Information Premium and Macro Dynamics

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ABSTRACT: Empirically, a large fraction of the market equity premium is realized on days with significant macroeconomic announcements. Major announcements also have significant and long lasting impact on macroeconomic quantities including consumption, investment, and industrial output. We present a model with production and recursive multiple prior preference to account for the reaction of asset markets and macroeconomic quantities to announcements. Our model generates a macroeconomic announcement premium in the aggregate and in the cross section. It also replicates well the impulse response of macroeconomic quantities to announcements in the data.

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1 Introduction

The paper provide a theory and empirical evidences that macroeconomic announcements carry significant information about the growth prospect of the economy and require a substantial risk compensation on the equity market. We present a production based asset pricing model to explain the macroeconomic announcement premium and its impact on economic growth.

Empirically, a large fraction of equity premium is realized on a small number of trading days with significant macroeconomic announcements (see, for example, Savor and Wilson (2013) and Lucca and Moench (2015)). For example, during the period of 1967-2018, the cumulative return of the S&P500 index in excess of the risk-free rate is 4.28% during the 45 days per year with significant macroeconomic announcements, accounting for 68% of the annual equity premium during this period.

Ai and Bansal (2018) provide a theory for announcement premium. They show that in representative agent models, a necessary and sufficient condition for information revelation to be associated with the realization of equity premium is that preferences satisfies generalized risk sensitivity. The key premise of the Theorem of Generalized Risk Sensitivity in Ai and Bansal (2018) is that revelation of information must contain information about future continuation utility, which can be modeled as information about the prospect of future economic growth. This leaves open the question whether macroeconomic announcements do contain information about future economic growth and whether the information content in macroeconomic announcements can quantitative account for the magnitude of announcement premium in well calibrated asset pricing models. This paper provides empirical evidence on the impact of macroeconomic announcement on real economic growth and and develop a production-based asset pricing model to account for these patterns as well as the macroeconomic announcement premium.

We first present three stylized facts on the impact of macroeconomic announcements. First, a large fraction of the market equity premium is realized on a relatively small number of trading days with pre-scheduled macroeconomic announcements. During the 1967-2018 period, on average, thirty trading days per year have significant macroeconomic announcements. The average stock market excess return is 9.6 bps on announcement days and 0.96 bps on days without major macroeconomic announcements. As a result, the cumulative stock market excess return on the thirty announcement days averages 428% per year, accounting for about 68% of the annual equity premium (626%) during this period. This evidence is consistent with the previous literature (see, e.g., Savor and Wilson (2013) and Ai and Bansal (2018)).

Second, we present evidence for the announcement premium in the cross section of equity returns and demonstrate that the expected return-β relationship is positive and significant on macroeconomic announcement days. We sort portfolios by their β with respect to the market return and show that the expected return-β relationship is positive with a significant slope on announcement days, and close to zero on non-announcement days. Our result is consistent with the previous literature for example, Savor and Wilson (2014) and Wachter and Zhu (2018). Because the slope of the security market line is the market equity premium, the robustness of CAPM coorborate with the evidence for large equity premium on announcement days.

Third, we demonstrate that macroeconomic announcements have significant and long lasting impact on economic growth, including the growth rates of consumption and investment. We use the price changes of the Fed Funds Futures contract on the announcement day to identify the impact of announcements on growth rate expectations. We use the local projection method (Jorda (2005)) to plot the impulse response functions of consumption and investment growth rate with respect to identified macroeconomic announcement shocks. We show that one standard deviation of macroeconmic announcement shocks is associated with 0.1% increases in consumption and 2% increases in investment for up to 12 quarters.

We next develop a general equilibrium model with production to account for the impact of macroeconomic announcements on macroeconomic quantities and asset prices. Our model features a standard production economy with adjustment cost as in Croce (2014). The representative agent has a preference with generalized risk sensitivity modeled through the recursive multiple prior preference of Chen and Epstein (2002). In our model, the aggregate productivity growth is driven by a latent state variable unobservable to investors in the economy. We model macroeconomic announcements as revealing, on a prescheduled basis, signals that are informative about the latent state variable. We calibrate our model and demonstrate that our model is able to account for the significant announcement premium on announcement days, as well as the persistent impact of announcements on future economic growth.

It is important to note that macroeconomic announcements in our model refer to events that reveal information about future economic growth. Therefore, as demonstrated in Figure 4 of Ai and Bansal (2018), our theory can account for the pre-announcement drift as long as information about the content of announcement is revealed to the market ahead of the announcements. Information might be revealed to the market through a variety of mechanisms, for example, investor attention and information acquisition. We do not attempt to study the mechanism through which information might be revealed to the market ahead of the announcements, but as Ai and Bansal (2018), our model allows for the possibility that information may be revealed ahead of announcements to generate a pre-announcement drift.

Related literature Our paper is most related to the recent paper by Ai and Bansal (2018) that take a revealed preference approach and establish the equivalence between the announcement premium and generalized risk sensitivity in an endowment economy. In a related paper, Wachter and Zhu (2018) provide a recursive-preference based model where macroeconomic announcements reveal the probability of disasters. Both of the above papers study endowment economies where consumption and investment do not respond to announcements endogenously. We study production economies and calibrate our model to match the response of consumption with respect to announcements.

Our evidence on the macroeconomic announcement premium is consistent with the previous literature. Savor and Wilson (2013) document that stock market returns and Sharpe ratios are significantly higher on days with macroeconomic news releases in the U.S., Brusa, Savor, and Wilson (2015) provides evidence that a similar phenomenon is true internationally. Lucca and Moench

(2015) provide evidence for the FOMC announcement day premium a pre-FOMC announcement drift. Cieslak, Morse, and Vissing-Jorgensen (2015) provide evidence for significant stock market return over FOMC announcement cycles. Mueller, Tahbaz-Salehi, and Vedolin (2017) document an FOMC announcement premium on the foreign exchange market and attribute it to compensation to financially constrained intermediaries. Our evidence for the announcement premium is consistent with the previous work by Savor and Wilson (2014) and Ai, Han, Pan, and Xu (2020).

More generally, our paper builds on literature on asset pricing with non-expected utility. We refer the readers to Epstein and Schneider (2010) for a review of asset pricing studies with the maxmin expected utility model; Ju and Miao (2012) for an application of the smooth ambiguity-averse preference; Hansen and Sargent (2008) for the related robust control preference. Skiadas (2009) provides an excellent textbook treatment of recursive-preferences and non-expected utility in asset pricing theory.

Our model is also related to the literature on asset pricing in production economies. Kaltenbrunner and Lochstoer (2010) and Croce (2014) developed asset pricing models in production economies with persistent productivity growth. Ai (2010) studies asset pricing in a production economy with learning. Kung and Schmid (2015) develop an endogenous growth model with long-run risks. Ai, Croce, and Li (2011) develop an asset pricing model with intangible capital. None of the above paper studies the impact of macroeconomic announcements on quantities and asset prices.

The rest of the paper is organized as follows. We present our empirical evidence in Section 2. We develop a general equilibrium model with production in Section 3 of the paper. We discuss the quantitative results on the model in Section 4. Section 5 concludes.

2 Empirical evidence

In this section, we summarize several empirical evidence on the impact of macroeconomic announcements on financial markets and the real economy. To demonstrate the significance of these announcements, we focus on a relatively small set of them that are released at the monthly or a lower frequently. Within this category, we select the top five announcements ranked by investor attention by Bloomberg users, which are unemployment/non-farm payroll (EMPL/NFP), producer price index (PPI), Federal Open Market Committee's decision regarding the monetary policy interest rate (FOMC), gross domestic product (GDP) and the Institute for Supply Management's Manufacturing Report (ISM). The five selected announcements constitute forty five days per year for the period of 1961-2018. We summarize our main findings below and provide details about the data construction in Appendix 6.1.

1. A large fraction of the market equity premium is realized on a relatively small number of trading days with pre-scheduled macroeconomic announcements (See also Savor and Wilson (2013) and Lucca and Moench (2015)).

   In Table 1, we report the mean and standard deviation of market excess returns on macroeconomic announcement days and non-announcement days during the 1961–2014 period. The

Table 1: Announcement Premium

	# dyas p.a.	Daily prem.	Daily Std.	Premium p.a.	T-stat
Market	252	2.49	97.55	6.26	2.98
Announcement	45	9.6	102.63	4.28	5
No Announcement	207	0.96	96.36	1.98	1.05
Non-FOMC	40	8.2	102.48	3.25	4.09

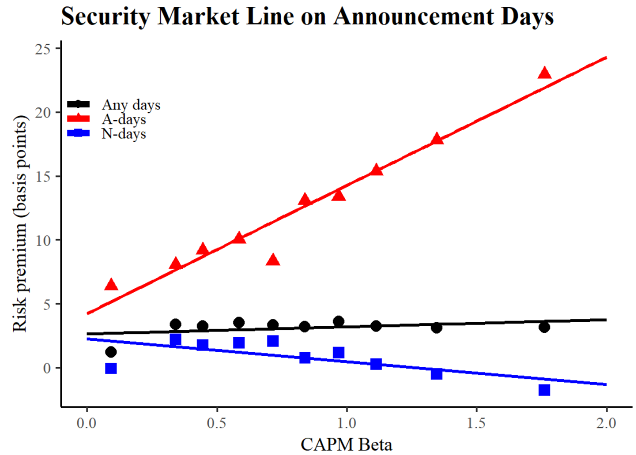
column " # days p.a." is the average number of trading days per annum. The second column is the daily market equity premium on all days, that on all announcement days, that on days with no announcement and that on all non-FOMC announcement days, where non-FOMC announcements include EMPL/NFP, PPI, GDP and ISM announcements defined above. The column "daily std." is the standard deviation of daily returns. The column "premium p.a." is the cumulative market excess returns within a year, which is computed by multiplying the daily premium by the number of event days and converting it into percentage points.

