NBER WORKING PAPER SERIES

UNCERTAINTY, WAGES, AND THE BUSINESS CYCLE

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Working Paper 27951
http://www.nber.org/papers/w27951

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
October 2020

For very helpful comments, we thank Morten Ravn, Martin Andreasen, Nicholas Bloom, Susanto Basu, Luca Dedola, Bart Hobijn, Giovanni Lombardo, Sylvain Leduc, Francisco Ruge-Murcia, Nora Traum, Markus Riegler, Felix Wellschmied, Francesco Zanetti, and audiences at various seminars and conferences. We are indebted to Giovanni Pellegrino for providing the codes to estimate the Interacted VAR and to Gabriel Züllig for invaluable research assistance. Financial support from the Social Sciences and Humanities Research Council of Canada and from HEC Montréal Direction de la Recherche is gratefully acknowledged. The viewpoints stated are the responsibility of the individual contributors, and do not necessarily reflect the views of Danmarks Nationalbank or the NBER.

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NBER Working Paper No. 27951
October 2020
JEL No. E2,E32

ABSTRACT

We show that limited wage flexibility in economic downturns generates strong and state-dependent amplification of uncertainty shocks. It also explains the cyclical behavior of empirical measures of uncertainty. Central to our analysis is the existence of matching frictions in the labor market and an occasionally binding constraint on downward wage adjustment. The wage constraint enhances the concavity of firms' hiring rule, generating an endogenous profit-risk premium. In turn, uncertainty shocks increase the profit-risk premium when the economy operates close to the wage constraint. This implies that higher uncertainty can severely deepen a recession, although its impact is weaker on average. Non-linear local projections and VAR estimates support the model predictions. Additionally, the variance of the unforecastable component of future economic outcomes always increases at times of low economic activity. Thus, measured uncertainty rises in a recession even in the absence of uncertainty shocks.

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A data appendix is available at http://www.nber.org/data-appendix/w27951

1 Introduction

The cyclical behavior of wages and its implications for the propagation of business cycle shocks are central questions in macroeconomics. Since Keynes (1936), a vast literature suggests wage setting frictions have important implications for aggregate dynamics. For instance, sluggish wage adjustment plays a key role for the transmission of monetary policy shocks (e.g., Christiano, Eichenbaum, and Evans, 2005, and Huang and Liu, 2002); accounts for the largest share of cyclical fluctuations in the labor wedge (Gali, Gertler, and Lopez-Salido, 2007); and, by preventing sufficient downward wage adjustment, may have exacerbated the fall in employment during the Great Recession in the U.S. (Daly, Hobijn, and Lucking, 2012, Shimer, 2012, and Yellen, 2014).

Less is known about the consequences of wage setting frictions at times of high macroeconomic uncertainty, a potential factor shaping the depth and duration of recessions as suggested by recent research.[1] This paper shows occasionally binding downward wage rigidity has important implications for the propagation of uncertainty shocks and the cyclical behavior of empirical measures of uncertainty. First, the existence of an occasionally binding constraint (OBC) on wage adjustment generates strong and state-dependent amplification of uncertainty shocks. The impact of an exogenous increase in uncertainty is an order of magnitude larger at times of low economic activity relative to economic expansions. Second, the OBC on wage adjustment implies empirical measures of aggregate uncertainty can display marked countercyclicality even in the absence of any exogenous change in uncertainty (i.e., absent second-moment shocks). This result is consistent with the empirical finding in Ludvigson, Ma, and Ng (2018) that heightened macroeconomic uncertainty can be an endogenous response to business cycle fluctuations.

We cast the analysis in the context of a general equilibrium model featuring search and matching frictions in the labor market. Firms and workers bargain over wages in every period subject to an occasionally binding constraint: downward wage adjustment becomes unfeasible when wages fall enough relative to their trend. When the constraint is not binding, the wage payment splits the match surplus according to efficient Nash bargaining, accounting for the possibility that the wage constraint may be binding in the future.

The first contribution of the paper is to the literature on the propagation of second-moment

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[1] Heightened uncertainty has been suggested as a major contributor to the magnitude of the slump experienced by the U.S. economy over the period 2007-2012, including the dramatic increase in the spell of unemployment duration, the historically low vacancy yield, and the fall in recruiting intensity. Stock and Watson (2012) and Baker, Bloom, and Davis (2012) estimate that the increase in uncertainty explains a substantial portion in the fall of U.S. GDP during the Great Recession. Leduc and Liu (2013) find that increased policy uncertainty accounts for two-thirds of the shifts of the Beveridge curve over the same period.

shocks. The OBC on downward wage adjustment implies higher uncertainty can severely deepen a recession. By contrast, both flexible wage setting and wage rigidity that binds at all times imply a negligible propagation of uncertainty shocks (barring the introduction of additional sources of amplification of second-moment shocks in the model). Assuming the wage constraint binds only 5% of the time, we find the mean increase in uncertainty observed in the data leads to an output decline equal to 0.25% at the trough. However, this average effect masks substantial heterogeneity. When output is 4% below its trend level, the same uncertainty increase induces an average output loss equal to 0.5%. If the uncertainty increase is of a magnitude comparable to what was observed in the Great Recession, the output loss is about 1%. Analogous uncertainty shocks have near-zero effects in economic expansions. Overall, the effects of uncertainty shocks operating through downward wage rigidity can be sizable and long-lasting. The average cumulative output loss over a one-year horizon is equal to 0.6% for the uncertainty mean increase. In a deep recession, this figure can be as high as 2%. Non-linear local projections and VAR estimates support the model predictions.

The second contribution of the paper adds to an important debate on the origins of the cyclicality of several empirical measures of economic uncertainty documented in post-war U.S. data. Our theoretical framework implies that the variance of the unforecastable component of future economic outcomes—a well-documented countercyclical measure of uncertainty—always increases at times of low economic activity, reflecting the endogenous response of the economy to first-moment shocks.[2] Thus, measured uncertainty increases in recessions, even in the absence of uncertainty shocks.

The intuition for our results is the following: when a match is formed and agents enter into multi-period employment contracts, the constraint on wage bargaining influences job creation by affecting the present discounted value of the stream of wage payments. As we illustrate in a simple three-period model, the OBC enhances the concavity of firm profits with respect to productivity, generating a large profit-risk premium. The closer the economy operates to the constraint, the larger the difference between the expected stream of profits and the profit stream from expected productivity. At times of low aggregate demand and employment, an increase in the probability of more extreme productivity realizations leads to a sizable increase in the profit-risk premium, since the wage constraint is expected to bind with higher probability in the future. In turn, the sharp

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[2] The aggregate measures of uncertainty considered in the empirical literature include the volatility of stock and bond markets, the volatility of output and exchange rates, measures of disagreement among professional forecasters, their self-reported subjective forecast uncertainty, the variance of future output growth conditional on current information (see Bloom, 2014) and the conditional variance of the forecast error from an econometric forecasting model (Jurado, Ludvigson, and Ng, 2015 and Ludvigson, Ma, and Ng, 2018).

reduction in the firm's expected surplus leads to an immediate reduction in job creation.

When wages are unconstrained or unconditionally rigid, the propagation of uncertainty shocks through the labor market is negligible. Eliminating the OBC leaves little nonlinearity in the firms' profit function for risk consideration to have a substantial impact through the wage channel. Thus, the impact of uncertainty shocks does not depend only on the size of the deviations of wages and profit from their efficient levels, but on the amount of concavity wage adjustment generates in the profit function.[3]

Turning to the behavior of measured uncertainty, our model implies the forecast error variance of output and employment display pronounced countercyclical movements already in response to first-moment shocks. Agents anticipate job creation responds more strongly to productivity shocks when the economy operates close to the wage constraint. By contrast, when the constraint binds with low probability, efficient surplus splitting results in cyclical wages, lowering the volatility of output and employment for any given realization of productivity. Accordingly, the forecast error variance becomes less sensitive to aggregate conditions.

Our paper provides a methodological contribution using a novel implementation of the penalty function method to solve a model with an occasionally binding constraint and stochastic volatility. In contrast to the previous literature, we do not rely on a local approximation of a given differentiable (non-polynomial) function, since Taylor approximations do not necessarily inherit properties such as monotonicity and convexity of the postulated functional form. We assume instead that the penalty function is a fourth-order polynomial and then approximate the model equilibrium conditions with a fourth-order Taylor approximation.

Related Literature A large and growing literature studies the relationship between macroeconomic uncertainty and business cycle dynamics. Our results encompass and complement the two main explanations for the cyclical behavior of measured uncertainty proposed thus far. One strand of the literature focuses on the transmission of uncertainty shocks. Mechanisms explored in the literature include fixed costs and investment irreversibility (e.g., Bloom, 2009, Bloom, Floetotto, Jaimovich, Eksten, and Terry, 2018, Schaal, 2017); nominal rigidities (Basu and Bundick, 2017, Fernandez-Villaverde, Guerron-Quintana, Kuester, and Rubio-Ramirez, 2015, Fernandez-Villaverde, Guerron-Quintana, Rubio-Ramirez, and Uribe, 2011, Leduc and Liu, 2016); financial

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[3] Ilut, Kehrig, and Schneider (2018) document empirically that concave establishment-level responses of employment to TFP shocks induce significant skewness, movements in volatility, and amplification of negative aggregate shocks.

frictions (Arellano, Bai, and Kehoe, 2019, Christiano, Motto, and Rostagno, 2014, Gilchrist, Sim, and Zakrajsek, 2014); and ambiguity aversion (Ilut and Schneider, 2014). These models explain the countercyclicality of measured uncertainty in one of two ways. Either uncertainty shocks explain a large share of the variance of output or, when the variance of output is mostly driven by first-moment shocks, uncertainty shocks are ex-post negatively correlated with first-moment shocks. An alternative approach suggests that time-varying uncertainty is an equilibrium outcome resulting from agents' optimal decisions during recessions, reflecting a variety of mechanisms such as time-variation in risk-incentives, information availability, or cross-sectional capital allocation (Bachmann and Moscarini, 2011, Fajgelbaum, Schaal, and Taschereau-Dumouchel, 2017, Saijo, 2017, and Van Nieuwerburgh and Veldkamp, 2006).

