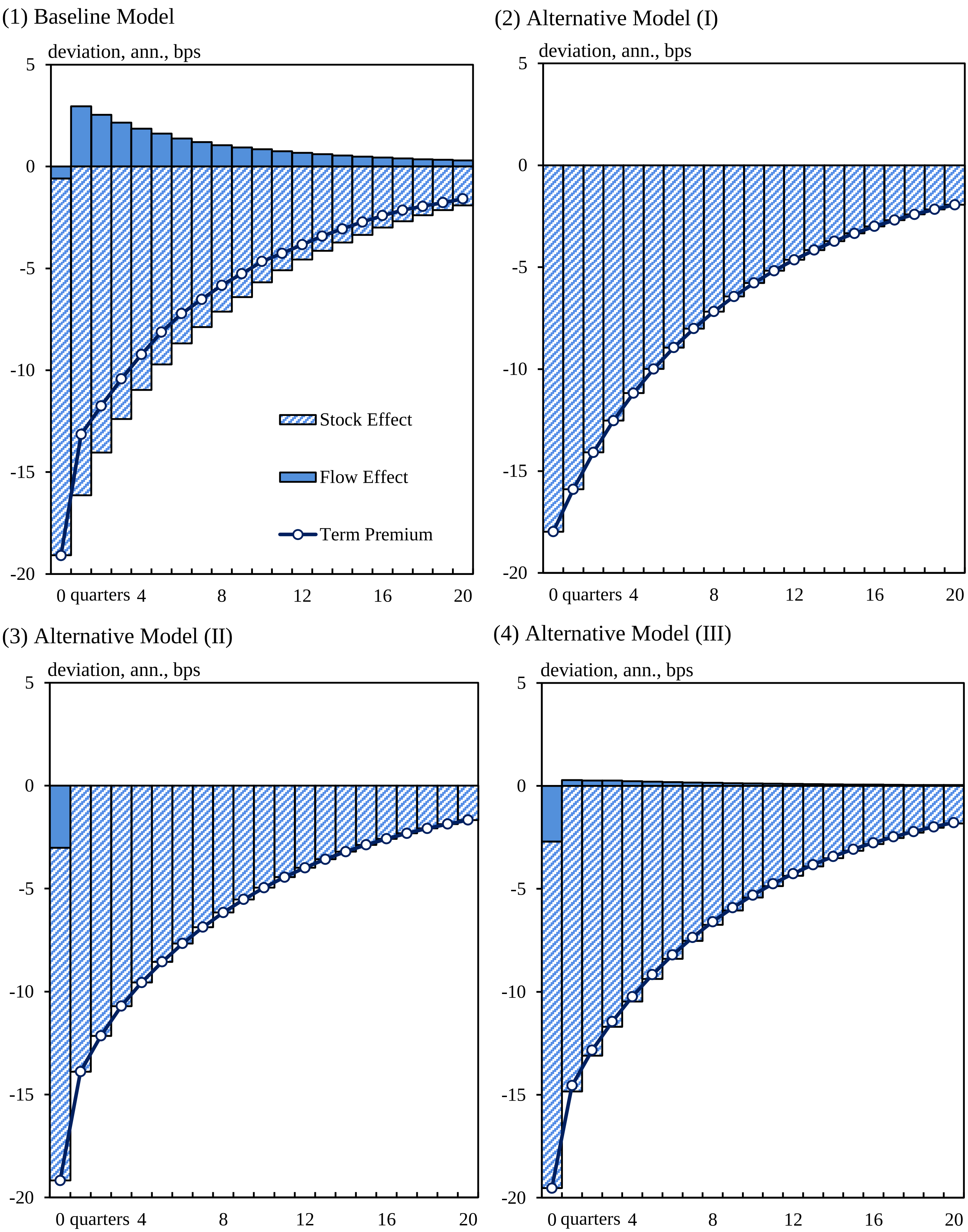
(2) Historical Decomposition of Long-Term Nominal Interest Rates



Notes: 1. The solid line in (1) represents the median of the estimated reductions, and the shaded areas represent the 95% intervals of the estimate.
2. Contributions of stock effect and flow effect are impacts on the term premium component of the long-term nominal interest rate.
3. The decomposition in (2) is the median of the estimated historical decompositions.

Source: Ministry of Finance, "Interest Rate."

Figure 6: Impulse Response Functions under Alternative Models



Notes: 1. Each panel shows the impulse response functions to a temporary QE shock.
2. The size of the shocks is equal to 10% of GDP. The series are deviations from the non-stochastic steady state.
3. Each solid line represents the median of the estimated impulse responses.
4. In (2) ~ (4), the persistence of the central bank's balance sheet is equalized to the posterior mean in the baseline.