In this period, on average, forty-five trading days per year have significant macroeconomic announcements. At the daily level, the average stock market excess return is 9.6 bps on announcement days and 0.96 bps on days without major macroeconomic announcements. As a result, the cumulative stock market excess return on the forty five announcement days averages 428% per year, accounting for about 68% of the annual equity premium (626%) during this period. The above pattern is robust with or without including FOMC announcement days. As shown in Table, Table 1, the average number of non-FOMC announcement days is 40 during the period of 1961-2014, and the average daily return is 8.2bps on non-FOMC announcement days.

2. The slope of the security market line, that is, the relationship between expected returns and β is positive and significant on announcement and is virtually flat on non-announcement days (see also Savor and Wilson (2014)).

   In Figure 1, we plot the expected return-beta relationship for beta sorted portfolios on announcement days on non-announcement days. We compute trailing one year (i.e. 252 trading day) stock-level beta at a daily frequency using the CRSP dataset. We then construct decile bins by sorting on beta on every first business day of the month. We construct a daily value-weighted excess return and a value-weighted beta for each decile bin. We plot the time-series average of excess returns of the portfolio on announcement days (triangles), that on non-announcement days (squares) and that for all trading days including announcement and non-annoucement days (circles) against portfolio betas. As shown in Savor and Wilson (2014), the expected return-beta relationship is positive and significant on announcement days. Because the slope of the security market line is just the market equity premium, the positive and significant slope is the evidence for a large equity risk premium on announcement days from

Figure 1: Security market line on announcement and non-announcement days



the cross section of stock returns.

3. Macroeconomic announcements have a significant and persistent impact on aggregate consumption and investment.

   To demonstrate the impact of macroeconomic announcement on aggregate quantities, we use the local projection method to plot the impulse response functions of aggregate consumption and investment with respect to macro economic announcement shocks. Specifically, we consider regressions of the form $Y_{t+h} = \beta_h Z_t + \sum_{s=1}^{p} \beta_s^h Y_{t-s} + \epsilon_t$, where Y_t is the outcome variable of interest, for example aggregate consumption or investment and Z_t stands for identified shocks to growth rate expectations contained in macroeconomic announcements at time t. As shown by Jorda (2005), the local projection method avoids making structural assumptions on the data generating process and is robust to model mis-specifications.

   We use asset returns, specifically, the returns on Fed funds futures contract with four months maturity, realized during short announcement windows to identify the impact of announcements on expectations of future economic growth. There are several advantages in using Fed Funds Futures contracts to identify shocks to growth rate expectations. First, changes in Fed Funds Futures contract during a pre-scheduled macroeconomic announcement day is likely to reflect changes in real rate and not inflation. All of the above announcements are pre-scheduled. It is unlikely that the Federal Reserve Bank makes surprise interest rate changes during the short windows of pre-schduled announcements. As a result, changes in Fed Funds Futures during a short announcement window are a good measure of changes in the real interest rate. Second, real interest rates reflect only growth rate expectations in a large class of structural models including the real business cycle model and the New Keynesian model. Stock prices, by comparison, may be affected by other shocks revealed on macroeconomic announcement days, such as shocks to risk premium. Third, Fed Fund Futures is an index of a very liquid market, and therefore allows us to identify the impact of macroeconomic announcements that occur during a short window.

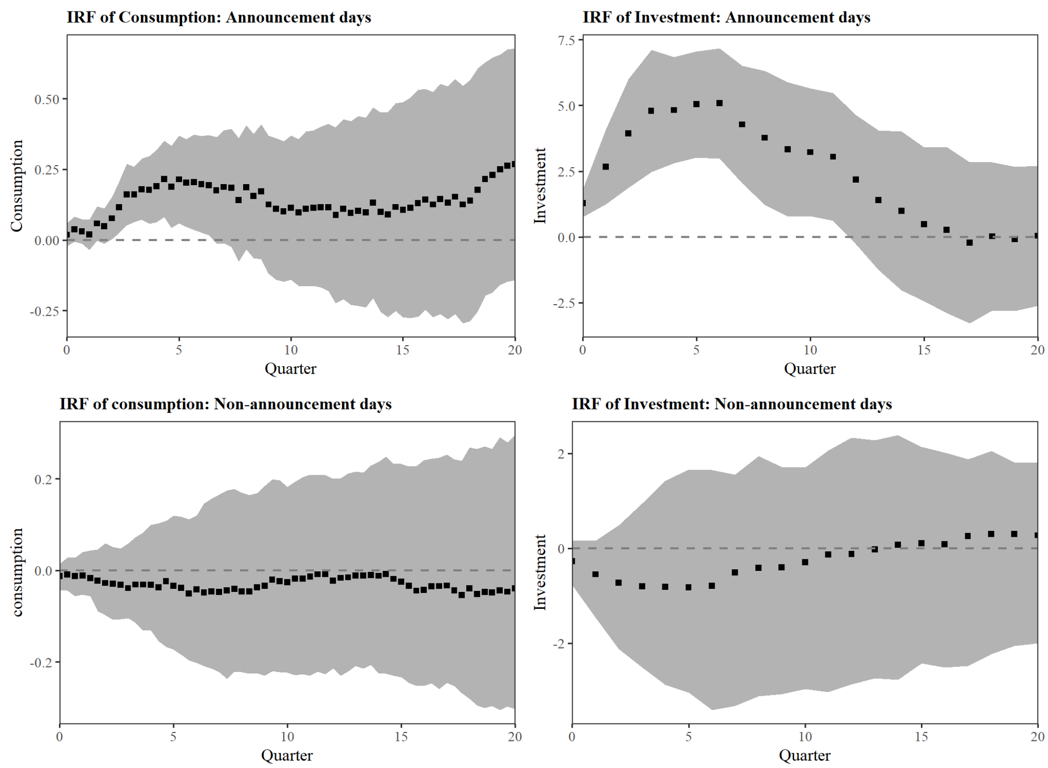


Figure 2: Announcement impact on macroeconomic activities

Results show Jorda regression of form $Y_{t+h} = \beta_h Z_t + \sum_{s=1}^{p} Y_{t-s} + \epsilon_t$. Announcement day shock is Z_{it} the short-term implied rate changes measured as the average of implied rate change in federal funds futures of maturities ranging from two to six months. Multiple announcements in a period are averaged. The announcement shock proxy is standardized using the full times series. Results are reported up to a 20-quarter horizon forward of the announcement. The top row shows the impact of announcement shock on log consumption and log investment, and the bottom rows show the impact of the non-announcement shock on log consumption and log investment. Jorda regression includes 12-month lags for consumption and 4-quarter lags for investment. Top row figures show coefficients on standardized shock proxy as well as their 95% confidence bands. Bottom row panels repeat exercises by randomly selecting non-announcement day shock for each month. Random 100 samples and empirical median and 5%, 95% bands on coefficients for each horizon are reported.

Using shocks to growth rate expectations identified as surprise interest rate increases implied by Fed Funds futures contract, In Figure 2, we plot the impulse response of aggregate consumption (top left panel) and that of aggregate investment (top right panel) with respect to a one-standard deviation of announcement shocks, where announcements include all four top ranked announcements by investor attention except the FOMC announcements. We exclude the FOMC announcements, because changes in the Fed Funds futures contract after FOMC announcement may reflect interest policy changes rather than growth rate expectations. For comparison, in the bottom two panels of Figure 2, we also plot the impulse response functions of one standard deviation of innovations of Fed funds futures contract on non-announcement days. Upon a one standard deviation increase in growth rate expectations upon macroeconomics announcements, consumption increases slowly but persistently by roughly 0.2% in a one-year horizon, and the impact stays at roughly 0.1% after 12 quarters. The increase in investment shows a similar pattern although the magnitude is higher: it increases by about 4% at the one-year horizon and stays at 2% after 12 quarters.

In the next sections, we present a general equilibrium model with production to account for the above facts on the impact of macroeconomic announcements on asset prices and macroeconomic quantities.

3 A production economy with macro announcements

3.1 Model setup

Preferences and technology We consider a representative agent economy where the agent is endowed with a recursive multiple prior preference (Chen and Epstein (2002)). Time is infinite and continuous and all uncertainty in the economy is generated by a probability space $(\Omega, \mathcal{F}, P)$, on which a vector of J Brownian motions $B = [B_1, B_2, \cdots B_J]$ is defined. Let $\{\mathcal{F}_t\}$ be the filtration generated by B. The agent's preference is specified by a constant intertemporal elasticity of substitution (IES) utility function with an IES of ψ and a set of probability measures defined on $(\Omega, \mathcal{F}, P)$, denoted $\mathcal{P}$. That is, the agent compute his time-t utility using:

$$V_t = \inf_{Q \in \mathcal{P}} E_t^Q \left[\int_t^\infty e^{-\beta(s-t)} \frac{1}{1-\gamma} C_s^{1-\frac{1}{\psi}} ds \right]. \tag{1}$$

Here, $\mathcal{P}$ captures the notion of ambiguity aversion (Gilboa and Schmeidler (1989)). That is, the agent is ambiguous about the true data generating process and entertain a set of probability measures to compute the worse-case scenario over $\mathcal{P}$ when ranking stochastic consumption streams. It will be clear that in our model, the infimum is always achieved and we will replace inf with min in the rest of the paper. We specify $\mathcal{P}$ by using a density generator as in (Chen and Epstein (2002)). Let $\kappa = [\kappa_1, \kappa_2, \cdots, \kappa_J]$ be a non-negative vector. The density generator is defined as:

$$\Phi(\kappa) = \left\{ \{z_t\} : z_t = e^{-\frac{1}{2}\int_0^t \upsilon_s ds - \int_0^t \upsilon_s dB_s}, |\upsilon_{j,t}| \le \kappa_j, \textit{ and adapted to } \mathcal{F}_t, \ \forall j, \forall t \right\}. \tag{2}$$

Intuitively, the set $\mathcal{P}$ represents probability distortions and the density generator identifies elements in $\mathcal{P}$ as their Radon-Nikodym derivatives with respect to P. The Radon-Nikodym derivatives are specified using exponential martingales of the form $z_t = e^{-\frac{1}{2}\int_0^t \upsilon_s ds - \int_0^t \upsilon_s dB_s}$ and $\Phi(\kappa)$ is the set of exponential martingales with the restriction $|\upsilon_{j,t}| \leq \kappa_j, \forall j, \forall t$, which requires that the probability distortions must be close to the reference probability measure P.