Our results closely relate to previous studies addressing the role of labor-market adjustment for the transmission of uncertainty shocks. Basu and Bundick (2017) show in real business cycle models with frictionless labor markets, higher uncertainty can be expansionary, since precautionary saving induces a negative wealth effect that increases hours supply; however, with price stickiness output becomes demand-determined, and the reduction in aggregate demand ultimately results in lower output and labor.[4] Leduc and Liu (2016), our closest antecedent, incorporate search and matching frictions and real wage rigidity that binds at all times in a New Keynesian model. They show search frictions provide a mechanism for uncertainty shocks to generate an increase in unemployment via an option-value channel. With search frictions, a job match represents a long-term employment relationship that is irreversible. When times are uncertain, the option value of waiting increases and the match value declines. The authors show this option-value channel has small effects on vacancy posting and employment unless nominal rigidities are present. Our model highlights a related, yet hitherto, unexplored channel that is quantitatively important in models with long-term employment relationships. Occasionally binding downward wage rigidity amplifies the impact of uncertainty shocks because the one-sided constraint introduces a profit-risk premium that increases when uncertainty rises. This mechanism operates regardless of the presence of nominal rigidities.[5]

Our work is also related to a strand of the literature that studies how occasionally binding constraint and financial frictions affect the propagation of firm-level volatility shocks. Arellano,

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[4] When prices cannot fully accommodate the drop in demand, firms bias their prices upward in response to higher uncertainty, lowering demand and output in equilibrium (Fernandez-Villaverde, Guerron-Quintana, Kuester, and Rubio-Ramirez, 2015).

[5] Nakata (2013) finds that higher uncertainty is more recessionary when the economy is at the zero lower bound (ZLB), while Plante, Richter, and Throckmorton (2018) show that the output forecast error variance increases endogenously when the economy is at or close to the ZLB.

Bai, and Kehoe (2019) consider a model where producers face a credit constraint that affects their ability to finance the cost of labor. When the variance of the idiosyncratic shocks increases, the probability of default increases at a given level of employment. As a result, firms become more cautious and decrease employment, leading to a fall in aggregate output. Gilchrist, Sim, and Zakrajsek (2014) discuss the role of limited liability for the impact of changes in uncertainty on firms' investment decision. Christiano, Motto, and Rostagno (2014) show that volatility shocks to the quality of capital account for a significant portion of output fluctuations.

Our paper builds on an extensive empirical literature documenting the existence of constraints on downward wage adjustment in a large number of countries (for an overview, see Dickens, Goette, Groshen, Holden, Messina, Schweitzer, Turunen, and Ward, 2007). While we model a constraint on the level of wages (in deviation from their trend), macroeconomic models with spot labor markets typically assume a constraint on the growth rate of wages relative to the previous-period (e.g., Schmitt-Grohe and Uribe, 2016). In this case, wage cuts are capped (or even precluded) irrespective of the past history of wage changes and business cycle dynamics. In contrast, our approach implies the maximum feasible size of successive wage cuts becomes progressively smaller as the economy approaches the constraint.

The key message of the paper does not hinge on the specific modeling of downward wage rigidity. What matters is that asymmetric wage flexibility introduces a concavity in the firm's profit function. As a result, the implications for the transmission of uncertainty shocks are qualitatively the same.[6] We favour our formulation for the following reasons. First, it imposes a milder constraint on wage adjustment, taking a conservative view with respect to the frequency of wage cuts and freezes—an issue that remains debated empirically.[7] Second, our approach directly captures the notion that labor market institutions *de jure* introduce a floor on downward wage adjustment. For instance, since the early 1990s, several European countries have adopted two-tier bargaining structures in which plant-level bargaining supplements national or industry-wide agreements (Boeri, 2014). In plant-level negotiations, wages cannot fall below the base level established at the national or industry level in a given time period (e.g., Fougere, Gautier, and Roux, 2018).[8] Finally, the

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[6] With a lower bound on wage-growth, our results about the state-dependent effects of uncertainty shocks relate to the growth-rate of output, rather than its level relative to trend.

[7] In a recent survey of the literature, Elsby and Solon (2019) conclude that wage cuts from one year to the next appear quite common, typically affecting 15–25 percent of job stayers in periods of low inflation. Nominal wage freezes are less frequent, affecting about 8 percent of job stayers. See also Kurmann and McEntarfer (2019) and Grigsby, Hurst, and Yildirmaz (2019). Kudlyak (2014) finds evidence of procyclicality in the user cost of labor, while various studies find the wage of new hires is more flexible than the wages of incumbent workers (e.g., Pissarides (2009)).

[8] Carneiro, Guimar, and Portugal (2012) show that in Portugal and Germany firms adopt a wage cushion—a premium over the wage agreed upon in the collective bargaining agreement—which is highly cyclical for new hires.

quantification of the effects of uncertainty shocks would be more challenging with a constraint on wage growth. For a search-and-matching model with Nash bargaining and TFP-level shocks it is difficult to generate empirically-plausible wage-growth dynamics.[9] While introducing additional shocks (e.g., trend shocks) could address this issue, it would also render the analysis less comparable relative to the existing literature without adding much additional insight.

2 Model

In this section, we introduce an OBC on wage adjustment in a real business cycle model that features search frictions and random matching in the labor market.

Household Preferences

The economy is populated by a unit mass of atomistic, identical households. Each household is thought of as a large extended family containing a continuum of members along a unit interval. The measure of family members who work is determined by a random-matching process. We assume full consumption insurance between employed and unemployed individuals. The representative household maximizes the expected intertemporal utility function

$$E_t \left[\sum_{s=t}^{\infty} \beta^{s-t} \tilde{C}_s^{1-\gamma} / \left(1-\gamma\right) \right],$$

where $\tilde{C}_t$ is aggregate consumption, $\beta \in (0,1)$ is the subjective discount factor, and $\gamma > 0$ is the inverse of the intertemporal elasticity of substitution. As is standard practice in the literature (e.g., Ravenna and Walsh, 2011), aggregate consumption includes both consumption of market goods, C_t, and home production from unemployed workers, $h_p \left(1 - L_t\right)$, where L_t is the mass of employed household's members. Unemployment workers also receive unemployment benefits from the government, b, financed by lump-sum taxes, T_t.[10]

The household accumulates physical capital and rents it to producers in a competitive capital market. Households also choose the rate of utilization of the installed physical capital, ω_t, which in turn affects its depreciation rate, δ_t. Effective capital rented to firms, K_t, is the product of physical

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[9] When TFP follows an AR(1) process, Nash bargaining implies that wage growth inherits the underlying dynamics of TFP growth, which is weakly autocorrelated. As a result, expansions (periods in which TFP is above trend) are associated to negative wage growth after the impact period. The opposite is true in a recession. These counterfactual dynamics would bias the quantitative assessment of the effects of second-moment shocks.

[10] The distinction between home production and unemployment benefits follows Mortensen and Pissarides (2002).

capital, $\tilde{K}_t$ and the utilization rate: $K_t = \omega_t \tilde{K}_t$. Physical capital obeys a standard law of motion:

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

Depreciation depends on utilization via a quadratic functional form:

$$\delta_t = \delta + \delta_2 (\omega_t - \omega) + (\delta_2/2) (\omega_t - \omega)^2 .$$

The household maximizes welfare subject to the resource constraint:

$$C_t + I_t = w_t L_t + r_{K,t} K_t + b (1 - L_t) + \Pi_t + T_t,$$

where w_t denotes the real wage, $r_{K,t}$ is the rental rate of capital, and Π_t are profits rebated to the household. The first-order conditions for capital and investment leads to a standard Euler equation:

$$1 = E_t \beta_{t,t+1} (r_{K,t+1} \omega_{t+1} + 1 - \delta_{t+1}) ,$$

where $\beta_{t,t+1} \equiv \beta \left(\tilde{C}_{t+1} / \tilde{C}_t \right)^{-\gamma}$ denotes the stochastic discount factor of households.

Production

A unit mass of symmetric, perfectly competitive firms uses labor and capital as inputs of production. To hire new workers, firms need to post vacancies, incurring a cost of κ units of consumption per vacancy posted. The probability of finding a worker depends on a constant-return-to-scale matching technology which converts unemployed workers, U_t, and aggregate vacancies, V_t, into the total number of new matches per period $M_t = \chi U_t^{\varepsilon} V_t^{1-\varepsilon}$, where $\chi > 0$ and $0 < \varepsilon < 1$. Each firm meets unemployed workers at a rate $q_t \equiv M_t / V_t$. As in Krause and Lubik (2007) and other studies, we assume that newly created matches become productive only in the next period. The inflow of new hires in $t + 1$ is therefore $q_t V_t$.

Firms and workers separate exogenously with probability $\lambda \in (0, 1)$.[11] Since separations can occur for existing productive matches or for matches which have not yet started production, the

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[11] Hall (2005) and Shimer (2005) argue that the separation rate varies little over the business cycle, although part of the literature disputes this position; see Davis, Haltiwanger, and Schuh (1998) and Fujita and Ramey (2009).

law of motion for employment is given by

$$L_t = (1-\lambda)\left(L_{t-1} + q_{t-1}V_{t-1}\right). \tag{1}$$

The number of unemployed workers searching for jobs is $U_t = 1 - L_t$. Each firm produces output according to the constant-returns to scale technology $Y_t = e^{Z_t} K_t^{\alpha} L_t^{1-\alpha}$, where Z_t denotes aggregate productivity (in logs). We assume that Z_t follows a stationary autoregressive process:

$$Z_t = \rho_z Z_{t-1} + e^{\sigma_{Zt}} u_{zt},$$

where $u_{zt} \overset{i.i.d}{\sim} N(0,1)$ is an exogenous shock to the level of technology, and σ_{Zt} captures exogenous second-moment or "uncertainty" shocks. When the variance of productivity increases, there is higher uncertainty about the future time path of the stochastic process Z_t. The standard deviation σ_{Zt} (in logs) follows a stationary autoregressive process:

$$\sigma_{Zt} = \rho_\sigma \sigma_{Zt-1} + (1-\rho_\sigma)\sigma_Z + \sigma_\sigma u_{\sigma t},$$

where $u_{\sigma t} \overset{i.i.d}{\sim} N(0,1)$ represents second-moment shocks. Producers choose the number of vacancies and employment to maximize the expected present discounted value of their real profit stream:

$$\Pi_t \equiv E_t \sum_{s=t}^{\infty} \beta_{t,t+s}\left(Y_s - w_s L_s - r_{K,s}K_s - \kappa V_s\right).$$

The first-order condition for L_t and V_t imply the following job creation equation:

$$\frac{\kappa}{q_t} = (1-\lambda)E_t\left\{\beta_{t,t+1}\left[(1-\alpha)\frac{Y_{t+1}}{L_{t+1}} - w_{t+1} + \frac{\kappa}{q_{t+1}}\right]\right\}. \tag{2}$$

Equation (2) states that, at the optimum, the expected cost of filling a vacancy is equal to the expected discounted profit from the time-t match, $(1-\alpha)Y_t/L_t - w_t$, plus the expected discounted value of the vacancy creation cost per future match.