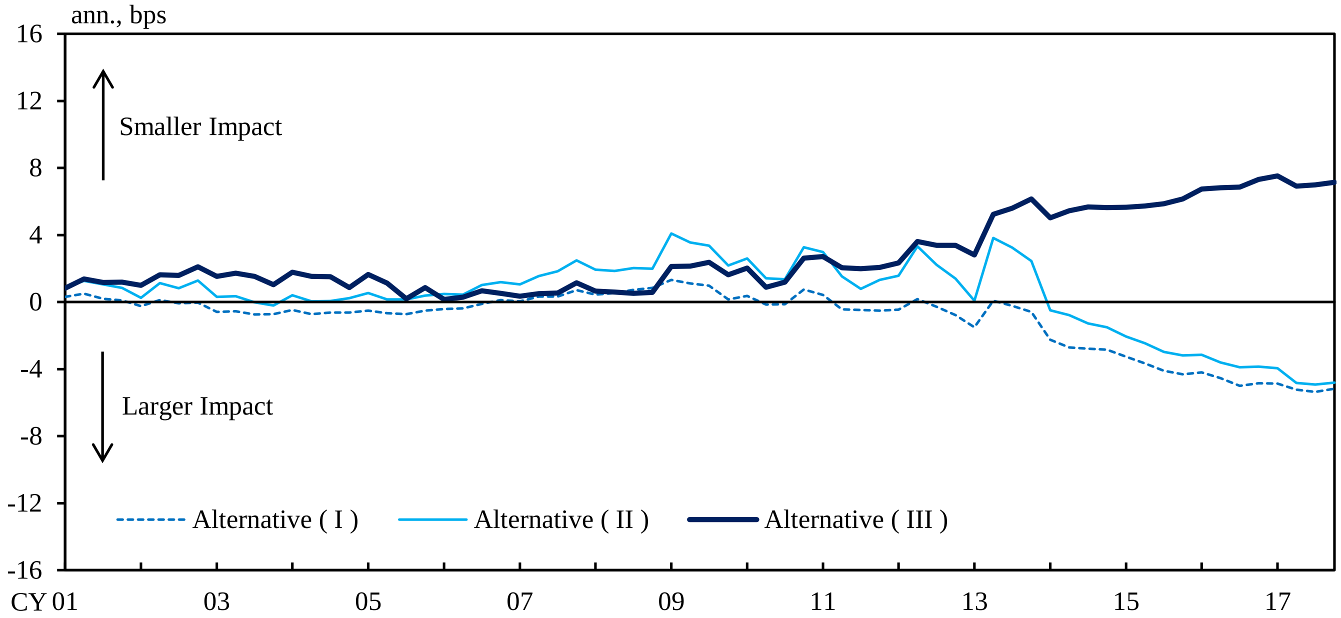
Figure 7: Impact on Term Premiums in the Alternative Models

(1) Specifications in the Baseline and Alternative Models

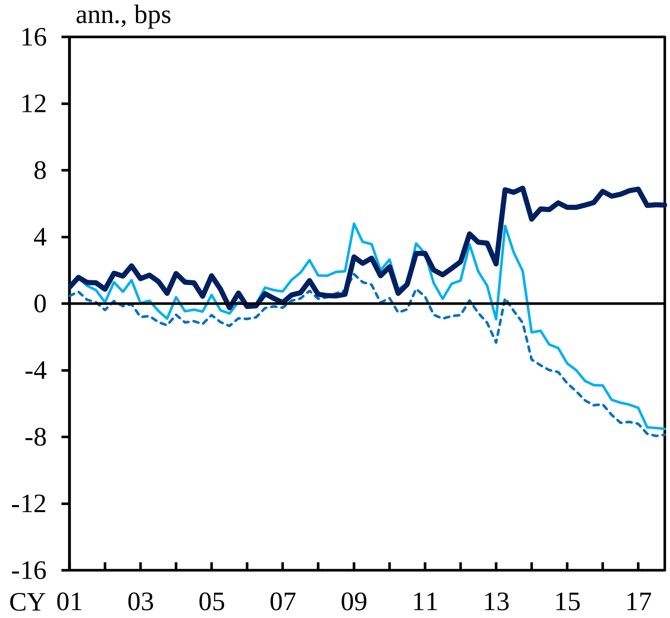
	Stock Effect	Flow Effect		
	Baseline Specification	Baseline Specification	$\varepsilon_{QE,t}$, $u_{QE,t}$	$\varepsilon_{QEGross,t}$
Baseline	○	○	—	—
Alternative (I)	○	—	—	—
Alternative (II)	○	—	○	—
Alternative (III)	○	—	—	○