Output is produced using standard production technology $Y_t = (A_t N_t)^{1-\alpha} K_t^{\alpha}$, where A_t is a labor augmenting technology that follows a diffusion process

$$dA_t = A_t \left[(\mu + x_t)\, dt + \sigma_A dB_{A,t} \right].$$

In the above equation, μ is the long-run average of productivity growth andx_t represents deviations from trend growth and is modeled by a continuous-time AR(1) (Ornstein–Uhlenbeck) process with the law of motion

$$dx_t = -a x_t dt + \sigma_x dB_{x,t},$$

and $[B_{A,t}, B_{x,t}]$are standard Brownian motions independent of each other. We assume inelastic labor supply and normalize $N_t = 1$ for all t. The capital accumulation technology is:

$$dK_t = (I_t - \delta K_t)\, dt,$$

where I_t represents investment goods produced using a standard quadratic adjustment cost function $G(I_t, K_t) = \frac{1}{2} g_0 \left(\frac{I_t}{K_t} - i^* \right)^2 K_t$ with parameter h, and i^* is set to be the steady-state level of investment. The aggregate resource constraint is then written as:

$$C_t + I_t + G(I_t, K_t) = (A_t N_t)^{1-\alpha} K_t^{\alpha}.$$

Information and learning under ambiguity The agents in the economy do not observe the true value of expected productivity growth x_t but can use two sources of information to update their belief about x_t. First, the realized productivity process contain information about x_t, and second, macroeconomic announcements reviews the true value of x_t periodically at pre-scheduled times $t = T, 2T, 3T, \cdots$.

Because the productivity A_t is observable and x_t is not, we assume that this agent is ambiguous about the Brown motion that drives the dynamics of x_t, $B_{x,t}$ but not about shocks to productivity, $B_{A,t}$. In this case, $\Phi(\kappa)$ can be represented as

$$\Phi(\kappa) = \left\{ \{z_t\} : z_t = e^{-\frac{1}{2}\int_0^t \upsilon_s ds - \int_0^t \upsilon_s dB_{x,s}}, |\upsilon_t| \leq \kappa, \forall t \right\}, \tag{3}$$

where κ and υ are scalars and z_t distorts only the distribution of $B_{x,t}$ but not that of $B_{A,t}$. By the results in (Chen and Epstein (2002)), the set of probabilities specified in (3) satisfies rectangularity and the decision rule generated from (1) is dynamically consistent.

To evaluate the agent's continuation utility defined in (1), we follow the procedure outlined in

(Chen and Epstein (2002)). First, we take a probability measure, indexed by $\{z_t\}$ in our formulation and compute the conditional distribution of x_t under the conditional probability using Bayes rule (Kalman filter). We evaluate the conditional expectation in (1) and minimize over all such conditional expectations generated from the family of probability distributions from $\Phi(\kappa)$.

Because the elements in $\Phi(\kappa)$ are identified by an adapted process $\{\upsilon_t\}$, we denote the probability measure generated this way as P^{υ}. By the Girsanov theorem, $B_{x,t}$ is a Brownian motion with drift under probability P^{υ}: $dB_{x,t} = dB^{\upsilon}_{x,t} - \upsilon dt$, where $B^{\upsilon}_{x,t}$ is a standard Brownian motion under the distorted probability P^{υ}. The law motion of x_t under P^{υ} is $dx_t = (-ax_t - \upsilon_t\sigma_x)\, dt + \sigma_x dB_{x,t}$. Therefore, in the interior of $(nT, (n+1)T)$, the conditional distribution of x_t is Gaussian with mean $\hat{x}_t$ and variance χ_t under the probability P^{υ}. This conditional distribution can be calculated recursively from the standard Kalman filter:

$$d\hat{x}_t = -\left(a\hat{x}_t + \upsilon_t\sigma_x\right) dt + \frac{\chi_t}{\sigma_A} d\tilde{B}^{\upsilon}_{A,t},$$

where $\tilde{B}^{\upsilon}_{A,t}$ is the innovation process relative to the belief under P^{υ}, which is defined as

$$d\tilde{B}^{\upsilon}_{A,t} = \frac{1}{\sigma_A}\left[\frac{dA_t}{A_t} - (\mu + \hat{x}_t)\, dt\right].$$

and χ_t is the posterior variance given by: $\chi_t = \frac{\sigma_x^2\left(1-e^{-2\hat{a}t}\right)}{(\hat{a}-a)e^{-2\hat{a}t}+a+\hat{a}}$, where $\hat{a} = \sqrt{a^2 + (\sigma_x/\sigma_A)^2}$. At announcements, because the true value of x_t is revealed, the posterior mean $\hat{x}_t$ is set to it true value and the posterior variance is set to zero: $\hat{x}_t = x_t$, $\chi_t = 0$ for $t = nT$.

3.2 Asset pricing

Solution to the planner's problem Let $V(A, \hat{x}, t, K)$ be the value function for the social planner's problem. The social planner's utility maximization problem can be written as

$$\begin{aligned}
V(A, \hat{x}, t, K) = \max_{\{C_{t+s}, I_{t+s}\}} \min_{\{\nu_{t+s}\}} E^{\nu}&\left[\int_0^{\infty} e^{-\beta s}\frac{1}{1-\gamma} C_{t+s}^{1-\frac{1}{\psi}} ds\right] \\
s.t. C_{t+s} + I_{t+s} + G\left(I_{t+s}, K_{t+s}\right) &= \left(A_{t+s}N_{t+s}\right)^{1-\alpha} K^{\alpha}_{t+s} \\
dK_{t+s} &= \left(I_{t+s} - \delta K_{t+s}\right) ds \\
dA_{t+s} &= A_{t+s}\left[(\mu + \hat{x}_{t+s})\, dt + \sigma_A d\tilde{B}^{\upsilon}_{A,t+s}\right] \\
d\hat{x}_{t+s} &= -\left(a\hat{x}_{t+s} + \upsilon_{t+s}\sigma_x\right) dt + \frac{\chi_{t+s}}{\sigma_A} d\tilde{B}^{\upsilon}_{A,t+s} \\
|\nu_{t+s}| &\leq h,
\end{aligned}$$

where the notation E^{ν} stands for the expectation operator under the probability measure generated by the density associated with the choice of $\{\nu_t\}$. A convenient property of the (Chen and Epstein (2002)) formulation of ambiguity aversion is that the minimizing probability measure can be identified before solving for the optimal consumption and investment policies. It is the most pessimistic probability measure that sets $\nu_t = -h$ for all t. As a result, in the interior of $(nT, (n+1)T)$, the value function must satisfy the following HJB:

$$\beta V(A_t, \hat{x}_t, t, K_t) = \max \left\{ \frac{1}{1-\frac{1}{\psi}} C_t^{1-\frac{1}{\psi}} + \mathcal{L}V(A_t, \hat{x}_t, t, K_t) \right\}, \tag{4}$$

where $\mathcal{L}V(A_t, \hat{x}_t, t, K_t) = \lim_{\Delta \to 0} \frac{1}{\Delta} E_t^{-h} [V(A_{t+\Delta}, \hat{x}_{t+\Delta}, t+\Delta, K_{t+\Delta}) - V(A_t, \hat{x}_t, t, K_t)]$, where E^{-h} indicates that the expectation is taken with respect to the probability measure obtained by setting $\nu_t = -h$ for all t. In addition, at announcement times, $t = T, 2T, 3T, \cdots$, the value function satisfies $V(A_{nT^-}, \hat{x}_{nT^-}, nT^-, K_{nT^-}) = E[V(A_{nT^+}, \hat{x}_{nT^+}, nT^+, K_{nT^+})]$. We denote the policy functions of the social planner's problem as $C(A, \hat{x}, t, K)$ and $I(A, \hat{x}, t, K)$.

Stochastic discount factor In our economy, the standard welfare theorems apply and the stochastic discount factor can be computed from the marginal utility of the representative agent: $e^{-\beta t} C_t^{-\gamma}$. Let $q(A_t, \hat{x}_t, t, K_t)$ be the Tobin's q of the representative firm. Given the functional form of the quadratic adjustment cost, standard q theory relationship implies that

$$q(A_t, \hat{x}_t, t, K_t) = \left(1 + g_0 \left(\frac{I(A_t, \hat{x}_t, t, K_t)}{K_t} - i^*\right)\right) \tag{5}$$

$$= E_t^{-h} \left[\int_0^\infty e^{-(\beta+\delta)s} \left(\frac{C_{t+s}}{C_t}\right)^{-\frac{1}{\psi}} \left(\alpha \left(\frac{A_{t+s} N_{t+s}}{K_{t+s}}\right)^{1-\alpha} - G_K(I_{t+s}, K_{t+s}) \right) ds \right]. \tag{6}$$

Note that the expectation is taken with respect to the distorted probability measure obtained by setting $\nu_t = -h$ for all t. Intuitively, the term $\left(1 + g_0 \left(\frac{I(A_t, \hat{x}_t, t, K_t)}{K_t} - i^*\right)\right)$ is the marginal cost of investment, and the term is the present value of the marginal benefit of investment: new investment add to the existing capital stock, which depreciate at rate δ, and $\alpha \left(\frac{A_t N_t}{K_t}\right)^{1-\alpha} - G_K(I_t, K_t)$ is the marginal benefit of one unit of capital in period t.

Let $\{z_t\}_{t=0}^\infty$ be the exponential martingale associated with the worst case probability measure. Equation (5) can be written in terms of the objective probability measure:

$$q(A_t, \hat{x}_t, t, K_t) = E_t^{-h} \left[\int_0^\infty e^{-(\beta+\delta)s} \frac{z_{t+s}}{z_t} \left(\frac{C_{t+s}}{C_t}\right)^{-\frac{1}{\psi}} \left(\alpha \left(\frac{A_{t+s} N_{t+s}}{K_{t+s}}\right)^{1-\alpha} - G_K(I_{t+s}, K_{t+s}) \right) ds \right]. \tag{7}$$

We provide the expression for z_t in Equation (19) in Appendix 6.2.

