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Monetary Policy and Natural Disasters in a DSGE Model: How Should the Fed Have Responded to Hurricane Katrina?

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ABSTRACT

In the immediate aftermath of Hurricane Katrina, speculation arose that the Federal Reserve might respond by easing monetary policy. This paper uses a dynamic stochastic general equilibrium (DSGE) model to investigate the appropriate monetary policy response to a natural disaster. We show that the standard Taylor (1993) rule response in models with and without nominal rigidities is to *increase* the nominal interest rate. That finding is unchanged when we consider the optimal policy response to a disaster. A nominal interest rate increase following a disaster mitigates both temporary inflation effects and output distortions that are attributable to nominal rigidities.

I. Introduction

In late August 2005, Hurricane Katrina hit the U.S. Gulf coast with a catastrophic fury that caused unprecedented damage to the region. Burton and Hicks (2005) calculate that the total damage to homes, businesses, and infrastructure was more than $150 billion, making Katrina the costliest hurricane ever.[1] That estimate, in economic terms, represents about 0.4 percent of the Bureau of Economic Analysis's figure for total fixed capital and consumer durables at the end of 2004. Economic activity in the Gulf coast region also was disrupted during and immediately after the hurricane. As a result, quarterly U.S. GDP growth is estimated to have declined by around 0.4 percent in the third quarter of 2005.[2]

The magnitude of the disaster fueled speculation by financial market participants that the Federal Open Market Committee (FOMC) might ease policy at its meeting of September 20 by postponing a widely expected 25 basis point increase in the federal funds rate. The change in expectations was widely reported by the financial press. For example, an article in the *Cincinnati Post* on September 7 stated that, "Before the hurricane … economists considered it a foregone conclusion that Fed policy makers would boost short-term interest rates by another quarter percentage point… Now, a growing number of economists say the odds are rising that the Fed might take a pass …"

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[1] Estimates on the economic losses from Hurricane Katrina vary. Risk Management Solutions, for example, on September 9, 2005, estimated that insured losses were between $40 and $60 billion, while total economic losses exceeded $100 billion.

[2] A quarterly decline of 0.4% in U.S. third quarter GDP is based on estimates by the forecasting firms Macroeconomic Advisors and Global Insight. According to Cashell and Labonte (2005), Macroeconomic Advisors lowered their third quarter GDP annual growth forecast from 4.6% to 3.2% and their fourth quarter forecast from 3.6% to 3.3%. Insight lowered its forecast for annual GDP growth in the second half of 2005 by 0.7%. Evaluating these magnitudes for a single quarter, at a non-annualized rate, suggests an impact on output of approximately 0.4%.

Data from federal funds futures markets also confirm this shift in expectations. Figure 1 shows that the expected average funds rate for September and October began falling on the day after Katrina's landfall. From August 29 to September 6, the expected rate derived from the September contract fell 5 basis points, while the expected funds rate for October fell by 11 basis points.

At the September 20 meeting, the FOMC raised the federal funds rate by 25 basis points, as was widely expected before Katrina. The press release following the meeting stated that "While these unfortunate developments have increased uncertainty about near-term economic performance, it is the Committee's view that they do not pose a more persistent threat" [FOMC (2005)].[3] Given the FOMC was expected to raise its funds rate target prior to Katrina, the Committee's subsequent decision to follow that course of action indicate that monetary policy did not respond to the disaster.[4]

This paper uses a dynamic stochastic general equilibrium (DSGE) model to investigate how monetary policy should respond to catastrophic events such as Hurricane Katrina. We model infrequent catastrophic events using a two-state Markov switching process. Most of the time, the economy is in the non-disaster (or normal) state. In each period, however, a small probability exists that the economy will experience a disaster. A disaster is characterized by the destruction of a portion of the capital stock and a temporary negative technology shock that reduces output. We then analyze the impact of a disaster shock in model specifications with and without nominal price and wage rigidities.

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[3] In his lone dissent, Governor Olsen recommended no change in the federal funds rate "pending the receipt of additional information on the economic effects resulting from the severe shock of Hurricane Katrina."

[4] Although the FOMC did not respond directly to Hurricane Katrina, the Committee did take explicit action in the wake of a previous catastrophic event: the 9/11 attack. The 9/11 event differed from other disasters in that it threatened to disrupt the efficient functioning of the financial system [Neely (2004)].