(2) Impact of Long-Term Bond Purchases on Term Premiums

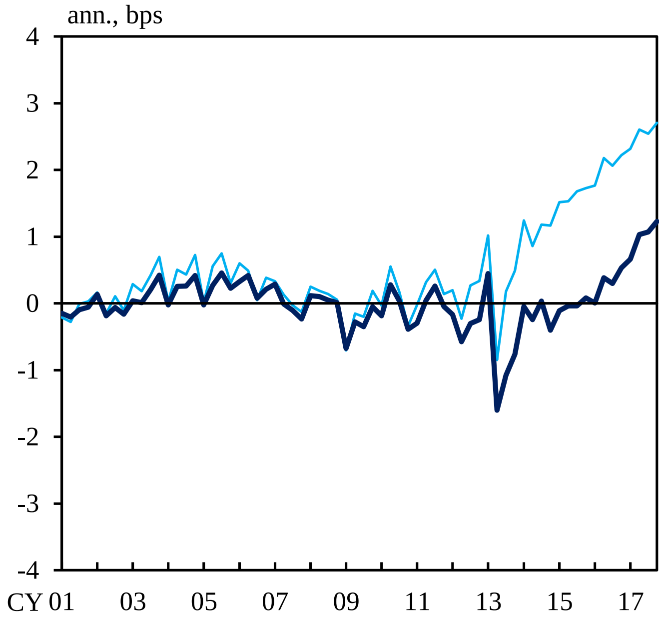
(a) Total Impact



(b) Contribution of Stock Effect



(c) Contribution of Flow Effect

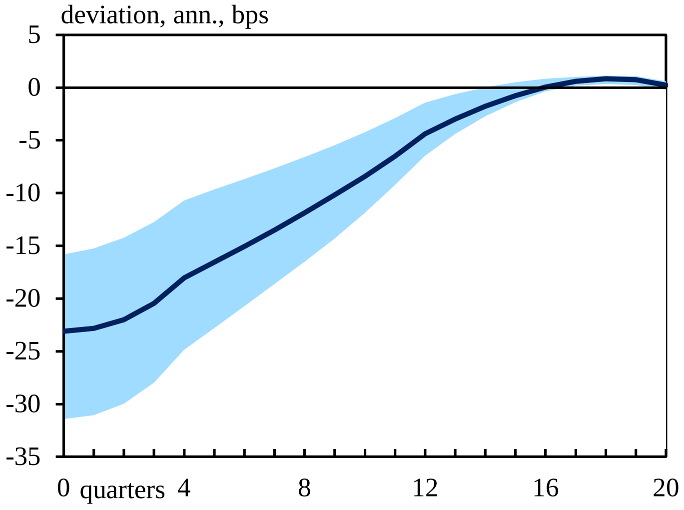


Note: The figures for (2) are calculated by taking the differences between the estimated impacts in the alternative models and the corresponding values in Figure 5(2).

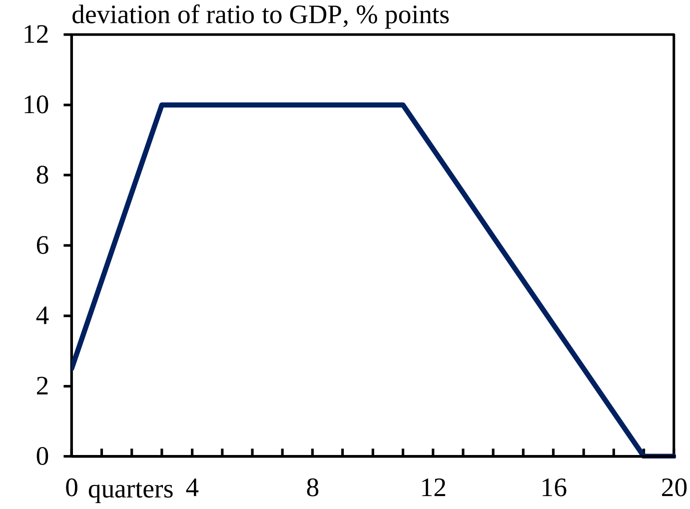
Appendix Figure: Effect of Expectations for Future Long-Term Bond Purchases