Preference for early resolution The results from Ai and Bansal (2018) imply that the (Chen and Epstein (2002)) preference satisfies generalized risk sensitivity and will be able to generate an equilibrium announcement premium. As noted in (Ai and Bansal (2018)), generalized risk sensitivity does not necessarily imply preference for early resolution of uncertainty. The (Chen and Epstein (2002)) preference with rectangularity is indifferent between the timing of resolution of uncertainty

Table 2: Parameters

Parameter	Value	Description
β	0.01	discount rate
ψ	1.5	risk aversion
h	20	ambiguity aversion
μ	1.5%	average productivity growth
a	0.02	mean reversion in productivity growth
σ_x	0.18%	STD of long-run productivity growth
σ_A	5%	STD of short-run productivity growth
g_0	21	Adjustment cost
i^*	7%	steady-state investment-capital ratio
T	$\frac{1}{12}$	length of announcement cycle (in years)

This table displays annualized parameter values used in the main model.

(see Ai, Bansal, Guo, and Yaron (2020)). Our model therefore provides an example that generates the announcement premium without assuming preference for early resolution of uncertainty.

4 Quantitative implications

In this section, we calibrate our model to evaluate its implications on the impact of the macroeconomic announcement premium on equity market returns as well as macroeconomic quantities.

Parameter values We choose an IES of 1.5 as in standard long-run risk models and set the discount rate $\beta = 0.01$ to match the average risk-free interest rate in the U.S. in the post-war period. We set the average productivity growth $\mu = 1.5\%$ in our model to match the average economic growth rate and the standard deviation of productivity, $\sigma_A = 5\%$ to match the standard derivation of the growth rate of output for the same sample. We set the mean reversion parameter of productivity growth $a = 2\%$ so that the first-order auto-correlation of annual consumption growth rate implied by our model matches its data counterpart of 49%. We choose the volatility of the persistent component of productivity growth, $\frac{\sigma_x}{\sigma_A} = 3.6\%$ as in standard long-run risk based production models such as Ai, Croce, and Li (2011). We choose the adjustment cost coefficient $\eta = 21$ to match the average annual market equity premium of 3.71% with a financial leverage of 3. We set the steady state investment-to-capital ratio $i^* = 7\%$. We choose the ambiguity aversion parameter $h = 20$ to match the average announcement premium. We list the calibrated parameter values in Table 2.

Aggregate moments In Table 3, we show that quantitatively, our model is broadly comparable to leading production-based asset pricing models in terms of matching conventional macroeconomic

Table 3: Aggregate moments

Moments	Description	Model	Data
$E\left[\frac{C_{t+1}}{C_t}\right]$	Average consumption growth	1.8%	2.0%
$Std\left[\frac{C_{t+1}}{C_t}\right]$	Standard deviation of consumption growth	2.89%	2.93%
$Std\left[\frac{I_{t+1}}{I_t}\right]$	Standard deviation of investment growth	16.4%	2.89%
$E\left[R_M - R_f\right]$	Market equity premium	3.71%	5.75%
$Std\left[R_M - R_f\right]$	Standard deviation of market excess return	15.95%	19.42%
$E\left[R_f\right]$	Average risk-free interest rate	1.72%	0.86%
$Std\left[R_f\right]$	Standard deviation of risk-free rate	0.43%	0.97%

This table displays annualized parameter values used in the simulations. Appendix **??** summarizes the details of the numerical and calibration procedures.

moments and asset prices. In our production economy, the calibrated parameter values are similar to standard production economies such as Kaltenbrunner and Lochstoer (2010) and Croce (2014). We make several observations. First, our model generates an volatile pricing kernel despite the low volatility consumption growth. The volatility of consumption growth in our model is comparable to that in the data. Thanks to the generalized risk sensitivity, modeled as recursive multiple prior preferences, our model features a volatile stochastic discount factor, which generates an annualized market equity premium of 3.71% per year. In calculating the market equity premium, we assume a financial leverage, defined as the ratio of debt to equity of 100% as in Croce (2014).

Second, our model features a significant volatility of market returns. Generating a volatile return on the claim to corporate profit is a well-know difficulty in production based asset pricing models, as highlighted in Kaltenbrunner and Lochstoer (2010), Croce (2014) and Ai, Croce, and Li (2011). The formulation of the recursive multiple prior preference plays an important role in generating this non-trivial volatility in equity market returns. When agents do not observe the true value of the state variable x_t, ambiguity aversion implies that the minimizing probability chooses the worse-case scenario, which is associated with constant negative drift in the expected growth of the economy. As the expected growth become increasing pessimistic, the price-to-dividend ratio drops gradually, until the belief is corrected at the next announcement. As a result, the price-to-dividend ratio for the claim to the representative firm exhibits volatile movements between announcements, which account for the volatility of equity returns.

Third, our model also features a low and smooth risk-free interest, consistent with empirical evidence. The low volatility of interest rate is the consequence of the high IES of preferences. In our model, expected growth rate under the pessimistic belief changes frequently, it drifts downwards after announcements and resets to the true value of x_t upon announcements. Despite this frequent changes in expected growth rate, interest rates remains smooth because of the high IES. The aspect of our calibration inherits properties of the long-run risk models.

Finally, volatility of investment in model is lower than its data counterpart. As shown in Croce (2014), simultaneously accounting for the high volatility of investment and high level of equity premium is a well-known difficulty in long-run risk based production economies. The reason is that a high adjustment cost is typically needed to generate a significant reaction of equity premium with respect to productivity shocks, and therefore an equity risk premium. However, a high adjustment cost also dampens the volatility of investment in the model. Various solutions has been proposed to resolve this tension, for example, learning and heterogeneity in productivity (Ai, Croce, Diercks, and Li (2018)) and agency frictions (Tong and Ying (2020)). Because modeling the volatility of investment is not the focus on our paper, we abstract from these features.

Impact on macroeconomic quantities The premise of the Theory of Generalized Risk Sensitivity is that to generate an announcement premium, information revelation must impact the prospect of future economic growth, which is encoded in continuation utility in representative agent models. In our production economy, the information revealed in macroeconomic announcement impact future economic growth through investors' policy functions.

Figure 3: Impulse response functions implied by the model

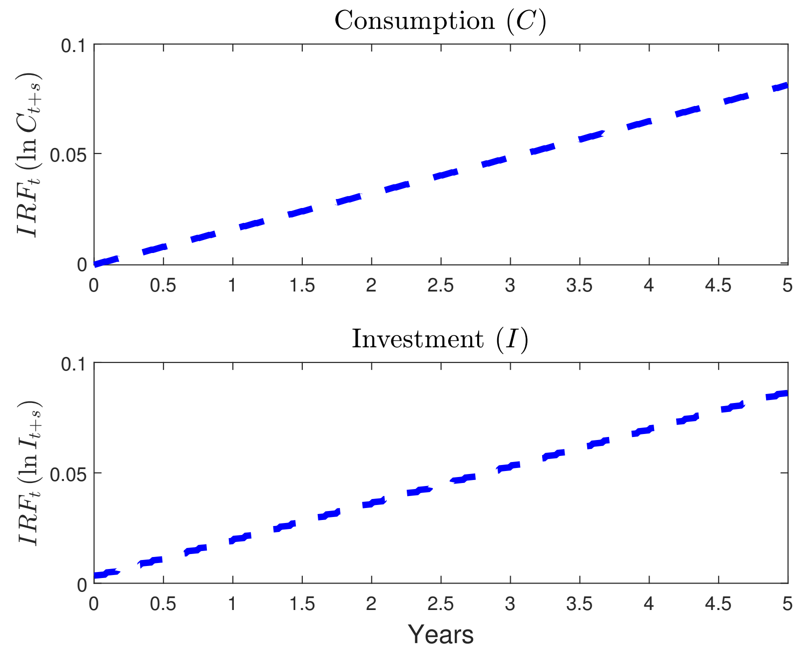


Figure 3 plots the model implied impulse response function for a one-standard deviation announcement shock for consumption (top panel) and investment (bottom panel).

In Figure 3, we plot the impulse response functions of the rate of consumption and investment from our model with respect to one-standard-deviation of announcement surprise. We define the impulse response function of consumption at time t, denoted $IRF_t\,(\ln C_{t+s})$ as the expected consumption growth rate s period ahead conditioning on a one-standard-deviation positive shock in

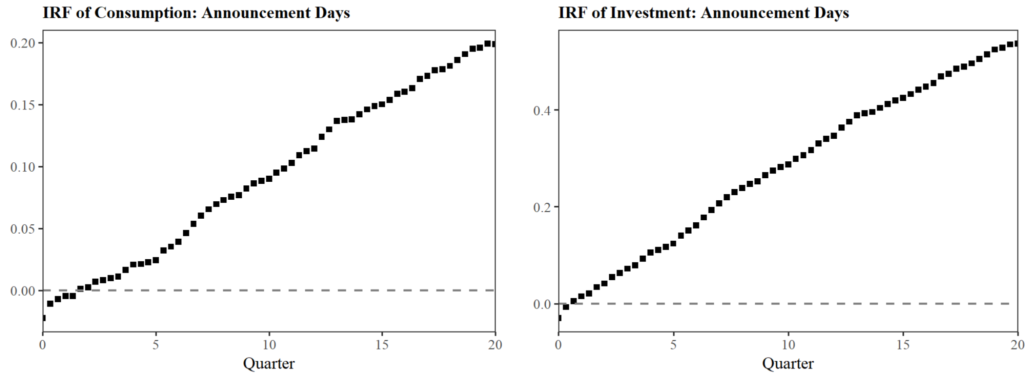


Figure 4: Announcement impact on macroeconomic activities inside the model
Results show Jorda regression of form $Y_{t+h} = \beta_h Z_t + \sum_{s=1}^{p} Y_{t-s} + \epsilon_t$. Announcement day shock Z_{it} is the change in risk-free rate. The announcement shock proxy is standardized using the full times series. Results are reported up to a 20-quarter horizon forward of the announcement. The top row shows the impact of announcement shock on log consumption and log investment, and the bottom rows show the impact of the non-announcement shock on log consumption and log investment. Jorda regression includes 12-month lags for consumption and 4-quarter lags for investment. Top row figures show coefficients on standardized shock proxy. Bottom row panels repeat exercises by randomly selecting non-announcement day shock for each month.

announcement surprise:

$$IRF_t\left(\ln C_{t+s}\right) = E\left[\ln C_{t+s} - \ln C_{t^-} | A_{t^-}, \hat{x}_{t^-} + \epsilon, q_{t^-}, K_{t^-}\right],$$

where $(A_{t^-}, \hat{x}_{t^-}, \chi_{t^-}, K_{t^-})$ is the steady state value of state variables, and t^- stands for the instant right before an announcement. The shock ϵ stands for the posterior belief of the agent after a one-standard deviation shock upon the upcoming announcement. In our model, announcements reveal the true value of the latent state variable x_t, and therefore the standard deviation caputured by ϵ is the same as the standard deviation of the posterior mean, $\hat{x}_t$. We define the impulse response function of investment in the same way.