Our results indicate that the monetary authority should *raise* its nominal interest rate target following a disaster. This prescribed increase in the federal funds rate clearly runs contrary to the conventional wisdom following Hurricane Katrina. The press and financial markets based their beliefs on an assumption that the Federal Reserve is motivated to dampen the fall in output caused by a disaster. When conducting monetary policy within a Taylor (1993) rule framework, however, the nominal interest rate responds primarily to higher inflation rather than to lower output. This finding also holds when an explicit disaster variable enters the policy rule. Using optimal-control theory, as applied by Woodford (2002) and others, the monetary authority should strive to replicate the dynamics of a flexible price and wage equilibrium. Generating these dynamics requires an increase in the nominal interest rate in response to higher inflation—and also to the higher real interest rate associated with depletion of the capital stock. Such a policy minimizes real distortions due to nominal price and wage rigidities.

The paper proceeds as follows. Section II outlines the model. Section III presents the specification of our disaster shock and its effects on the capital stock and output. Section IV examines the impact of a disaster when the Federal Reserve follows a standard Taylor rule. Section V analyzes the optimal monetary policy response to a disaster. Section VI concludes.

II. Model Framework

We examine a fully articulated DSGE model where firms are monopolistically competitive producers of goods and households are monopolistically competitive suppliers of labor. Imperfect competition in the goods and labor markets enables us to consider models with price and nominal wage rigidities. Specifically, we consider three different specifications of our benchmark DSGE model: flexible prices and wages ("flexible model"), sticky prices and flexible wages ("sticky price model"), and sticky prices and sticky wages ("sticky price and wage model").[5]

Households are infinitely lived agents who maximize expected discounted utility over consumption, leisure, and real money balances. They hold money for liquidity purposes, trade bonds between themselves, invest in physical capital subject to Hayashi (1982) style adjustment costs, and participate in state-contingent securities markets. Each period, households supply differentiated labor services to firms in a monopolistically competitive market. Total labor supply then is calculated as a Dixit and Stiglitz (1977) continuum of labor services provided by the households. Wage adjustment opportunities follow a Calvo (1983) specification. That is, the probability that a household can optimally adjust its nominal wage is η_w, while the probability that the nominal wage rises by only the steady-state inflation rate is $(1 - \eta_w)$.[6]

Firms rent capital and labor services from the household sector to produce differentiated goods in a monopolistically competitive market according to a Cobb-Douglas production function. Aggregate output comprises a Dixit and Stiglitz continuum of differentiated products and price adjustment follows a Calvo process. In each period, a random fraction, η_p, of firms can optimally adjust their price, while the remaining firms, $(1 - \eta_p)$, can adjust only by the steady-state inflation rate.

Monetary policy is implemented by targeting the nominal interest rate, R_t. Specifically, the monetary authority uses a generalized Taylor rule:

$$\hat{R}_t = \theta_\pi \hat{\pi}_t + \theta_y \hat{y}_t + \theta_W \Delta\hat{W}_t + \theta_D \hat{D}_t + \varepsilon_t, \tag{1}$$

where ^ denotes a variable's log deviation from its steady state, y_t is output, π_t is the gross price inflation rate, ΔW_t is the gross wage inflation rate, D_t is a "disaster shock," and ε_t is a

[5] Our model is a variant of the model analyzed in Gavin, Keen, and Pakko (2009).

[6] Erceg, Henderson, and Levin (2000) also use this specification.

discretionary policy shock with a zero mean and variance of σ_ε^2. Appendix A provides a more detailed description of the model.

III. The Disaster Shock

We consider two crucial characteristics of a natural disaster like Hurricane Katrina. First, a disaster destroys an economically relevant share of the economy's productive capital stock. Second, a disaster temporarily disrupts production, which we model as a transitory negative technology shock. Since a disaster is an infrequent event, the disaster shock is modeled as a two-state Markov switching process. The negative shocks to the capital stock and to technology are specified then as functions of the two-state disaster variable.

The disaster shock variable, D_t, can take on one of two states. State 1 is the "normal" or "non-disaster" state, while state 2 is defined as a "disaster." The two states evolve according to a transition matrix with the following calibrated probabilities:

$$\begin{bmatrix} p_{11} & 1-p_{22} \\ 1-p_{11} & p_{22} \end{bmatrix} = \begin{bmatrix} 0.98 & 0.98 \\ 0.02 & 0.02 \end{bmatrix},$$

where $p_{ij} = prob(D_t = D^j \mid D_{t-1} = D^i).$ For the given probability values, there is a 2% probability a disaster will occur, regardless of the disaster variable's state in the previous period.