Wage Bargaining

In the benchmark search-and-matching model, the real wage splits the match surplus according to Nash-bargaining: $w_t^{flex} = \arg\max\left(J_t^{1-\eta} W_t^{\eta}\right)$, where J_t and W_t represent, respectively, the firm's and worker's surplus; $\eta \in (0,1)$ identifies the bargaining power of the worker. The firm surplus from an additional hire is

$$J_t = (1-\alpha)\, Y_t/L_t - w_t + (1-\lambda) E_t \left(\beta_{t,t+1} J_{t+1}\right).$$

Intuitively, J_t is the per-period marginal value product of the match, net of the current wage bill, plus the expected present discounted continuation value of the match. The worker's surplus, W_t, is the difference between the worker's asset value of being employed, H_t, and the value of being unemployed, $U_{u,t}$ (see Appendix A for their definitions):

$$W_t = w_t - (b + h_p) + (1-\lambda)\,(1-p_t)\, E_t \left(\beta_{t,t+1} W_{t+1}\right),$$

where $p_t \equiv M_t/U_t$ is the probability of finding a job in period t. Intuitively, the worker's surplus is the present discounted value of the difference between the stream of wage payment minus flow value of unemployment (the value of non-market activity plus unemployment benefits).

The optimal sharing rule implies leads to the following wage schedule:

$$w_t^{flex} = \eta \left[(1-\alpha) \frac{Y_t}{L_t} + \kappa \frac{p_t}{q_t} \right] + (1-\eta)\,(h_p + b)\,. \tag{3}$$

We now introduce the constraint $w_t \geqslant w_m$ at the bargaining stage. With a balanced growth path, w_m can be interpreted as a wage floor relative to trend-level of wages.[12] The OBC implies that standard perturbation methods cannot be applied to obtain the rational expectations solution of the model. The reason is that local approximations require the model equations to be differentiable over the state space, at least to an order commensurate with the degree of accuracy of the approximation. To accommodate the use of perturbation methods, we solve the Nash bargaining problem subject to the OBC by adding to the objective function a term that prescribes a high cost for the violation of the constraint. This approach follows a well-established methodology in the field of applied mathematics—the penalty function method—which converts an optimization problem containing an inequality constraint into an unconstrained problem.[13] Under fairly general conditions, it is

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[12] With steady-state growth, w_t represents wages in deviation from trend, denoted by A_t: $w_t \equiv \tilde{w}_t/A_t$, where $\tilde{w}_t$ is the non-stationary level of wages. Denote with $\bar{w}_t \equiv wA_t$ the value of steady-state wages along the balanced growth path and with $\tilde{w}_{m,t} = w_m A_t$ the trending wage-level below which wages cannot fall. Then $\tilde{w}_t \geqslant \tilde{w}_{m,t}$ implies $w_t \geqslant w_m$. Notice that $\tilde{w}_{m,t}/\bar{w}_t = \gamma$, where $0 < \gamma < 1$. This implies that $\tilde{w}_t \geqslant \gamma \bar{w}_t$, a constraint on the deviation of wages from their long-run trend, even if wages $\tilde{w}_t$ are growing at a positive rate in each period.

[13] Recent contributions that use a penalty function approach in dynamic stochastic general equilibrium models include, among others, Kim, Kollmann, and Kim (2010), Preston and Roca (2007), and Rotemberg and Woodford (1999).

possible to prove that for a given objective function $f(\mathbf{x})$, a constrained set of the vector $\mathbf{x}$, and a given penalty function $\Gamma(\mathbf{x},\psi)$, the sequence of solutions to the optimization problem converges to the solution of the original problem when $\psi \rightarrow \infty$ (Luenberger, 1973). Intuitively, the term ψ parameterizes the speed at which the penalty function increases as $\mathbf{x}$ gets closer to the boundary of the feasible set. Since the penalty term in the unconstrained problem is a smooth function of the model variables, it is possible to apply standard perturbation techniques to approximate the model solution up to an arbitrary degree of accuracy.

We modify the Nash bargaining problem by assuming that the Nash surplus is equal to $J_t^{1-\eta} W_t^{\eta} - \Gamma_t$, where $\Gamma_t \equiv \Gamma\left(w_t, \psi\right)$ is a continuous and differentiable penalty function that satisfies the following requirement:

$$\lim_{\psi \longrightarrow \infty} \Gamma\left(w_t, \psi\right) = \begin{cases} 0 & w_t \geqslant w_m \\ \varsigma & w_t < w_m \end{cases}, \tag{4}$$

where ς is a value such that any $w_t < w_m$ results in a non-positive Nash surplus and lies outside the feasible bargaining set. This implies that while any wage in the bargaining set is ex ante feasible, the penalty function Γ_t changes the Nash surplus in such a way that the firm and the worker never stipulate a wage payment that violates the constraint. As discussed in the next section, we approximate $\Gamma_{w,t}$ using a fourth-order polynomial.

The first-order condition of the constrained Nash bargaining problem implies the following sharing rule:

$$\eta J_t + (\eta - 1) W_t - \Gamma_{w,t} J_t^{\eta} W_t^{1-\eta} = 0, \tag{5}$$

where $\Gamma_{w,t} \equiv \partial \Gamma_t / \partial w_t$. As shown in Appendix A, the sharing rule results in the following wage schedule:

$$w_t = w_t^{flex} - \Lambda_t + (1 - \lambda)\left(1 - p_t\right) E_t\left(\beta_{t,t+1} \Lambda_{t+1}\right), \tag{6}$$

where w_t^{flex} is defined as in (3) and $\Lambda_t \equiv \Gamma_{w,t} J_t^{\eta} W_t^{1-\eta}$. The presence of the OBC affects the wage payment in two ways. First, productivity outcomes that imply a violation of the constraint result in large negative values of Λ_t, since $\Gamma_{w,t}$ takes increasingly larger negative values for wage-levels w_t close to w_m. The corresponding surplus loss implies that in equilibrium, the wage is above the unconstrained Nash wage. Second, the forward-looking term Λ_{t+1} shows that w_t can differ from the unconstrained Nash bargaining wage, w_t^{flex}, even when the constraint is not binding at time t (i.e., when $\Lambda_t = 0$). The simple three-period model presented in Section 5 shows analytically that this result holds even when the OBC is not approximated with a penalty function. The reason is that the worker's and firm's surplus depend on the present discounted value of the expected stream of future wage payments. As long as there is a positive probability that the wage constraint will bind in the future, the Nash surplus accounts for this change in the continuation value of the match relative to the unconstrained wage scenario. For instance, when the firm and the worker expect that the economy will be operating closer to the wage constraint at time $t+1$, w_t falls relative to its unconstrained Nash-bargained level other things equal. In such circumstances, the firm and the worker stipulate a lower wage today to account for the fact that the wage constraint may be binding in the future.[14]

Equilibrium

In equilibrium, profits are equal to $\Pi_t = Y_t - w_t L_t - r_{K,t} K_t - \kappa V_t$, while the government collect taxes to finance unemployment benefits: $T_t = -b\left(1 - L_t\right)$. The aggregate resource constraint implies that total output is equal to the sum of market consumption, investment in physical capital, and the costs of posting vacancies: $Y_t = C_t + I_t + \kappa V_t$.

3 Solution Method and Parameterization

We approximate the model policy functions by computing a fourth-order Taylor expansion of the equilibrium conditions around the deterministic steady state. Below, we refer to this approximation as the "unpruned" state space. We rely on a fourth-order approximation for two reasons. First, up to the third order, the approximated policy functions do not preserve important properties of the non-linear equilibrium conditions of the model. In particular, as shown in Appendix C, the history of past shocks does not affect the impact response of endogenous variables following second-moment shocks. The second reason is that a fourth-order Taylor expansion markedly improves the accuracy of the approximation of the OBC relative to a third-order approximation. We discuss the computational approach below.

Since local approximations can produce explosive simulations when the order of approximation is greater than one, we resort to pruned policy functions when computing second moments. Pruning discards the solution terms that have a higher order relative to the approximation order. The pruning algorithm follows Andreasen, Fernandez-Villaverde, and Rubio-Ramirez (2018)—see Appendix

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[14] While the way in which the penalty terms Λ_t and Λ_{t+1} enter the first-order condition (6) have a clear economic intuition, their interpretation can only be qualitative. This is the case since the actual values of $\Gamma_{w,t}$ and $\Gamma_{w,t+1}$ depend on the parameter ψ and on the adopted polynomial specification for $\Gamma_{w,t}$.

C for the analytical details about pruned and unpruned policy functions.[15] Unless otherwise noted, simulations are computed using the unpruned policy functions.[16]

Parameterization

We parameterize the model at quarterly frequencies and choose parameter values to match features of the U.S. economy. We set the discount factor, β, equal to 0.994, the risk-aversion coefficient, γ, equal to 2, and the capital share in the production function to 0.33, conventional values in the business cycle literature. We set $\delta_1 = \beta^{-1} - 1 + \delta$ based on steady-state relationships and calibrate δ_2 such that the elasticity of capital utilization with respect to the rental rate of capital matches the value from Christiano, Eichenbaum, and Evans (2005).

We set the elasticity of matches to unemployment, ε, equal to 0.4, in line with Blanchard and Diamond (1989). To maintain comparability with much of the existing literature, we assume the worker's bargaining power, η, is equal to ε. This value is also consistent with the evidence in Flinn (2006), who estimates $\eta = 0.38$ for the U.S. We set the unemployment benefits replacement rate, b/w, equal to 0.3. Following Hagedorn and Manovskii (2008), we set the value of non-market activity h_p so that $(h_p + b)/w = 0.95$. This parameterization of the flow value of unemployment is sufficient to generate plausible employment dynamics even when the wage constraint is not binding (e.g., during economic expansions).[17] We set the exogenous separation rate, λ, equal to 10% (Shimer, 2005). Finally, we choose the cost of vacancy posting, κ, and the matching efficiency parameter, χ, such that the steady-state job-finding probability and the probability of filling a vacancy are 83% and 70%, respectively (Shimer, 2005 and den Haan, Ramey, and Watson, 2000).