It is straightforward to replicate the the local projections using model simulated data. We aggregate consumption and investment from our continuous time model to the quaterly level, and we use the local projection method to compute model implied impulse response functions from model simulated data, which we plot in Figure 4. Note that in the model, both consumption and investment increases after a positive news shock on announcement days, and this effect continues persistently into the future after 20 quaters. This pattern of impulse response is quite similar to the ones in Figure 2 in Section 2 of the paper.

Announcement premium In our model, announcements are pre-scheduled at time $t = 0, T, 2T, \cdots$. In the steady-state equilibrium, the equilibrium value and policy functions repeat themselves after every T period, for example, for all t and for all $(A, \hat{x}, K)$, the Tobin's q satisfies $q\left(A, \hat{x}, t, K\right) = q\left(A, \hat{x}, nT + t, K\right)$. For simplicity, we focus on one announcement cycle between $[0, T]$. To understand the asset pricing implications of the model, we first derive an expression for the stochastic discount factor. Equation (7) implies that the SDF of our model can be written as $e^{-\beta s}\frac{z_{t+s}}{z_t}\left(\frac{C_{t+s}}{C_t}\right)^{-\frac{1}{\psi}}$. In Appendix 6.2, we show that the law of motion of z_t can be written as:

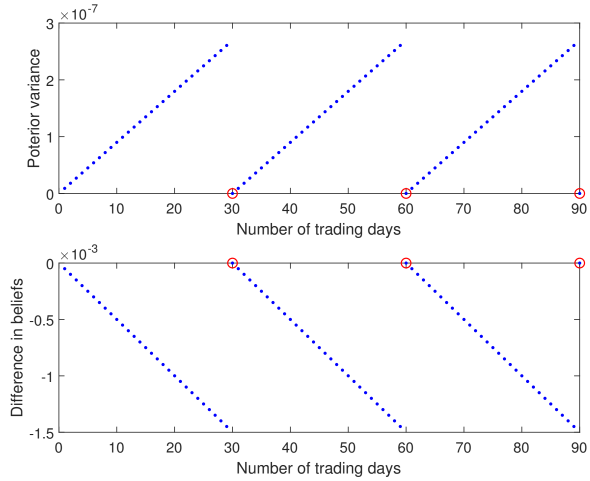
$$dz_t = -z_t \frac{\Delta_t}{\sigma_A} d\tilde{B}_t,$$

where $\Delta_t = E_t^{-h}[x_t] - E_t[x_t]$ is the difference between the posterior belief about x_t under the objective measure and that under the worst-case probability measure. In addition, $d\tilde{B}_t = \frac{\Delta_t}{\sigma_A}dt + d\tilde{B}_t^v$ is a Brownian motion under the objective measure. Therefore the instantaneous risk premium for the representative firm can be written as

$$-Cov_t\left(\frac{d\left[z_t C\left(A_t, \hat{x}_t, t, K_t\right)^{-\frac{1}{\psi}}\right]}{z_t C\left(A_t, \hat{x}_t, t, K_t\right)^{-\frac{1}{\psi}}}, \frac{dq\left(A_t, \hat{x}_t, t, K_t\right)}{q\left(A_t, \hat{x}_t, t, K_t\right)}\right). \tag{8}$$

In Figure 5, we plot the trajectories of posterior variance χ_t (top panel) and the difference in belief Δ_t (bottom panel) for three announcement cycles. The circles indicate announcement day. Note that at announcements, the true value of x_t is revealed and therefore both the posterior variance χ_t and the difference in belief Δ_t drops to zero. Note that Δ_t is a measure of the distance between the objective measure and the pessimistic measure, and therefore a measure of ambiguity about x_t. As t increases, the Markov state variable x_t drifts aways from it previous value. Investors in the eonomy do not observe the true value of x_t and can only learn from the observed output. As a result, the posterior variance χ_t increases. In addition, as posterior variance increases, the probability distortion also accumulates over time. Δ_t drops below zero and decreases over time, indicating the ambiguity about x_t also builds up over time and investors become increasingly pessimistic. At the next announcement, both χ_t and Δ_t are reset to zero, because the announcement again reveals the true value of x_t.

Figure 5: Divergence of beliefs



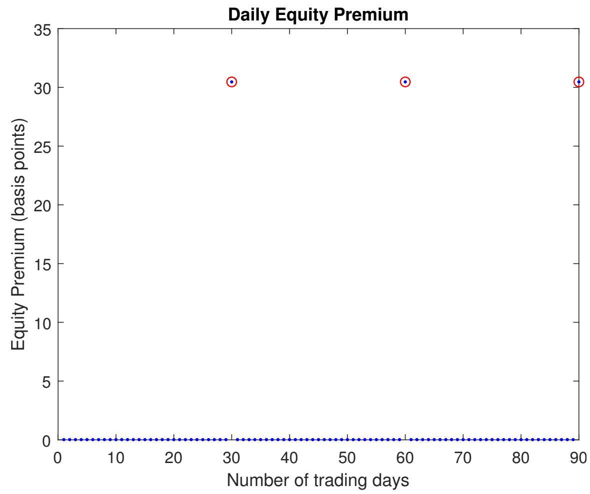
This figure shows the IRF of aggregate consumption and output in the model.

In our model, the magnitude of announcement premium is determined by the magnitude of the probability distortion and is an increasing function of Δ_t. Due to generalized risk sensitivity, our model generates a non-trivial announcement stochastic discount factor (A-SDF). Let T^- be the instant right before the announcement, and let T^+ be the instant right after the announcement, the A-SDF is written as: $\frac{Z_T^+}{Z_T^-}\left(\frac{C_T^+}{C_T^-}\right)^{-\frac{1}{\psi}}$, and Tobin's q at announcement satisfies the following present value relationship:

$$q\left(A_T, \hat{x}_{T^-}, T^-, K_T\right) = \left(\frac{Z_T^+}{Z_T^-}\left(\frac{C\left(A_T, x_T, T^+, K_T\right)}{C\left(A_T, \hat{x}_{T^-}, T^-, K_T\right)}\right)^{-\frac{1}{\psi}}, q\left(A_T, x_T, T^+, K_T\right)\right). \tag{9}$$

In the above equation, because the announcement fully reveals the true state variable x_T, at T^- all policy functions depends on the posterior mean at T^-, $\hat{x}_{T^-}$. At time T^+, after the announcement, the value of x_T is publicly known and all policy functions depends on x_T. In Figure 6, we plot the daily risk premium for non-announcement days with dots and that for announcement days with circles. The model matches the patterns in the data quite well: the announcement day return averages about 30 basis point per day, and the none-announcement day return average return is below 1 basis point. The significant announcement premium in the model is due to the accumulation of distortion of belief, Δ_t over time.

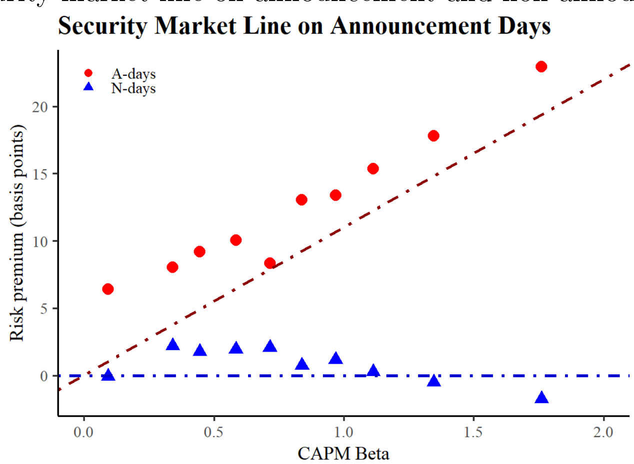
Figure 6: Risk-premium on announcement and non-announcement days



This figure shows the IRF of aggregate consumption and output in the model.

In Figure 7, we plot the model implied security market line on announcement days (solid line) and that on non-announcement days (dash dotted line). Note that the expected return-beta relationship, or the slope of the security market line is the market equity premium. In Figure 7, the slope of the security market line for announcement days is positive and significant, as in the data. That for non-announcement days, however, is almost flat, because the risk premium on non-announcement days is almost zero.

Figure 7: Security market line on announcement and non-announcement days



Consumption response and announcement premium Consumption-based asset pricing models can generate an announcement premium for two reasons: covariance of return with respect to consumption growth and covariance of return with respect to continuation utility. Ai and Bansal (2018) assume that consumption does not respond to announcements during a short announcement window and demonstrate that the announcement premium identifies generalized risk sensitivity in preferences.

In our production economy, consumption is allowed to respond to announcements, and in principle, the endogenous response of consumption with respect to announcements itself can generate a correlation between consumption and announcement returns. However, as we demonstrate below, this endogenous response is quantitatively too small to generate a significant announcement premium. In addition, the sign of the announcement premium due the endogenous response of consumption is typically negative.