The disaster shock affects both the level of technology and the capital stock. First, technology is an economy-wide factor that enters each firm's Cobb-Douglas production function multiplicatively. The overall technology shock, Z_t, comprises the typical technology shock, z_t, that follows a first-order autoregressive process and an additional component related to the disaster variable's state:

$$\hat{Z}_t = \hat{z}_t + \zeta(\hat{D}_t). \tag{4}$$

Second, the disaster shock directly influences the accumulated capital stock. The timing of the disaster shock is important. In period *t–1*, the nondepreciated capital, $(1-\delta)k_{t-1}$, and new investment, i_t, are combined to get the amount of capital, k'_t, carried into period *t*:

$$k'_{t+1} = i_t + (1-\delta)k_t - AC_t, \tag{5}$$

where AC_t represents a capital adjustment cost.[7] A disaster, if it occurs, then will be realized at the beginning of period *t*, destroying a portion of the previously accumulated capital. The remaining capital available for production in period *t* is

$$\hat{k}_t = \hat{k}'_t - \kappa(\hat{D}_t). \tag{6}$$

This regime-shifting framework is mapped into the canonical difference-equations structure of the model by log-linearizing the Markov-switching process. Details of the derivation are described in Appendix B.

IV. Simulation Experiments

A. *Calibration*

The disaster shock variable is calibrated to reflect the magnitude of Hurricane Katrina's economic impact. First, the ratio D^2/D^1 is set to 1.004, providing a baseline magnitude for the shock's impact. The effect of $\hat{D}_t$ on capital and technology are calibrated to generate specific impulse responses consistent with the impact of Hurricane Katrina. In particular, the disaster variable's effect on the capital stock and technology are calibrated such that both the capital stock and output decline by 0.4% in the flexible price and wage equilibrium when the economy is in the "disaster" state. In terms of equations (4) and (6), this requires that we set $\zeta(\hat{D}_t) = -0.606\hat{D}_t$ and $\kappa(\hat{D}_t) = \hat{D}_t$.

[7] The specific functional form of the capital adjustment costs is outlined in Appendix A.

The existence or absence of nominal price and wage rigidities depends on the calibration of the probability of price adjustment, η_p, and the probability of wage adjustment, η_W. The probability of price adjustment equals 1 when prices are flexible and 0.25 when prices are sticky. Our calibration for the sticky price specification indicates that firms reset their price, on average, once per year, which is consistent with findings in Rotemberg and Woodford (1992). The probability of wage adjustment is set to 1 if wages are flexible and 0.25 if wages are sticky. The sticky wage calibration, which is consistent with Erceg, Henderson, and Levin (2000), suggests that nominal wage readjustment occurs, on average, once every year. Appendix A details the calibration of the model's other parameters, except the parameters in the policy rules (which are discussed below). Table 1 summarizes the model's calibrated parameters.

B. *Taylor Rule Responses*

Figure 2 illustrates the impact of a disaster on the flexible model, sticky price model, and the sticky price and wage model when the central bank follows a Taylor rule with $\theta_\pi = 1.5$ and $\theta_y = 0.125$.[8] We calibrate the shock to deliver a 0.4% fall in output for the flexible model. The negative shock to the capital stock and productivity factor prompts firms to lower their output and raise prices. That decline in output and rise in inflation is moderated when prices are sticky because some firms cannot optimally reset their price. To compensate for lost productivity and a lower capital stock, the non price-adjusting firms must increase their labor to maintain their production levels. Conversely, price adjusting firms reduce their labor demand as output falls. As a result, employment increases in the sticky price model and sticky price and wage model, but decreases in the flexible model.

[8] This calibration of the response to output is the equivalent of a coefficient of 0.5 on annualized percent changes. In addition, the coefficients on the gross wage inflation rate and the disaster shock are set to zero.

The larger output decline in the flexible model lowers household income giving them fewer resources to invest in capital than in the price stickiness models. In the period after the disaster, the return of productivity to its pre-disaster level permits firms to increase output, which lifts households' income and enables them to increase their investment in physical capital. That process continues for a number of periods as the capital stock is slowly reconstructed. In the longer term, the protracted rebuilding of the capital stock is associated with below-trend output and persistent, above-trend paths for employment, investment, and inflation.[9]

The endogenous response of monetary policy to inflation and output, via the Taylor rule, drives the movements in the nominal interest rate. The policy reaction to higher inflation after a disaster puts upward pressure on the nominal interest rate, while the decline in output generates downward pressure. In the standard Taylor rule calibration, the inflation rate effect dominates, so that an increase in the nominal interest rate is the prescribed monetary policy response. The initial increase in the nominal interest rate is over 80 basis points in the flexible model, while it rises only by about 30 basis points in the sticky price model and the sticky price and wage model. Destruction of the capital stock also increases future capital rental rates, which causes the equilibrium real interest rate to rise. The real interest rate rises initially by around 50 basis points in the flexible model, but only by about 20 basis points in the models with nominal rigidities. Finally, the gradual reconstruction of the capital stock keeps inflation and inflation expectations above their steady states for an extended period of time in all of the models.