Following a consolidated approach in the literature (e.g., Fernandez-Villaverde, Guerron-Quintana, Kuester, and Rubio-Ramirez, 2015, Fernandez-Villaverde, Guerron-Quintana, Rubio-Ramirez, and Uribe, 2011, and Born and Pfeifer, 2014), we estimate the exogenous stochastic processes for Z_t and σ_t with likelihood methods. We use data on quarterly TFP adjusted for capital utilization from the Federal Reserve Bank of San Francisco following Fernald (2012) from 1954:Q1 to 2015:Q1. We overcome the nonlinear interaction between productivity and volatility innovations by estimating

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[15] Lombardo and Uhlig (2018) show that this pruned approximation can be interpreted as a standard Taylor approximation taken with respect to an appropriately chosen perturbation parameter. Lan and Meyer-Gohde (2013) also show that pruning can be understood as a Taylor expansion in an appropriate domain.

[16] A limitation of pruned approximations in models with stochastic volatility is that, even at the fourth-order, pruning eliminates several terms accounting for state dependence of second-moment shocks. Appendix C provides a detailed discussion of this issue.

[17] When Nash bargaining is unconstrained, low values of the worker's outside option result in a counterfactually low volatility of employment relative to output. Thus, both first- and second-moment shocks would have no effects on employment unless when the wage constraint is binding.

the stochastic process with a particle filter as in Fernandez-Villaverde, Guerron-Quintana, and Rubio-Ramirez (2010). We choose Beta priors for the autoregressive coefficients ρ_Z and ρ_σ with mean 0.5 and standard deviation 0.2. We choose an Inverse-Gamma distribution for the standard deviation of first- and second-moment shocks. We set the mean of the (log) TFP volatility, σ_{Zt}, equal to -5.3 and the variance equal to 0.1. We set the mean of σ_σ at 0.5 and the variance equal to 2.[18] Appendix B reports the posterior estimates and summarizes the model parameters. Appendix D plots the prior distributions and provides additional details about the estimation procedure. We use posterior-median estimates when simulating the model.

Penalty Function

The penalty function Γ_t can be any differentiable function that can be parameterized to approach arbitrarily close the non-differentiable function in (4). However, when the model is solved with a Taylor expansion, the model policy functions are a polynomial approximation. Thus, regardless of the choice of the penalty function, the law of motion of its first derivative $\Gamma_{w,t}$—the function entering the model equilibrium condition—will be a polynomial of the same order as the order of the Taylor expansion.

In contrast to the previous literature, we do not rely on a local approximation of a given differentiable (non-polynomial) function $\Gamma_{w,t}$. The reason is that Taylor approximations do not necessarily inherit properties such as monotonicity and convexity of the postulated functional form for $\Gamma_{w,t}$. Even a fourth-order Taylor expansion of the penalty function can be inaccurate in regions of the state space that are of economic interest (Den Haan and De Wind, 2012 and Brzoza-Brzezina, Kolasa, and Makarski, 2015). For this reason, we propose an alternative approach that directly selects a fourth-order polynomial for the first-derivative $\Gamma_{w,t}$ in the approximated law of motion of the model.

To illustrate our procedure, notice first that a n^{th}-order Taylor expansion of a differentiable function $\Gamma_{w,t}$ would guarantee that the approximation error is of order $n+1$ within the radius of convergence to the approximation point. However, alternative n^{th}-order polynomials can provide a more accurate approximation in regions of the state space that are of economic interest (i.e., further away from the approximation point), yet preserving a sufficient degree of accuracy in the neighborhood of the approximation point. We assume that $\Gamma_{w,t}$, is a fourth-order polynomial

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[18] We use the Sequential Importance Resampling particle filter to evaluate the likelihood. We use a Tailored Randomized Block Metropolis-Hastings algorithm to maximize the posterior. We obtain similar results when using the priors in Born and Pfeifer (2014). Results are available upon request.

parameterized by the vector of coefficients α. We choose α such that $\Gamma_{w,t}$ satisfies selected global properties discussed below. We then approximate the equilibrium law of motion of the model with a fourth-order Taylor expansion of the equilibrium conditions.[19] Appendix E presents the details of the procedure. Here we highlight the key features of our approach.

We choose the elements of α to match properties of the unconditional wage distribution. The procedure is iterative and requires solving the model with a given candidate polynomial $\Gamma_{w,t}$ at every step, verifying ex post whether the equilibrium of the model meets the specified criteria. We parameterize $\Gamma_{w,t}$ to match the following properties. First, we require that $\Gamma_{w,t}$ is sufficiently small for any wage such that $w_t > w$, where w is the steady-state wage. Since we assume $w > w_m$, this criterion ensures that $\Gamma_{w,t}$ is approximately equal to zero in the region of the state space where $w_t \gg w_m$.[20] Second, we require that the OBC eliminates a given fraction of wage outcomes in the left-tail of the ergodic wage distribution of the unconstrained model. We conservatively assume that the OBC eliminates 5% of wage outcomes. This choice is informed by an extensive literature assessing the extent of downward wage rigidity using micro wage-data. For instance, Kurmann and McEntarfer (2019) using state-payroll data find that excess zero spikes—defined as the mass of year-over-year zero log-hourly wage changes relative to what a symmetric wage change distribution would predict—ranges from 3% to 10.5% between 1999 and 2014. Using British payroll data, Elsby, Shin, and Solon (2016) find that in most years since the late 1970s the share of zero-nominal wage changes in the hourly wage distributions ranged from 0.9% to 9.1%. In a panel of OECD countries, Dickens, Goette, Groshen, Holden, Messina, Schweitzer, Turunen, and Ward (2007) document, that an average of 26% of wage adjustments are subject to downward real wage rigidity, in the sense that 26% of real wage cuts that would have taken place in an unconstrained economy are prevented by the rigidity in wage contracting. In Appendix E, we consider a higher fraction of wage outcomes eliminated by the OBC.

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[19] Appendix F compares our approach relative to the case in which $\Gamma_{w,t}$ is approximated by a fourth-order Taylor expansion of a benchmark exponential function.

[20] For $w_t < w$, the function $\Gamma_{w,t}$ can take values below 0, depending on the vector α. In turn, the iterative procedure selects these values so that the unconditional wage distribution meets the specified targets. As the order of the polynomial for $\Gamma_{w,t}$ increases, these values get arbitrarily close to 0 for $w_t > w_m$.

4 Model Properties and First-Moment Shocks

Wage Dynamics and Ergodic Wage Distribution

Although our calibration strategy only targets first moments of the data, the model successfully accounts for the cyclical behavior of key macroeconomic time series. In particular, the model reproduces well the volatility of employment, investment, capital utilization, and wages relative to output. The contemporaneous correlation between output and the remaining macro variables is also in line with the data (see Appendix D for details).

Figures 1 and 2 present the ergodic wage distribution for the model with the OBC and the model with unconstrained wages, respectively. Each figure also reports the hypothetical distribution that would be obtained if wage outcomes below the median followed a distribution symmetric to the outcomes above the median. This counterfactual distribution makes it is possible to assess whether outcomes depend on the OBC relative to any other nonlinearity of the model. The existence of a wage lower-bound has two implications. First, it prevents the wage from falling below w_m. Second, it skews the wage distribution towards the wage floor. The skewness of the constrained-wage distribution is equal to 0.3, approximately 3 times larger relative to the unconstrained-wage distribution.

The skew in the wage distribution results from the impact of the OBC on wages at low values of productivity. Figure 3 illustrates this point, presenting a scatter plot of wage outcomes against the corresponding productivity level (both in percentage deviations from steady state). Circles refer to the model with the OBC, while diamonds refer to the model with flexible wages. The figure shows that far away from the OBC, the relationship between wages and productivity is virtually identical to the one implied by the model with unconstrained Nash bargaining. By contrast, for sufficiently low values of productivity, the wage never falls more than 2%, the floor implied by our parameterization. Notice that, since wages depend on the total surplus of the match (which in turn depends on expected future wages), w_t is different from the unconstrained-Nash wage $\widetilde{w}_t^{nash}$ already when productivity Z_t is approximately 1.5% below the steady state.

First-Moment Shocks

We now discuss how the OBC on wage adjustment affects the propagation of first-moment shocks, i.e., shocks to the level of productivity Z_t. To build intuition, we consider three alternative wage-setting protocols: (i) OBC on wage adjustment, (ii) unconstrained Nash bargaining, and (iii) wage rigidity that binds at all times. In the model with the OBC, the wage is determined as in equation (6) and $w_t \geqslant w_m$. Unconstrained Nash bargaining implies that $w_t = w_t^{flex}$. To study the role of unconditional wage rigidity, we follow Hall (2005), and assume that w_t is a weighted average of the unconstrained Nash wage and the steady-state wage: $w_t = (1 - \xi)\, w_t^{flex} + \xi w$. We set $\xi = 0.25$ for illustrative purposes. Wage rigidity that binds at all times increases the volatility of employment by approximately 30% relative to the OBC economy; the volatility of wages falls by 20%.

Figure 4 plots the response of key macroeconomic variables following a reduction in Z_t equal to one standard deviation. We generate impulse responses at the ergodic mean in the absence of shocks, labeled by Juillard and Kamenik (2005) the "stochastic steady state."[21] Lower productivity reduces the present discounted value of new and existing matches, reducing, other things equal, vacancy posting. As pointed out by Shimer (2005) and Hall (2005), the response of employment is larger the smaller the elasticity of wages to productivity. As shown in Figure 4, this elasticity is small in the presence of wage rigidity (solid line), leading to the strongest response in unemployment, and larger with unconstrained Nash bargaining (dashed line).

Consider now the economy with the OBC (continuous line). The negative productivity shock increases the likelihood that the wage constraint will bind in the future. Relative to the model with unconstrained bargaining, this would require lowering the time-t wage by a larger amount to compensate for the risk that future wages may be constrained by the OBC, thus setting $w_t < w_t^{flex}$. However, since wage setting at time t is also constrained, the equilibrium wage ends up being close to the one in the unconstrained-Nash case. The difference in the response of employment is somewhat more pronounced. The reason is that the impact on L_t is driven by the present discounted value of the stream of wage payments, and not just by the per-period wage. The OBC implies that the negative productivity shock lowers the expected value of a match by more relative to the unconstrained Nash bargaining scenario. As a result, vacancy posting responds more strongly, leading to lower employment and output. However, the OBC implies a smaller drop in employment relative to the case in which wages are unconditionally rigid. In the latter case, the wage constraint is binding in all periods, further reducing the expected profit from a match and vacancy posting. As we show next, the more powerful amplification of first-moment shocks implied by unconditionally rigid wages does not carry over to the transmission of second moment shocks.