Equation (9) implies that via a log-linear approximation, the announcement premium can be written as:

$$\frac{1}{\psi}\left[\frac{\partial \ln C\left(A_T,\hat{x}_T,T,K_T\right)}{\partial \ln \hat{x}_T}\right]\left[\frac{\partial \ln q\left(A_t,\hat{x}_t,t,K_t\right)}{\partial \ln x_t}\right]+\left[\frac{\partial \ln Z_T^{+}}{\partial \ln \hat{x}_t}\right]\left[\frac{\partial \ln q\left(A_t,\hat{x}_t,t,K_t\right)}{\partial \ln \hat{x}_t}\right]. \tag{10}$$

The first term reflects the impact of endogenous response of consumption on announcement premium, and the second term reflect the effect of generalized risk sensitivity on announcement premium.

In Figure 8, we plot the impulse response functions (IRF) for consumption (top panel), continuation utility (second panel), SDF (third panel), and Tobin's Q with respect to a one-standard deviation of innovations in announcements with respect to x_t, where the horizontal axis is the number of years after announcement, and the vertical axis is log deviations from steady state. We make several observations here. First, upon a positive news about future, consumption responds negatively and the first term in (10) is negative. An IES of $\psi = 2$ in our calibration implies that the substitution effect dominates the income effect and consumption drops upon postive news about productivity in the future. Due to the resource constraint, a drop in consumption must be associated with an increase in investment as output does not respond instantaneously to news. Note that Tobin's Q is an increasing function of investment as shown in equation (5). As a result, consumption and Tobin's Q move in opposite directions upon a positive news about future, and the endogenous response of consumption contribute negatively to the announcement premium.

Second, both Tobin's Q and continuation utility respond positively to news, generating a positive announcement premium. Because the minimizing probability must be negatively correlated with continuation utility, it is negatively correlated with Tobin'q and therefore results in a positive announcement premium. A positive news about future is always associated with an increase in continuation utility. Due to a strong generalized risk sensitivity, the innovations in SDF is mostly dominated by the changes in continuation utility, i.e. the second term in (10). As shown in Figure 8, continuation utility responds positively to news and SDF responds negatively to news. In addition, the magnitude of the response of continuation utility and SDF with respect to the announcement is many times higher than that of consumption. Consequently, the second term in equation (10), the part of the announcement premium that comes from generalized risk sensitivity dominates and result in a significant equity premium on announcement days.

The fact that endogenous response of consumption contributes negatively to announcement premium does not depend on whether the income or the substitution effect dominates. It is merely the

Figure 8: **Impulse Response Functions**

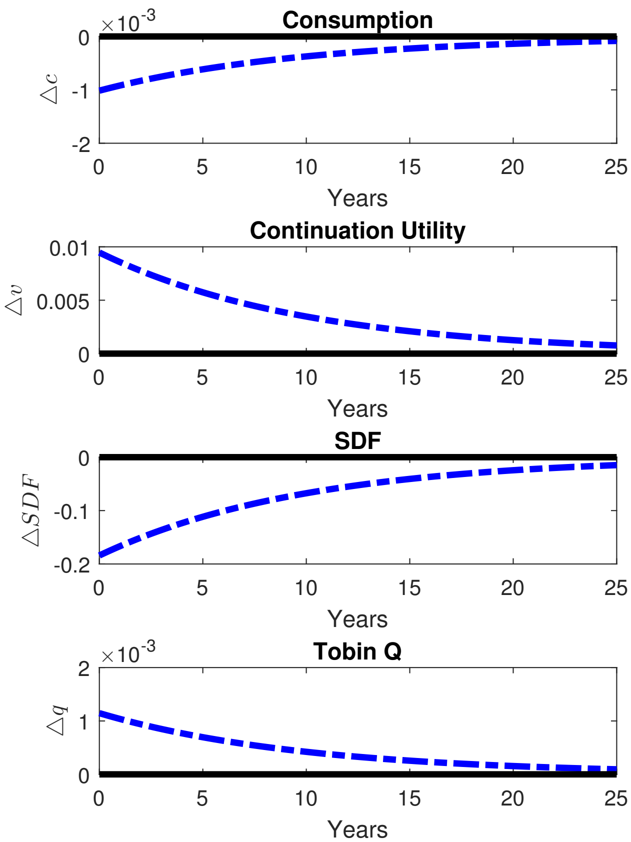


Figure 8 plots the impulse response functions of consumption, continuation utility, SDF and Tobin's Q with respect to one standard deviation in innovation of announcement in the production economy with $\gamma = 20$ and $\psi = 2$.

implication of the resource constraint and the optimality condition of investment (5). The resource constraint implies that consumption and investment must move in opposite directions, and the convexity of the adjustment cost function implies that Tobin's Q is a monotone function of investment. As a result, the immediate response of consumption and Tobin's Q with respect to announcements must be in opposite directions. Of course, over time, a positive news is often associated with increases in both consumption and investment in the future, but this channel does not affect the announcement premium unless the utility features generalized risk sensitivity. In other words, the announcement premium generated from the endogenous response of consumption remains negative for low IES when income effect dominates. In the case of low IES, the income effect dominates, consumption rises after the announcement and investment and Tobin's Q drop. Again, the negative co-movement between consumption and Tobin's produces a negative announcement premium.

5 Conclusion

We show that major announcements have significant and long lasting impact on macroeconomic quantities including consumption, investment, and industrial output. We present a model with production and generalized sensitivity to account for the reaction of asset markets and macroeconomic quantities to announcements. Our model generates a macroeconomic announcement premium in the aggregate and in the cross section. It also replicates well the response of macroeconomic quantities to announcements in the data.

6 Appendix

6.1 Data appendix

On data sources and coverage.

Table 6.1 on page 22 summarizes all data used throughout the paper of their sources, sample coverages, frequencies, and usages. Five major announcements(e.g. NFP, PPI, FOMC, GDP, and ISM) are selected based on the five events with the highest relevance ratings reported by Bloomberg's Economic Calendars(also known as ECO) as of 2017. The ECO dataset collects more than 160 major announcements that relate to the economy and capital markets in general, mostly released by various entities such as government agencies, central banks, data collectors, and market analyst institutions. Bloomberg users may select to receive alerts on any subset of various announcements provided on the ECO platform, where the relevance rating is computed as a percentile based on the frequency of users setting alerts on announcements. The relevance rating is updated to reflect the popularity as of the date accessed, and the historical values(i.e. ranks in the past) are not presented to the users. ECO dataset begins in late 1996, where all five announcements of interest start considerably earlier. Therefore, we obtain announcement dates information from the respective agencies responsible for each announcement via Federal Reserve Economic Data (FRED) platform which goes back further into the 1950s for announcements date back further.

Data	Source	Items
Announcements dates	BLS via FRED	Nonfarm Payroll(NFP)
	BLS via FRED	Producer Price Index(PPI)
	FRB via FRED	Federal Open Market Committee(FOMC)
	BEA via FRED	Gross Domestic Product(GDP)
	ISM representative	Institute for Supply Management(ISM) Manufacturing
Announcements survey	Bloomberg	Economic Calendar(ECO)
Market returns	Fama-French data library	Market excess return and riskfree rates
Stock returns	CRSP via WRDS	All stocks listed on AMEX, NYSE, NASDAQ
Federal funds futures prices	Bloomberg	Contracts from 30 days to 6 months
Macroeconomic series	BEA via FRED	Real Consumption (PCES+PCEND)
	BEA via FRED	Real Gross Private Domestic Investment (GPDIC1)

Table 4: Data descriptions

On measuring direct announcement shocks.

The ECO dataset includes the realized value of announcements(e.g. federal funds rates target for FOMC and GDP growth rates for GDP) as well as professional analyst forecast survey values for each announcement. The nature of the surveys such as the number of analysts and composition varies across announcements and times. Surveys on the ECO normally start one to two weeks before a release and are updated on a real-time basis leading up to the announcement release. In computing announcement shock, we take the difference between actual and survey values as the announcement shock, which is in the unit according to the announcement (e.g. percent of an interest rate for the federal funds rate announcements by FOMC and percent growth for the GDP announcement). We standardize the raw difference using the sample mean error and standard deviation specific to the respective announcement. The standardization effectively transforms announcement shocks to be a zero-mean unit standard deviation variable across all announcements. We define announcement days to be any days of the five major announcements. If events happen more than once in a period of interest(e.g. month or quarter), then we compute the average of the standardized shocks to be the shock in the period.

On measuring rate change implied by federal funds future prices.

We obtain federal funds futures prices from Bloomberg quoted by the Chicago Mercantile Exchange(CME) group at a daily frequency. Data on the first 6-month delivery are often populated whereas price data on longer-term delivery dates up to 30 months suffer from more severe missing value problems. We make use of the federal funds prices data up to a 6-month delivery horizon mainly because we are interested in the short-term risk-free rate changes inferred from the prices. Due to the institutional details on pricing of the federal funds futures, we can back out expectations of rates. The contract price of the federal funds futures is determined by the realized effective federal funds rates during the contract month. Consider a 30-day contract (i.e. current month) then the price quoted per 1 dollar is given by $P_{t,d} = 1 - \mathbb{E}_{t,d}\left[\bar{R}_t\right]$ where t is the month, and calendar day d of the month can be from 1 to the $D(t)$, the last day of the month t. $\bar{R}_t$ is the arithmetic average of the daily effective federal funds rates in the month of t, that is $\bar{R}_t = \frac{1}{D(t)} \sum_i^{D(t)} R_{t,i}$. This means that at time $1 \leq d < D(t)$, the futures contract price $P^n_{t,d}$ where $n = 1$ denotes the contract delivery in happens within 1 month from time (t, d) is given by

$$P^1_{t,d} = 1 - \frac{1}{d}\sum_{i=1}^{d} R_{t,i} - \frac{1}{D(t) - d}\mathbb{E}_{t,d}\left[\sum_{i=d+1}^{D(t)} R_{t,i}\right]$$