Both components of the disaster shock—the destruction of the capital stock and the temporary decline in technology—affect key economic variables after such a shock. Table 2 decomposes the contemporaneous impact of a disaster shock on output, inflation, and the

[9] These longer-term effects distinguish our disaster shock from a simple, transitory technology shock. The persistent increase in inflation is one property of the Taylor rule policy that indicates its suboptimality.

nominal interest rate into the two separate components on the models in Figure 2. Immediately following the disaster shock, the temporary reduction in technology amplifies the decline in output and the rise in inflation and the nominal interest rate caused by the destruction to the capital shock. In subsequent periods, the persistent responses of the variables shown in Figure 2 are entirely attributable to the gradual rebuilding of the capital stock.

To evaluate the optimality of policy rules, we make use of Woodford's (2002) finding that an optimal monetary policy replicates the efficient level of output.[10] The introduction of monopolistic competition in our model creates an inefficiency wedge between the efficient level of output and the flexible price and wage level of output.[11] Those markup distortions, however, are nonstochastic, so that wedge remains constant. In particular, our disaster shock—which produces a temporary decline in technology and a loss of capital—has no effect on the wedge. Accordingly, the optimal monetary policy response to a disaster shock is closely approximated by the output dynamics of the flexible model.[12] Using this criterion, the dynamics illustrated in Figure 2 show that this calibration of the Taylor rule is suboptimal in the presence of nominal distortions. An optimal monetary policy should enable output to reach its flexible price and wage equilibrium.

V. Optimal Monetary Policy

The specifications of the Taylor rule considered in the previous section fail to generate

[10] Kim and Henderson (2005) also analytically derive this result in a model with one-period price and wage contracts.

[11] The efficient level of output occurs when the economy has no nominal rigidities and no distortions due to market power or taxes.

[12] Smets and Wouters (2003) also use this criterion for evaluating optimal monetary policy. It should be noted that this criterion identifies "optimal" policy as that which eliminates the distortions due to sticky prices. It does not address the welfare costs of inflation (area under the money demand curve) and the inefficiency of monopolistically competitive pricing, which remain even in the flexible price equilibrium.

the optimal monetary policy response to a disaster shock, and a discretionary departure from the Taylor rule can worsen the outcome from a welfare perspective. In this section, we consider systematic optimal monetary policy rules as derived in the literature and evaluate their implications for our disaster-shock model. Because such policy rules may not be feasible in practice, we also consider a constrained-optimal monetary policy in which the monetary authority responds directly to the disaster shock.

A. *An Example of Optimal Monetary Policy*

The optimal monetary policy rule depends on the source of nominal rigidities in the economy. Woodford (2002) argues that stabilizing the price level is the optimal monetary policy when prices are sticky. In a Taylor rule setting, that finding indicates that the parameter on inflation, θ_π, should be set to an extremely high value. Erceg, Henderson, and Levin (2000) find that it is optimal for the monetary authority to target the wage inflation rate when wages are sticky. That is, the monetary authority should place a large weight on the wage inflation parameter, θ_W, in the Taylor rule. In a sticky price and wage model, however, neither extreme monetary policy rule will suffice. A monetary policy rule vigorously targeting price inflation eliminates the effects of the price distortion but the wage rigidity remains. When wage inflation is the target of monetary policy, the effects of the wage distortion are removed from the model, but the impact of price stickiness remains.

The impact of a disaster shock when the monetary authority follows an extreme price-inflation control policy ($\theta_\pi = 10{,}000$) is illustrated in Panel A of Figure 3. When the monetary authority aggressively responds to price inflation, monetary policy effectively prevents price inflation from changing, which eliminates distortions due to the price rigidity. That policy is optimal for the sticky price model because it enables the model to generate precisely the same output response as the flexible model. Elimination of the price distortion also causes the sticky price and wage model to resemble a model with nominal wage rigidities. The reduction in output pushes down labor demand, which produces a decline in the real wage. Since price inflation is unchanged, the nominal wage inflation rate falls after a disaster shock in all of the models.