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[21] The ergodic mean in the absence of shocks is the fixed point of the fourth-order approximated policy functions. It is obtained by simulating the system with all shocks set to 0 for all time periods iterating forward until convergence.

5 The Transmission of Uncertainty Shocks

This section discusses how the OBC on wage adjustment affects the propagation of uncertainty shocks. To build intuition, we first discuss a simplified version of the model that abstracts from endogenous physical capital accumulation. Next, we quantify the effects of downward wage rigidity using the general equilibrium model of section 2. Finally, we provide empirical evidence supporting the model predictions.

Building Intuition: A Three-Period Model

We begin by studying a finite-horizon, partial-equilibrium version of the model[22]. We provide all the mathematical details in Appendix G. The mechanism we highlight is the following. Search frictions in the labor market imply that current job creation depends on the expected present discounted value of the stream of profits generated by a match over its tenure. The existence of an OBC on wage adjustment generates concavity in the firm's profit function, resulting in a profit-risk premium: the expected stream of profits is smaller than the profit stream from the expected productivity. An increase in the dispersion of future productivity realizations increases the profit-risk premium, inducing firms to optimally reduce current hiring and employment.

Consider the following simplifying assumptions. First, the economy only lasts three periods, $t = [0, 1, 2]$. Second, employee-firm matches are formed at the end of period $t = 0$ and are productive at time $t = 1, 2$. Third, the flow value of unemployment is zero ($b = h = 0$) and the surplus share η is 0.5. Fourth, each match produces output $y_t = 2Z_t$, where the c.d.f. $F(Z_t)$ is uniform. At the time of the hiring decision, the expected stream of revenues and wage payments are, respectively: $\overline{y}_0 = E_0 \sum_{t=1}^{2} y_t$ and $\overline{w}_0 = E_0 \sum_{t=1}^{2} w_t$.

Under these assumptions, we can prove the following two propositions:

Proposition 1 *With unconstrained Nash bargaining or fixed wages, an increase in the variance of Z_2 for given $E(Z_2)$ does not affect period-2 expected profits. When a lower bound w_m constraints wage bargaining, period-2 expected profits fall. The fall is larger the higher the increase in variance of Z_2.*

Proposition 2 *When an increase in the variance of Z_2 for given $E(Z_2)$ lowers period-2 expected profits, the total stream of expected profits falls with constrained Nash bargaining.*

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[22] In a similar framework, Cabrales and Hopenhayn (1997) discuss the impact of downward wage rigidity on job creation.

As previously discussed, wage rigidity increases the sensitivity of firms' profits to productivity—a fixed wage makes the firms' surplus more procyclical, resulting in more procyclical profits, hiring, and employment. By contrast, Proposition 1 establishes that both with flexible Nash bargaining and fixed wages, the variance of Z_2 is irrelevant for period-2 expected profits. Intuitively, both wage protocols imply the profit function is linear in productivity. Accordingly, higher moments of the productivity distribution do not affect expected profits. The result is very different when Nash bargaining is constrained by w_m. In this case, the profit function is concave, and the firms' surplus share is procyclical only when $w_t < w_m$. Thus, an increase in σ_{Z_2} lowers the expected profit for the period $t = 2$.

Setting w_m equal to a higher value will increases the productivity value Z^m for which the wage-setting constraint becomes binding. We show in Appendix G that as Z^m gets closer to the average productivity $E\{Z\}$, and $[E\{Z_t\} - Z^m]$ gets smaller, the same marginal increase in uncertainty will result in a larger reduction in expected profits. This mechanism explains why in the full general-equilibrium model, the impact of uncertainty on profits and employment becomes larger in a recession. When Z_t is a persistent process, low values of Z_t result in low values of $[E\{Z_{t+1}\} - Z^m]$. In turn, this implies that an increase in the variance of TFP shocks will have a larger impact on expected profits. The opposite is true in an expansion, implying that uncertainty shocks have a smaller effect. Finally, notice that an increase in the variance of productivity may also lead to higher profits if the profit function is not concave over the whole domain, a result known as the "Oi-Hartman-Able effect." (See Appendix G for a discussion.)

Proposition 2 establishes that not only period-2 profits, but the total value of a match $\overline{y}_0 - \overline{w}_0$ is concave in Z_2. This is the consequence of two results, which also apply to the general-equilibrium model. First, the constrained-Nash wage in $t = 1$ differs from the unconstrained Nash wage even when the constraint is not binding. This happens since the period-1 wage depends on the entire expected value of the match, which includes future outcomes in which wage adjustment could be precluded. Second, the possibility that the constraint will be binding at $t = 1$ implies that at time $t = 0$ the stream of expected profits, $\overline{y}_0 - \overline{w}_0$, is affected by a change in the variance of Z_2. Only if wage adjustment were unconstrained at $t = 1$, wages could be set to undo the effects of the wage constraint at $t = 2$. In this case, a change in the variance of Z_2 would have no consequences for job creation.

Quantification

The Effects of Uncertainty at the Stochastic Steady State

We now show that the intuition from the three-period model extends to the general equilibrium model. We first consider the response to a one-standard deviation increase in σ_{Zt} when the economy is at the stochastic steady state. The shock implies that the standard deviation of TFP increases from 0.006 (its unconditional mean level) to 0.0085. Following Basu and Bundick (2017), Born and Pfeifer (2014), and Fernandez-Villaverde, Guerron-Quintana, Rubio-Ramirez, and Uribe (2011), we measure the pure uncertainty effects of a change in the distribution of future shocks. This amounts to setting to zero the direct effect that a change in σ_{Zt} has on the realization of first moment shocks.[23]

Figure 5 compares aggregate dynamics under the three wage protocols: (i) OBC on Nash bargaining (cross-marked lines), (ii) unconstrained wages (dashed lines), and (iii) Hall's wage rigidity (dashed-dotted lines). The uncertainty shock is recessionary in all three cases: Employment and output fall when σ_{Zt} increases. However, the quantitative impact is very modest both with unconstrained wage adjustment and wage rigidity that binds at all times (output declines at most by 0.05%). Consistent with the intuition from the three-period model, an increase in the likelihood of more extreme first-moment shocks does not induce a large change in expected firm's profits, since both wage protocols have little impact on the concavity of the profit function.

By contrast, Figure 5 shows the uncertainty increase has a stronger effect in the presence of the OBC on wage adjustment. In relative terms, the response of output is five times larger (output declines by approximately 0.25%). The reason is that the OBC results in a sizable profit-risk premium which is increasing in the variance of future shocks. Higher TFP volatility leads to more extreme output outcomes, and the fall in expected profits associated with the increased likelihood of negative TFP innovations is larger than the expected gain associated to more likely positive TFP innovations. As a result, higher uncertainty reduces the firm's surplus, lowering vacancy posting even when the wage constraint is not binding. To summarize, while the employment response to first-moment shocks is smaller in the model with the OBC relative to the unconditionally rigid-wage scenario, the opposite is true for second-moment shocks.

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[23] This effect can be traced in the policy functions through the multiplicative terms in $u_{Z,t+s}$ and $\sigma_{Z,t-1}$, as discussed in Appendix C.

Business Cycle Dynamics

We now quantify the effect of uncertainty shocks on output and unemployment over the business cycle. The goal is twofold. First, we want to measure the average effect of time-varying volatility. Second, we want to assess whether existing macroeconomic conditions matter for the transmission, i.e., whether and how the sensitivity of the profit-risk premium varies over the business cycle.

Since we are interested in the "pure effect" of uncertainty shocks, we cannot simply compare aggregate dynamics with and without second-moment shocks—as previously discussed, results would be partly driven by realized uncertainty (a first-moment shock). We therefore resort to a model counterfactual that extends the approach commonly used to construct generalized impulse responses. We perform $N = 1000$ simulations with length $T = 250$. In each simulation, we draw shocks from time $t = 1$ to time $j \in [1, T]$ and draw an uncertainty shock in the absence of first-moment shocks at time $j + 1$. The net effect of the uncertainty shock is the the difference relative to what observed at time $j + 1$ in the absence of both first- and second-moment shocks. Thus, the approach measures the net impact of stochastic volatility conditional on the endogenous evolution of the state variables over the cycle. It accounts for the nonlinear dynamics in the size of the shock, the point in the state space where the shock occurs, and the distribution of future random shocks. It is also straightforward to construct impulse response functions for each of the uncertainty shock in the simulation.

We first compute generalized impulse responses for the mean increase in the TFP volatility shock observed in the simulations (approximately equal to a one-standard deviation shock). The first row in Figure 6 (continuous lines) plots the average response of output and unemployment when initial output is in the interval $[-5\% \,; -3\%]$. The initial output mean is approximately -4%, consistent with the trough in U.S. output during the Great Recession. Cross-lines plot the average response when initial output is in the interval $[3\% \,;5\%]$. As shown by the figure, the OBC results in strong state-dependence: In the recession, the increase in uncertainty reduces output by 0.55% (at the trough) while unemployment increases up to 0.4 percentage points. The impact is approximately ten times smaller during the expansion, where output on average falls by 0.05%.

These results are explained by the dynamics of the profit-risk premium. In the expansion, the likelihood the wage constraint will be binding in the future is small. As a result, higher dispersion of future productivity shocks has a negligible impact on the expected profit from a match. By contrast, in the recession, the economy is already close to the wage constraint. Therefore, higher uncertainty induces a sizable drop in the firm's expected profits, leading to a stronger fall in job creation.

The second row in Figure 6 considers the average effect of larger positive uncertainty shocks. Specifically, we consider innovations that are greater than one-standard deviation. The average shock is approximately an 80% increase relative to the steady state (two-standard deviations). This magnitude is comparable to the increase in various measures of uncertainty observed in the third quarter of 2008, including an estimate of TFP volatility for the U.S. economy, as discussed in the next subsection—see also Appendix H. Considering the same range of initial output levels discussed above, the output loss is on average 0.9% in the recessionary states. The average effect remains very modest in the expansions (output declines on average by 0.15%).