. For the last day of the month(i.e. $d = D(t)$) $P^1_{t,D(t)} = 1 - \frac{1}{D(t)}\sum_{i=1}^{D(t)} R_{t,i}$ exactly. 1-month delivery contract then has realized effective rates component and expectation component. We focus on 2-month or later delivery date from the times of measurement(i.e. $n > 1$), then only expectation of the delivery month effective rates matter for the prices. For $1 < d \leq D(t)$,

$$\begin{aligned}
\Delta P^n_{t,d} &= P^n_{t,d} - P^n_{t,d-1} \\
&= \frac{\mathbb{E}_{t,d-1}\left[\sum_{i=1}^{D(t)} R_{t,i}\right]}{D(t+n-1)} - \frac{\mathbb{E}_{t,d}\left[\sum_{i=1}^{D(t)} R_{t,i}\right]}{D(t+n-1)} \\
\implies \Delta\mathbb{E}_{t,d}\left[\bar{R}_{t+n-1}\right] &= -\Delta P^n_{t,d}
\end{aligned}$$

Hence, the change in expected average effective rates in n month ahead is the price change in n month contract. If we measure this at the first day of the month, then we simply take $-\Delta P^n_{t,1} = -P^n_{t,1} + P^{n+1}_{t,D(t+n)}$ to capture the rate difference because $n + 1$ delivery month contract of the day before becomes the n delivery month contract on day 1. We measure expected rate changes using respective contracts for 2 to 6 months horizon and simply measure the average of 2 to 3 months and 2 to the 6-month horizon by simply taking equal-weighted averages of the negative price changes of respective contracts.

On using federal funds futures in lieu of direct announcement shocks.

On using federal funds futures instead of direct announcement shocks. We say direct announcement shock is the shock measured in announcement relevant measures, such as GDP growth rates or federal funds rates, relative to the central tendency of the analyst forecast. These direct announcement shocks can be used to identify the impulse response function of the announcement shock to macroeconomic quantities, however, we resort to using short-term rate changes implied by the federal funds futures prices instead because of several advantages. First, rate changes on announcement have a reasonable correlation to the primitive announcement shocks. Second, federal funds futures prices data goes further back to 1989 whereas primitive announcement shocks begin Q4 of 1996. Also, the FOMC event in the ECO calendar records target rate intervals that Third, it is convenient to interpret and connect announcements to the short-term rates instead of the various values that actual announcements represent inside a model. Just from the five major announcements, the conceptual diversity of the quantities released from the announcements complicates the interpretation of shocks. Hence, we check that short-term rates response on announcement correlates to the direct announcement shocks and resort to using short-term rates changes to draw a connection between announcement and macroeconomic quantities inside the model.

On impulse response function estimation with data.

We use the local projection method by Jorda(2005) of form $Y_{t+h} = \beta_h Z_t + \sum_{s=1}^{p} \beta_{h,s} Y_{t-s} + \epsilon_t$ is used to draw connection between announcements and macroeconomic quantities, where Z_t is the standardized announcement shock(i.e. zero mean and unit standard deviation) measured on the announcement date that is in the calendar time period of t and Y_t is the macroeconomic quantity measured at the end of period t. We focus on two macroeconomic quantities, consumption and investment. Consumption is computed as the sum of real personal expenditures on services and non-durables. Investment is the real gross private domestic investment. The unit of time is a month for consumption and a quarter for investment as these variables are provided by the federal agencies in these frequencies. We carry out univariate local projection for investment and consumption, where unshown results including both do not substantially change results. We include 1-year lags (i.e. $p = 12$ for consumption and $p = 4$ for investment) and we are mostly interested in a 3-year horizon (i.e. $h \leq 36$ for consumption and $h \leq 12$ for investment). The estimated impulse response function with respect to the announcement shock Z_t is the series of local projection estimates $\{\beta_h\}$ which shows the impact of a unit standard deviation announcement shock of time t on Y_{t+h}.

On impulse response function estimation using non-announcement shocks.

For a given month, the majority of the business days are non-announcement days and it is unclear how information released on non-announcement can be analyzed in a similar sense to the announcements. To be more analogous to the local projection framework analyzing announcement impact on macroeconomic quantities, we take a random sampling approach. First, we take a random sample of non-announcement days for each period. We take one non-announcement per period using a uniform distribution among non-announcement days. We compute standardized shocks on those days and use them to estimate the IRF in the normal way. We repeat the exercise by taking 100 random samples of the non-announcement days and obtain coefficients characterizing IRF. We then take the empirical median, 5th, and 95th percentiles for respective horizon h using the data of 100 local projection coefficients. We report these values as IRF and confidence bands to show the connection between shocks on non-announcement days and macroeconomic quantities.

On local projection on simulated data generated from the model.

The model simulation generates daily macroeconomic quantities and riskfree rates. Announcement days take place every 30th days. Because different announcements fall within the month and do not necessarily fall on the last day of the month when the macroeconomic quantities are measured, we measure monthly macroeconomic quantities on the 14 days after the announcement. We take a 30-day trailing sum of consumption and investment every 14 days after announcements. We then transform these variables similarly to the consumption and investment series in the data, by taking the index of one when the simulated series achieves the sample mean by taking raw series scaled by the mean of the series. We then take the log index level to be used in the local projection. Announcement shocks in the model are defined as the change in riskfree rates on the day of the announcement. That is, simply take the first daily difference on announcement days serves as the announcement shock of the month that is measure 14 days after the announcement. For model calibration, we generate 1000 independent economies each with 60 years. We compute local projection coefficients for $0 \leq h \leq 36$ horizons and take empirical mean and median for each h. The estimates are reported in the simulated local projection as the impulse response.

On the construction of the security market line.

We compute trailing one year(i.e. 252 business day) stock-level beta at a daily frequency using the CRSP dataset. We then construct decile bins by sorting by beta on every first business day of the month. Using the stock level excess returns by return-rf, we construct a daily value-weighted excess return and a value-weighted beta of each decile bin. We have time-series data of excess return and betas for 10 decile bins. We take the time-series equal-weighted average of beta for each bin, which serves as the horizontal axis of the security market line. We take the time-series average of excess returns on all samples for any days' vertical axis values. We subsample announcement days and non-announcement days separately for the corresponding vertical axis values where announcement days are defined as any of the five major announcements.

6.2 Details of the solution to the model

HJB and boundary conditions The HJB equation (4) can be written as

$$\beta V(A,\hat{x},t,K) = \min_{|\upsilon|\leq h} \max_{C,I} \frac{(C)^{1-\frac{1}{\psi}}}{1-\frac{1}{\psi}} + V_t(A,\hat{x},t,K) + V_K(A,\hat{x},t,K)(I-\delta K) + V_x(A,\hat{x},t,K)(-a\hat{x}-\sigma_x \upsilon)$$
$$+\frac{1}{2}\frac{q^2}{\sigma_A^2}V_{xx}(A,\hat{x},t,K) + A(\mu+\hat{x})V_A(A,\hat{x},t,K) + \frac{1}{2}\sigma_A^2 A^2 V_{AA}(A,\hat{x},t,K) + AqV_{Ax}(A,\hat{x},t,K) \tag{11}$$

Because $V_K(A,\hat{x},t,K) > 0$ and $V_x(A,\hat{x},t,K) > 0$, it is optimal to set $\upsilon = h$. That is, the minimizing probability imposes the most pessimistic belief about the expected growth rate of productivity. Using $\upsilon = h$, the HJB becomes

$$\beta V(A,\hat{x},t,K) = \max_{C,I} \frac{(C)^{1-\frac{1}{\psi}}}{1-\frac{1}{\psi}} + V_t(A,\hat{x},t,K) + V_K(A,\hat{x},t,K)(I-\delta K) + V_x(A,\hat{x},t,K)(-ax-\sigma_x h)$$
$$+\frac{1}{2}\frac{q^2}{\sigma_A^2}V_{xx}(A,\hat{x},t,K) + A(\mu+\hat{x})V_A(A,\hat{x},t,K) + \frac{1}{2}\sigma_A^2 A^2 V_{AA}(A,\hat{x},t,K) + AqV_{Ax}(A,\hat{x},t,K) \tag{12}$$

The value function and the policy functions satisfy the following homogeneity properties:

$$V(K,\hat{x},t,A) = A^{1-\gamma}H\left(\frac{K}{A},\hat{x},t\right) = A^{1-\gamma}H(k,\hat{x},t),$$

$$C(K,\hat{x},A,t) = A\cdot c(k,\hat{x},t),$$

$$I(K,\hat{x},A,t) = A\cdot i(k,\hat{x},t)$$

where we use lower case to denote quantities normalized aggregate productivity A: $k = \frac{K}{A}$, $i = \frac{I}{A}$, and $c = \frac{C}{A}$. Using the above homogeneity properties, we can write the HJB for the normalized value function, $H(k, \hat{x}, t)$ as

$$
\begin{aligned}
0 = \max_{c,i} \quad & \frac{c^{1-\frac{1}{\psi}}}{1-\frac{1}{\psi}} + H(k,\hat{x},t)\left[(1-\gamma)(\mu+\hat{x}) + \frac{1}{2}\sigma_A^2\gamma(\gamma-1) - \beta\right] \\
& + H_t(k,\hat{x},t) + H_k(k,\hat{x},t)\left[(i-\delta k) - k(\mu+\hat{x}) + \gamma\sigma_A^2 k\right] \\
& + H_x(k,\hat{x},t)\left(-a_x\hat{x} - \sigma_\theta h + (1-\gamma)Q(t)\right) \\
& - kQH_{kx}(k,\hat{x},t) + \frac{1}{2}\sigma_A^2 k^2 H_{kk}(k,\hat{x},t) + \frac{1}{2}\frac{Q^2(t)}{\sigma_A^2}H_{xx}(k,\hat{x},t)
\end{aligned} \tag{13}
$$

The boundary condition is that for all $n = 1, 2, \ldots$,

$$
H\left(\hat{x}, A, nT^-\right) = E^h\left[H\left(x_{nT}, A, nT^+\right)|\hat{x}, Q\left(nT^-\right)\right]
$$