(1) Baseline

(a) Long-Term Nominal Interest Rate

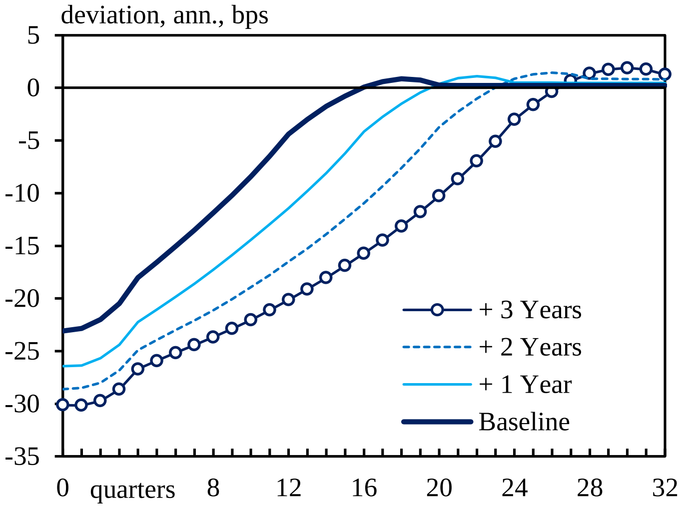


(b) Long-Term Bonds Held by the Central Bank

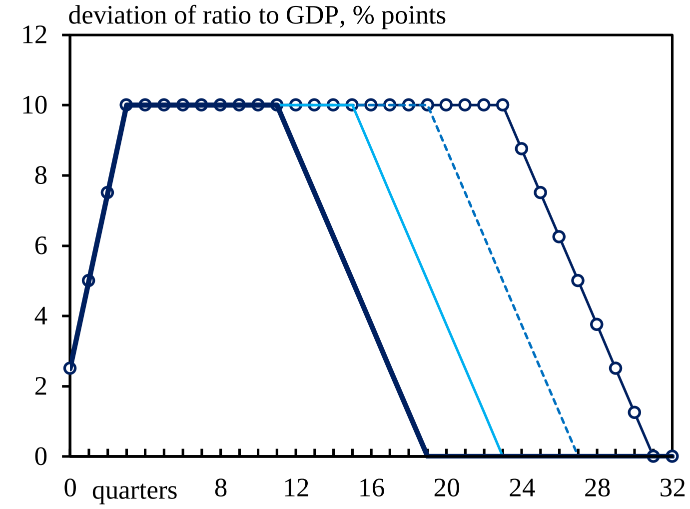


(2) Simulations with Different Length of Bond Holdings

(a) Long-Term Nominal Interest Rate

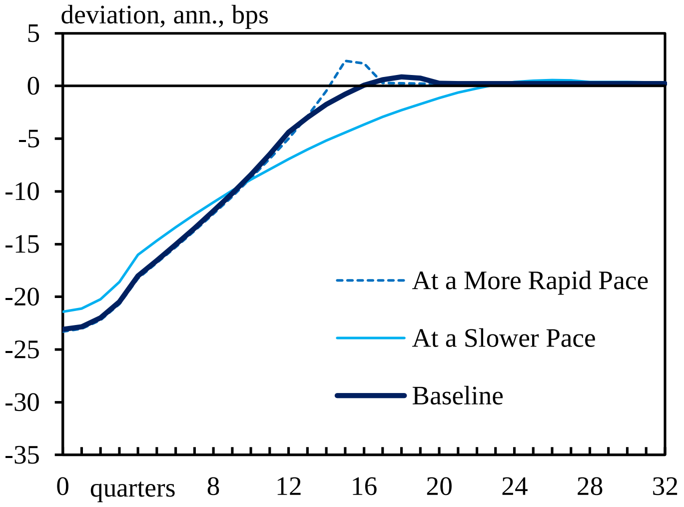


(b) Long-Term Bonds Held by the Central Bank

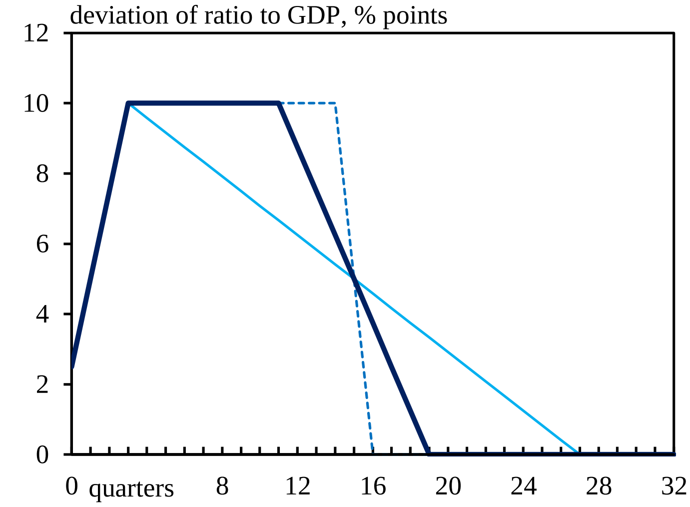


(3) Simulations with a Different Pace of Balance Sheet Adjustment

(a) Long-Term Nominal Interest Rate



(b) Long-Term Bonds Held by the Central Bank



Notes: 1. The series are deviations from the non-stochastic steady state.
2. Each line represents the median of the impulse response, and the shaded areas in (1) represent the 90% intervals of the estimate.