Finally, the third row in Figure 6 generalizes the results, presenting the average, cumulative one-year response of output and investment for a broader range of initial output levels—from -5% to 5% relative to the steady state. We consider again the two uncertainty shocks discussed above—the uncertainty mean shock (continuous line) and the average of uncertainty shocks greater than one-standard deviation (dashed line). After one year, the cumulative output effect of the uncertainty mean increase ranges between -1.25% (in the deepest recession) and zero. The cumulative decline in investment is between -3% and zero. Across the whole distribution, the average cumulative output loss after one year is -0.65%. These figures more than double when considering uncertainty shocks greater than one standard deviation. These result obtain assuming zero correlation between first- and second-moment shocks. If shocks happened to be negatively correlated, i.e., if positive uncertainty shocks were more likely to occur after negative realizations of first-moment shocks, the average impact of the OBC on wage adjustment measured over the business cycle would be even stronger.

To summarize, our results show that occasionally binding downward wage rigidity can be an important source of amplification of uncertainty shocks. In particular, lack of flexible wage adjustment implies that heightened uncertainty can substantially deepen a recession. At the same time, downward wage rigidity becomes progressively less important when the constraint is binding with low probability.

Empirical Evidence

A few recent contributions test whether uncertainty shocks have asymmetric effects over the business cycle.[24] We provide novel evidence of the state-dependent effects of uncertainty shocks by estimating smooth-transition local projections. Auerbach and Gorodnichenko (2012a) and Tenreyro and Thwaites (2016) popularized this method and we follow their approach. In addition, we also consider a specification where the state of the business cycle is identified with a dummy variable based on NBER recession dates (e.g., Ramey and Zubairy, 2018). While local projections have the advantage of not imposing any dynamic restriction, in Appendix H, we confirm the robustness of the results by estimating a non-linear Interacted VAR (I-VAR). We measure aggregate uncertainty using the TFP volatility series estimated in Section 3 to parameterize the exogenous uncertainty process in the model.

Let y_{t+h} denote the outcome variable of interest. We estimate the following set of h-steps ahead predictive regressions, for $h = 0, .., H$:

$$\begin{aligned} y_{t+h} = {} & F(\zeta_t)\left(\delta_h^R + \alpha_h^R \sigma_{Z,t} + \sum_{j=1}^{p} \beta_{j,h}^R X_{t-j}\right) \\ & + [1 - F(\zeta_t)]\left(\delta_h^{NR} + \alpha_h^{NR} \sigma_{Z,t} + \sum_{j=1}^{p} \beta_{j,h}^{NR} X_{t-j}\right) + u_{t+h}, \end{aligned} \tag{7}$$

where $\sigma_{Z,t}$ is the measure of exogenous uncertainty, X_t is a vector of controls, and u_{t+h} is the prediction error term. $F(\zeta_t)$ is a smooth transition function which indicates the state of the economy (Granger and Terasvirta, 1993):

$$F(\zeta_t) \equiv \frac{\exp\left(-\gamma \frac{\zeta_t - \bar{\zeta}}{\sigma_\zeta}\right)}{1 + \exp\left(-\gamma \frac{\zeta_t - \bar{\zeta}}{\sigma_\zeta}\right)} \in [0, 1],$$

where ζ_t is the transition variable and $\gamma > 0$ governs the smoothness of the transition between states.

We estimate equation (7) for each forecast horizon via ordinary least squares. The coefficient α_h^R (α_h^{NR}) gives the time $t + h$ response following a time-t uncertainty shock in the recessionary (non-recessionary) state. Thus, the local projections correspond to the set of coefficients α_h^R (α_h^{NR})

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[24] For instance, Caggiano, Castelnuovo, and Pellegrino (2017) show that the contractionary effects of higher uncertainty are statistically larger at the zero lower bound. Caggiano, Castelnuovo, and Pellegrino (2019) find stronger uncertainty effects on several indicators of U.S. real economic activity in a recession.

for $h = 0, .., H$. If the effects of heightened uncertainty are state dependent, we would expect α_h^R to be statistically significantly different than α_h^{NR}, at least at short horizons h.

We consider two outcome variables (y_t): real GDP and the unemployment rate. We measure uncertainty, $\sigma_{Z,t}$, using the median estimate from the backward-smoothing version of the particle filter on the stochastic volatility model of Section 3.[25] We include two lags of the following controls: the uncertainty measure, real GDP, the 4-quarter difference of the log-consumer price index excluding food and energy, the federal funds rate, and the outcome variable y_t. Following Auerbach and Gorodnichenko (2012a), the transition variable ζ_t is the deviation of the output growth rate from a smooth trend.[26] We set $\gamma = 1.5$, a standard choice for U.S. data (e.g., Auerbach and Gorodnichenko, 2012a and Auerbach and Gorodnichenko, 2012b).[27]

The first row in Figure 7 presents impulse responses following a one-standard deviation increase in uncertainty. Continuous lines identify the response in the recessionary state, while dashed lines correspond to the non-recessionary state. We plot 90 percent confidence bands based on Newey-West standard errors that account for the serial correlation at horizon $h > 0$. In the recessionary state, the increase in uncertainty lowers output by 1% percent at the trough, while unemployment increases by 0.5 percentage points at the peak. In the non-recessionary state, the response of output and unemployment is in general statistically not significant. The second row in Figure 7 shows that the difference between the response in the recessionary and non-recessionary states for output and unemployment is significant at the 90% confidence level.

For robustness, we consider an alternative approach to identify the recessionary and non-recessionary states. We replace $F(\zeta_t)$ with a dummy variable that takes value equal to one in quarters that correspond to the NBER recessions dates (approximately 12% of the sample) and 0 otherwise. As shown by the third row of Figure 7, the results are robust to this alternative specification. The difference between the responses in recessionary and non-recessionary states is also statistically significant (see the fourth row in Figure 7).

To summarize, the empirical analysis shows that the impact of uncertainty shocks varies over the business cycle, consistent with the model. An increase in uncertainty results in a significant drop in output only in a recession.

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[25] We follow Godsill, Doucet, and West (2004). The smoothed draws are computed using 1,000 draws from the posterior and 1,000 particles.

[26] We extract the trend using the Hodrick-Prescott filter with smoothing parameter $\lambda = 10,000$), accounting for the historical long-run decline in the mean of output growth.

[27] Granger and Terasvirta (1993) suggest imposing a fixed value for γ (see also Auerbach and Gorodnichenko, 2012a). The estimation of γ would rely on nonlinear moments and hence estimates may be sensitive to a handful of observations in short samples.

6 The Dynamics of Measured Uncertainty

A robust conclusion from the empirical literature is that several measures of aggregate uncertainty are countercyclical, including the volatility of stock and bond markets, the volatility of output and exchange rates, measures of disagreement among professional forecasters, their self-reported subjective forecast uncertainty, and the variance of future output growth conditional on current information (see Bloom, 2014).

In this section, we show that the OBC on wage adjustment can account for the negative correlation between recessions and empirical measures of uncertainty. We focus on the conditional volatility of the output forecast error, i.e., the conditional volatility of the unforecastable component of the $h - step$ ahead future values of the series (Jurado, Ludvigson, and Ng, 2015): $\sigma^*_{t+h} \equiv \sqrt{E\left[\left(Y_{t+h} - E\left(Y_{t+h}|I_t\right)\right)^2 |I_t\right]}$. The key insight from the analysis is that the OBC implies that σ^*_{t+h} is time-varying and countercyclical even when the conditional volatility of shocks does not change, i.e., in the absence of second-moment shocks. This result adds to the literature on endogenous uncertainty, showing that fluctuations in empirical measures of uncertainty can also stem from from agents' optimal decisions in response to first-moment shocks.

To illustrate this point, consider the following experiment. Assume that the conditional volatility of TFP is constant, $\sigma_{Z,t} = \sigma_Z$. Then compute the conditional volatility of the one-step ahead output forecast error, $\sigma^*_{t+1} \equiv \sqrt{E\left[\left(Y_{t+1} - E\left(Y_{t+1}|I_t\right)\right)^2 |I_t\right]}$, when TFP is either 1% above or 1% below the ergodic mean. We compute σ^*_{t+1} by drawing $10,000$ innovations for Z_{t+1}, obtaining the conditional distribution of the output forecast error $Y_{t+1} - E\left(Y_{t+1}|I_t\right)$. The conditional volatility of the output forecast error is $\sigma^*_{t+1} = 0.0115$ when Z_t is 1% above its ergodic mean, while $\sigma^*_{t+1} = 0.0204$ when Z_t is at -1%. Thus, σ^*_{t+1} is time-varying and state dependent even in the absence of second-moment shocks.

To understand these results, Figure 8 plots the distribution of $Y_{t+1} - E\left(Y_{t+1}|I_t\right)$ in the economic expansion and the recession. In the recession, the distribution is more dispersed, and the probability mass decreases around the median and increases both in the right and left tail. The higher dispersion reflects the stronger response of job creation to future innovations (both positive and negative ones) when the the wage constraint is binding with a higher probability. Intuitively, negative future shocks imply that wages will not be able to fully absorb the productivity drop. Positive productivity realizations will alleviate the wage constraint, stimulating vacancy posting. By contrast, during an economic expansion, the economy operates far away from the wage constraint. In this case, future shocks have a smaller impact on the match surplus and job creation, leading to a less dispersed distribution of outcomes. Notice that in the expansion, the distribution of the forecast error still displays asymmetric tails. This is also a consequence of the OBC. Intuitively, negative productivity shocks increase the probability that the wage constraint will bind in the future even in good times, inducing an asymmetric distribution in $t+1$ outcomes.

These intuitions are confirmed when inspecting the distribution of $Y_{t+1} - E\left(Y_{t+1}|I_t\right)$ in the model with unconstrained Nash bargaining. Figure 9 shows that in the absence of the OBC, the distribution is approximately identical in the recession and in the expansion. Thus, the higher forecast-error dispersion observed in a recession is the results of the OBC rather than of other nonlinearities in the model. In addition, with flexible wages the distribution has minimal skewness, both in a recession and in an expansion.

7 Conclusions

We have shown occasionally binding downward wage rigidity in frictional labor markets plays a central role in propagating uncertainty shocks and in explaining the countercyclicality of empirical measures of aggregate uncertainty.

With long-term employment relationships, the constraint on downward wage adjustment introduces a profit-risk premium by enhancing the concavity of firms' profits with respect to productivity. In turn, downward wage adjustment generates strong and state-dependent amplification of uncertainty shocks implying higher uncertainty can substantially deepen a recession. Model simulations show when output is 4% below its trend level, the average increase in TFP volatility observed in U.S. data induces an average output loss equal to 0.5%. If the uncertainty increase is of a magnitude comparable to what was observed in the Great Recession, the output loss is about 1%. Analogous uncertainty shocks have near-zero effects in economic expansions. Estimates from non-linear local projections provide support for these findings.