Using normalized policy functions, the resource constraint is written as:

$$
c + i + \frac{\eta}{2}\left(\frac{i}{k} - h_1\right)^2 k = k^\alpha. \tag{14}
$$

the first-order condition from (13) with respect to i is

$$
\left[k^\alpha - i - \frac{g_0}{2}\left(\frac{i}{k} - i^*\right)^2 k\right]^{-\gamma}\left(1 + g_0\left(\frac{i}{k} - i^*\right)\right) = H_k(k,\hat{x},t). \tag{15}
$$

Therefore, Tobin's q in this economy is

$$
q = G_I(I_t, K_t) = \left(1 + g_0\left(\frac{i}{k} - i^*\right)\right). \tag{16}
$$

Asset pricing Using z_t as the exponential martingale that represents the Radon-Nikodym derivative of the distorted probability measure with respect to P, we can calculate asset prices as

$$
P_t = E_t\left[\int_0^\infty e^{-\beta s}\frac{z_{t+s}u'(C_{t+s})}{z_t u'(C_t)}D_{t+s}ds\right],
$$

where D_t represent the dividend of the asset paid at time t. Below we derive an expression of the z_t process. Under the pessimistic probability measure, the expected growth rate evolves as

$$
d\hat{x}(t) = (-a_x\hat{x}_t - \sigma_\theta h)\,dt + \frac{\chi(t)}{\sigma_A}d\tilde{B}_t^v. \tag{17}
$$

Let $\tilde{x}_t$ denote the posterior mean for x_t under the objective probability measure. The law of motion of $\tilde{x}_t$ can be written as:

$$d\tilde{x}(t) = -a_x \tilde{x}_t dt + \frac{\chi(t)}{\sigma_A} d\tilde{B}_t. \tag{18}$$

Because the productivity process can be written as:

$$\frac{dA_t}{A_t} = (\mu + \hat{x}_t) dt + \sigma_A d\tilde{B}_t^v = (\mu + \tilde{x}_t) dt + \sigma_A d\tilde{B}_t.$$

Therefore, the two innovation processes $\tilde{B}_t$ and $\tilde{B}_t^v$ are related by:

$$d\tilde{B}_t = \frac{1}{\sigma_A} (\hat{x}_t - \tilde{x}_t) dt + d\tilde{B}_t^v.$$

We define $\Delta_t = \tilde{x}_t - \hat{x}_t$ to be the difference between the posterior mean for x_t under the objective measure and that under the worse-case measure. By comparing equations (17) and (18) and using the relationship between $\tilde{B}_t$ and $\tilde{B}_t^v$ above, we have:

$$d\Delta_t = [\sigma_\theta h - \omega(t) \Delta_t] dt,$$

where $\omega(t) = a_x + \frac{Q(t)}{\sigma_A^2}$. This allows us to explicit solve for the expression of Δ_t as

$$\Delta_t = e^{-\int_0^t \omega(s)ds} \Delta_0 + e^{-\int_0^t \omega(u)du} \int_0^t e^{\int_0^s \omega(u)du} [\sigma_\theta h] ds.$$

As announcement $t = 0$, the true value of x_t is revealed, and $\tilde{x}_t - \hat{x}_t = 0$. We therefore have $\Delta_t = e^{-\int_0^t \omega(u)du} \int_0^t e^{\int_0^s \omega(u)du} [\sigma_\theta h] ds$. Using this notation, the difference between the two Brownian motions can be written as: $d\tilde{B}_t = -\frac{\Delta_t}{\sigma_A} dt + d\tilde{B}_t^v$. Therefore, the exponential martingale that changes the objective measure into the worse-case measure is

$$z_t = \exp\left\{ \int_0^t \frac{\Delta_t}{\sigma_A} d\tilde{B}_s - \int_0^t \frac{1}{2} \left(\frac{\Delta_t}{\sigma_A} \right)^2 ds \right\} \tag{19}$$

in the interior of $(0, T)$.

At the boundaries, under the objective prob measure, $x_t - \tilde{x}_t \sim N(0, \chi_T)$. We need to find a probability density such that under this distorted probability measure,

$$x_t - \hat{x}_t = x_t - \tilde{x}_t + \frac{[\tilde{x}_t - \hat{x}_t]}{\chi_T} \chi_T \sim N(0, \chi_T).$$

We guess and verify that the density for the probability distortion can be constructed as:

$$\frac{Z_T^+}{Z_T^-} = \exp\left\{ -\frac{\Delta_T}{\chi_T} \left(x_T^+ - \tilde{x}_T \right) - \frac{1}{2} \frac{\Delta_T^2}{\chi_T} \right\}.$$

Therefore, in our model, upon announcement, the A-SDF can be written as:

$$\frac{Z_T^+}{Z_T^-}\left(\frac{C_T^+}{C_T^-}\right)^{-\gamma}.$$

The announcement premium for the claim to the representative firm can therefore be written as:

$$-Cov_T\left(\frac{Z_T^+}{Z_T^-}\left(\frac{C_T^+}{C_T^-}\right)^{-\gamma},\frac{Z_T^+}{Z_T^-}\right).$$

6.3 Numerical solutions using finite difference

We solve the partial differential equation (PDE) in (13) with a finite difference method that approximates the function $H(k,\hat{x},t)$ on a three-dimensional grid, where $k \in \left\{k_i^1\right\}_{i=1}^I$, $\hat{x} \in \left\{\hat{x}_j\right\}_{j=1}^J$ and $t = \{0, \triangle t, 2\triangle t, ..., T-\triangle t, T\}$. The distance between the grid points on k (m) is $\triangle k$ $(\triangle \hat{x})$. We use the notation $H_{i,j}^t \equiv H\left(k_i, \hat{x}_j, t\right)$.

For each t, we approximate the first derivatives of H using both backward and forward differences and second derivatives with central differences:

$$\begin{aligned}
\frac{\partial H_{i,j}^t}{\partial k} &\equiv \left(H_k^F\right)_{i,j}^t \approx \frac{H_{i+1,j}^t - H_{i,j}^t}{\triangle k},\\
\frac{\partial H_{i,j}^t}{\partial k} &\equiv \left(H_k^B\right)_{i,j}^t \approx \frac{H_{i,j}^t - H_{i-1,j}^t}{\triangle k},\\
\frac{\partial H_{i,j}^t}{\partial \hat{x}} &\equiv \left(H_{\hat{x}}^F\right)_{i,j}^t \approx \frac{H_{i,j+1}^t - H_{i,j}^t}{\triangle \hat{x}},\\
\frac{\partial H_{i,j}^t}{\partial \hat{x}} &\equiv \left(H_{\hat{x}}^B\right)_{i,j}^t \approx \frac{H_{i,j}^t - H_{i,j-1}^t}{\triangle \hat{x}},\\
\frac{\partial^2 H_{i,j}^t}{\partial k^2} &= \left(H_{kk}\right)_{i,j}^t \approx \frac{H_{i+1,j}^t - 2H_{i,j}^t + H_{i-1,j}^t}{\left(\triangle k\right)^2},\\
\frac{\partial^2 H_{i,j}^t}{\partial \hat{x}^2} &= \left(H_{\hat{x}\hat{x}}\right)_{i,j}^t \approx \frac{H_{i,j+1}^t - 2H_{i,j}^t + H_{i,j-1}^t}{\left(\triangle \hat{x}\right)^2},\\
\frac{\partial^2 H_{i,j}^t}{\partial k \partial \hat{x}} &= \left(H_{k\hat{x}}\right)_{i,j}^t \approx \frac{H_{i+1,j+1}^t - H_{i+1,j-1}^t - H_{i-1,j+1}^t + H_{i-1,j-1}^t}{4\triangle k \triangle \hat{x}},
\end{aligned} \tag{20}$$

where the choice of forward or backward derivatives depends on the sign of the drift function for the state variable.

Step 1: We start an initial guess of a pre-announcement value function $H_{i,j}^T$.

Step 2: We derive the investment policy $i_{i,j}^t \equiv i\left(k_i, \hat{x}_j, t\right)$ from equation (15) through root-finding algorithms. The consumption policy $c_{i,j}^t \equiv c\left(k_i, \hat{x}_j, t\right)$ is derived from the market clearing condition eqaution (14).

Step 3: We approximate the HJB equation (13) using the derivatives from equations (20) by the following upwind scheme under $\triangle t = \frac{1}{360}$ to capture daily frequency:

$$\begin{aligned} \frac{H_{i,j}^{t+1} - H_{i,j}^{t}}{\triangle t} - \left[(1-\gamma)(\mu + \hat{x}_j) + \frac{1}{2}\sigma_A^2 \gamma (\gamma - 1) - \beta \right] H_{i,j}^{t+1} &= \frac{\left(c_{i,j}^t\right)^{1-\gamma}}{1-\gamma} \\ + (H_k)_{i,j}^t \left[\left(e^{-\lambda\left(\hat{x}_j + \frac{\sigma_\theta h}{a_x}\right)} i_{i,j}^t - \delta k_i \right) - k_i (\mu + \hat{x}_j) + \gamma \sigma_A^2 k_i \right] & \\ + (H_{\hat{x}})_{i,j}^t \left(-a_x \hat{x}_j - \sigma_\theta h + (1-\gamma) Q(t) \right) & \\ -kQ(t) (H_{k\hat{x}})_{i,j}^t + \frac{1}{2}\sigma_A^2 k_i^2 (H_{kk})_{i,j}^t + \frac{1}{2}\frac{Q^2(t)}{\sigma_A^2} (H_{\hat{x}\hat{x}})_{i,j}^t & \end{aligned} \tag{21}$$

use the backward induction to calculate $H(k, \hat{x}, 0)$.

Step 4: Compute an updated pre-announcement value function $H(k, \hat{x}, T)$ using

$$H(k, \hat{x}^-, T^-) = E^{\tilde{Q}_v}\left[H(k, \hat{x}^+, 0) | \hat{x}^-, Q(T^-) \right]$$

Go back to Step 1 until the function $H(k, \hat{x}, T)$ converges.

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