The occasionally binding constraint in wage negotiations also implies the variance of the unforecastable component of future economic outcomes always increases at times of low economic activity. Thus, measured uncertainty increases during recessions even in the absence of exogenous uncertainty shocks.

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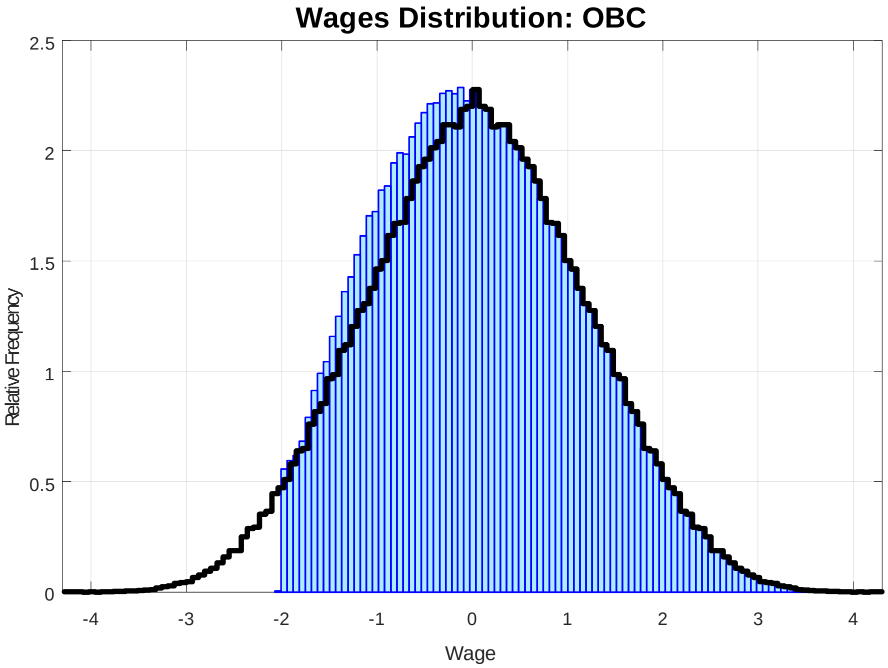

Figure 1. Ergodic wage distribution, model with the occasionally binding constraint on wage adjustment. Stairs plot: wage distribution that would be obtained if the wage realizations above the 50th percentile were symmetric around the median.

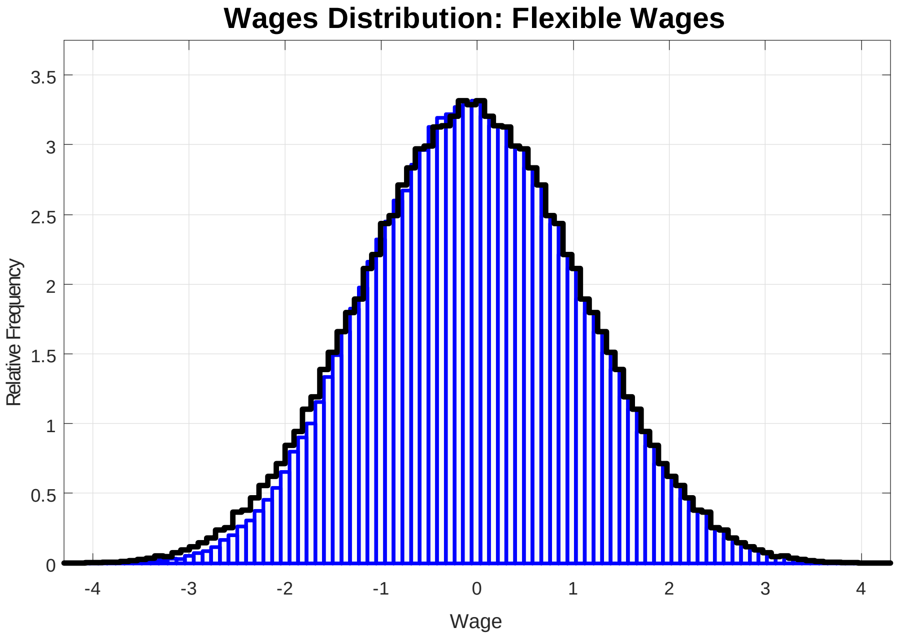

Figure 2. Ergodic wage distribution, model with unconstrained Nash bargaining. Stairs plot: wage distribution that would be obtained if the wage realizations above the 50th percentile were symmetric around the median.

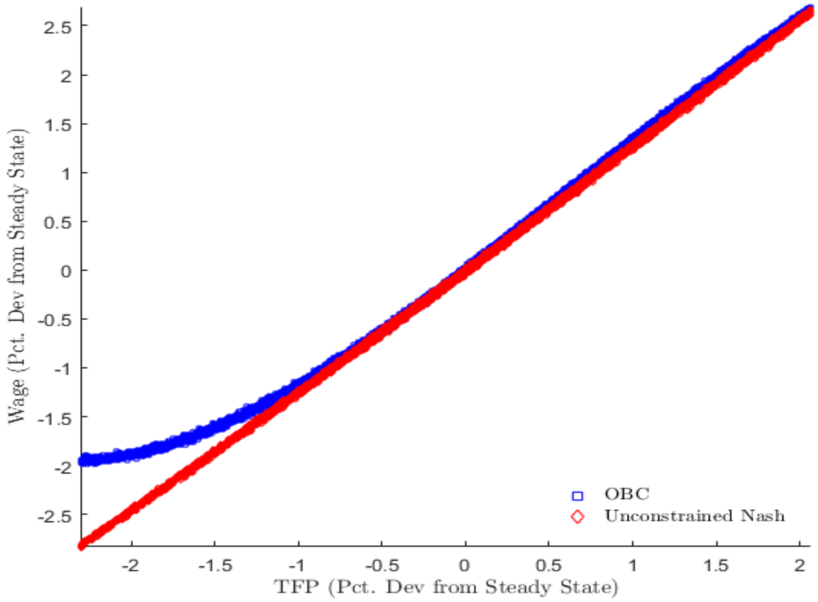

Figure 3. Scatter plot of wage outcomes, w_t, and TFP, Z_t. Model with the occasionally binding constraint on wage adjustment (squares) and model with unconstrained wage bargaining (diamonds).

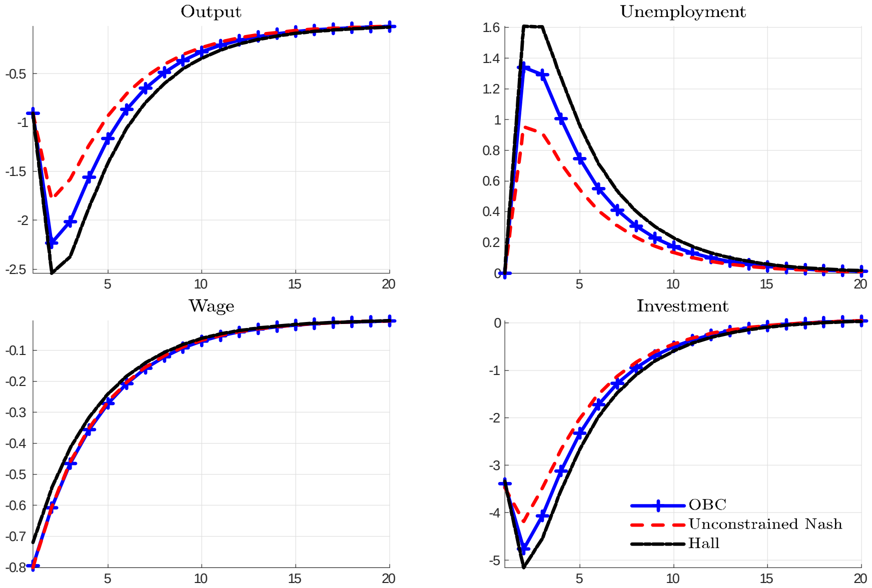

Figure 4. Impulse response function to a one-standard deviation decrease in productivity. *Cross-marked line*: OBC on wage adjustment; *Dashed line*: unconstrained Nash bargaining; *Solid line*: Hall (2005)'s real wage rigidity. Variables are in percentage deviations from the steady state, except unemployment which is in percentage points.

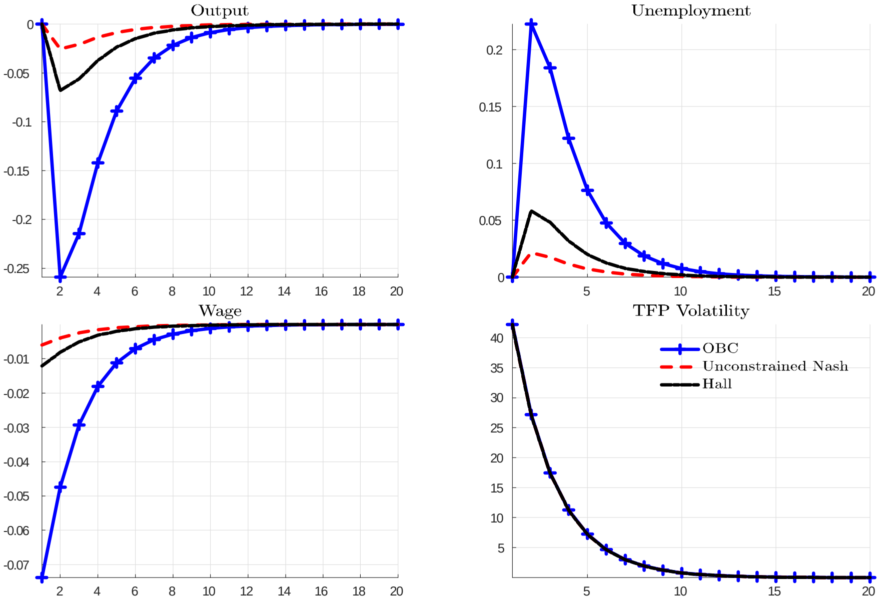

Figure 5. Impulse responses, one-standard deviation increase in the standard deviation of TFP, σ_{Z_t}. *Cross-marked line*: OBC on wage adjustment; *Dashed line*: unconstrained Nash bargaining; *Solid line*: Hall (2005) real wage rigidity. Variables are in percentage deviations from the steady state, except unemployment which is in percentage points.

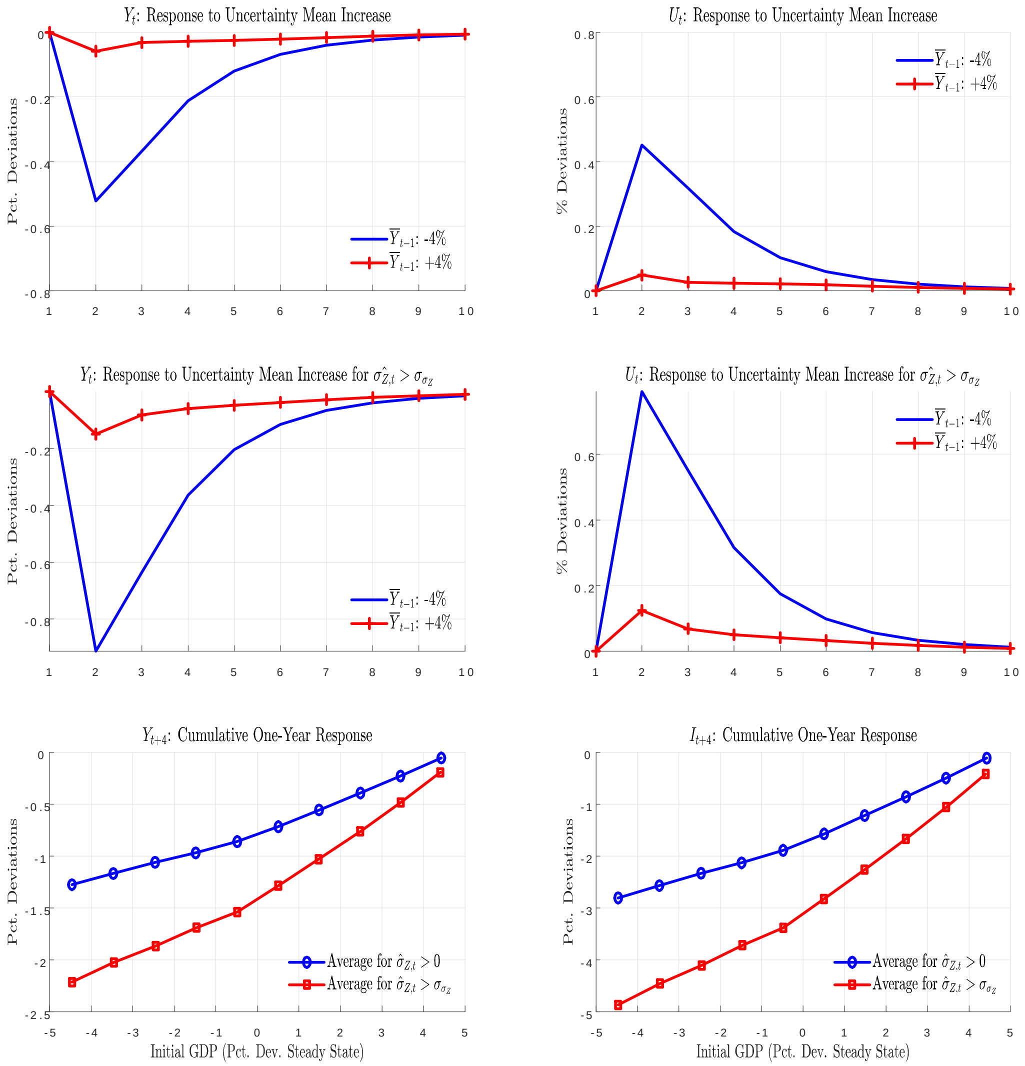

Figure 6. Average responses of aggregate variables to an increase in TFP uncertainty. *First row*: Uncertainty mean increase; average initial output level at -4% relative to steady state (solid line) and $+4\%$ (cross-marked line). *Second row*: Average of uncertainty shocks greater or equal to one-standard deviation; average initial output level at -4% relative to steady state (solid line) and $+4\%$ (cross-marked line). *Third row*: average, cumulative, one-year responses.

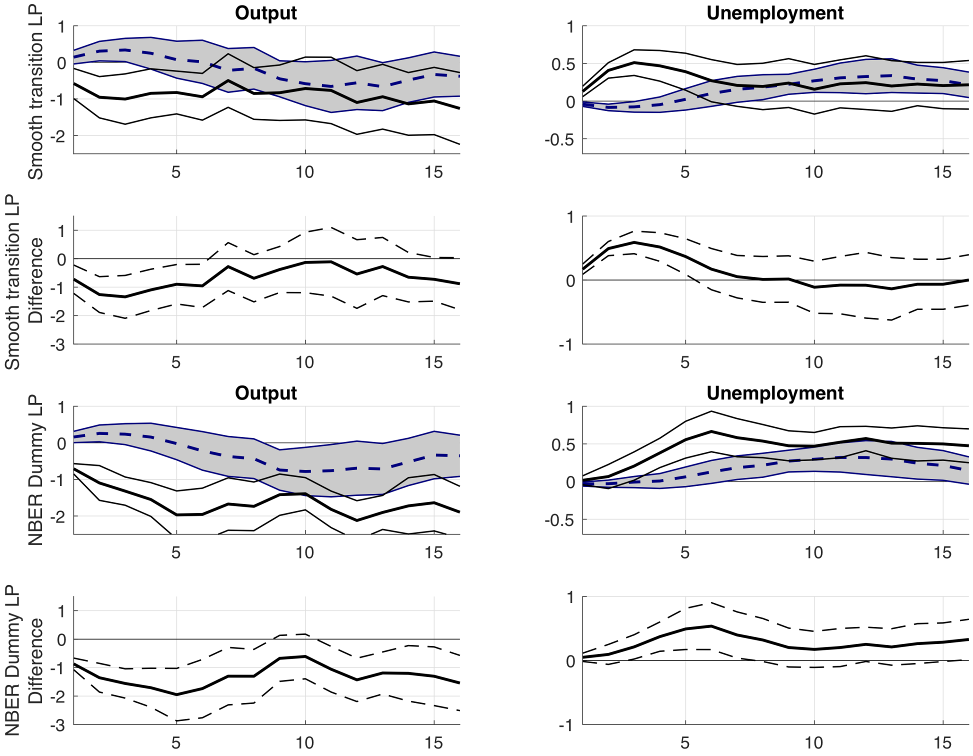

Figure 7. Local projections (LP) following an increase in TFP uncertainty. *First row*: smooth-transition LP, recessionary state (solid line) and non recessionary state (continuous lines); *Second row*: smooth transition LP, difference between responses in the recessionary and non-recessionary state; *Third row*: NBER-dates LP, recessionary state (solid line) and non recessionary state (continuous lines); *Fourth row*: NBER-dates LP, difference between responses in the recessionary and non-recessionary state. Confidence bands at 90% significance level.

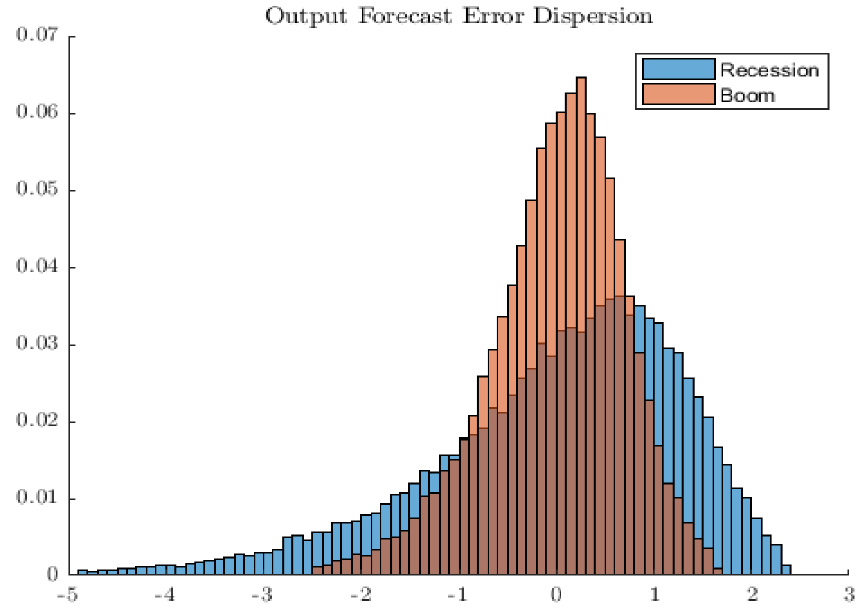

Figure 8. Time $t + 1$ output distribution following a negative (dark bars) and positive (light bars) one-standard deviation TFP shock at time t. Model with unconstrained Nash bargaining. Outcomes are in percentage deviations from the level of output at time t.

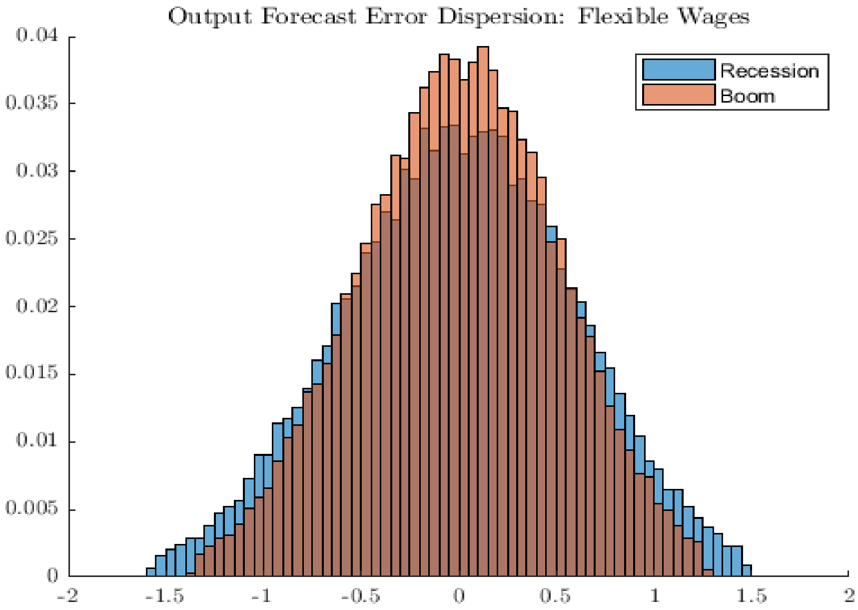

Figure 9. Time $t + 1$ output distribution following a negative (dark bars) and positive (light bars) one-standard deviation TFP shock at time t. Model with unconstrained Nash bargaining. Outcomes are in percentage deviations from the level of output at time t.