Panel B of Figure 3 shows the effect of a disaster shock when the monetary authority pursues an extreme wage-inflation target $(\theta_W = 10{,}000)$. By aggressively targeting the wage inflation rate, the monetary authority eliminates distortions caused by the nominal wage rigidity. Therefore, wage inflation is unchanged after a disaster shock in all three models. That policy causes the sticky price and wage model to resemble the sticky price model. Targeting wage inflation, however, is not optimal for either of the models with nominal rigidities because real output deviates from the flexible price and wage equilibrium. The lower real wage rate caused by lower labor demand combined with a monetary policy objective of maintaining a constant nominal wage rate forces price inflation to rise in all three models.

A monetary policy that aggressively targets both price inflation and wage inflation fails to eliminate the effects of either price or wage distortions. Panel C of Figure 3 shows the impact of a disaster shock for a policy that targets both price and wage inflation. In all of the models, price inflation rises but wage inflation declines. The wage inflation decline is caused by a falling real wage rate that dominates the price inflation increase. In the Taylor rule, the downward pressure from wage inflation cancels out the upward pressure on the nominal interest rate from the rising price inflation rate. Since the effects of both nominal rigidities are still present, the output response is suboptimal in both the sticky price model and the sticky price and wage model.

B. *Constrained-Optimal Policy Responses*

A monetary policy rule that vigorously responds to price or wage inflation fluctuations may be optimal in theory, but may not be feasible in practice. The impulse responses illustrated in Figure 3 require that the market participants believe the monetary authority will respond with "excessive force" to any price or wage deviations, so that prices or wages will never change. Assuming that such a policy is not feasible in practice, we consider an alternative strategy in which the monetary authority systematically and directly responds to a disaster shock in an otherwise standard Taylor rule.

We begin by searching for the optimal monetary policy response to the disaster shock, θ_D, in a standard calibration of the Taylor rule ($\theta_\pi = 1.5$, $\theta_y = 0.125$, and $\theta_W = 0.0$). Following Woodford (2002), the optimal policy response to a disaster shock in a model with nominal rigidities is the value of θ_D that minimizes variation of output from its flexible price and wage equilibrium. Figure 4 displays a grid-search across a range of values for θ_D, where a positive value for θ_D implies an increase in the nominal interest rate target.[13] In both models with nominal rigidities, the optimal value for θ_D is positive, which suggests that the optimal conditional response to a disaster shock is a policy tightening. A comparison of the output responses in Figure 5 indicates that when θ_D is set equal to its optimal value, the interest rate rises more than indicated by the Taylor rule alone, and the reduction in output more closely mirrors the flexible price and wage equilibrium.

The optimal coefficient on the response of the nominal interest rate target to a disaster shock can be negative in some circumstances. Figure 3 shows that when the optimal policy rule for sticky prices is applied to the sticky price and wage model, output declines more in that model than in the flexible model. Such a response suggests that the optimal coefficient on the disaster shock parameter in the Taylor rule can be negative.

[13] For each set of parameter values, the model is simulated 1000 times over a sample period of 160 quarters.

Figure 6 illustrates an example of a plausible policy rule calibration ($\theta_\pi = 5.0$, $\theta_y = 0.0$, and $\theta_W = 0.0$) where the optimal value of θ_D is found to be negative for the sticky price and wage model. In this case, the systematic response to price inflation in the policy rule now eliminates much of the distortion from the price stickiness. Inefficiencies from the nominal wage rigidity, however, remain in the sticky price and wage model. Eliminating that wage distortion requires an easing of monetary policy in direct response to a disaster shock (i.e., θ_D is negative). Figure 7 demonstrates that the output response to a disaster shock is much closer to the optimal output response from the flexible model when policy directly responds to the disaster shock. On the other hand, it also shows that the aggressive response of monetary policy to rising inflation still makes it optimal to raise the nominal interest rate target in response to a disaster shock. The direct response to the disaster (θ_D <0) only partly mitigates the increase in the nominal interest rate.

VI. Conclusion

Once the damage from Hurricane Katrina became apparent, the media and financial markets speculated that the Federal Reserve might ease policy by delaying an expected 25-basis-point increase in the federal funds rate. Three weeks later at its next meeting, however, the Federal Reserve decided to maintain its pre-Katrina policy stance and raise the federal funds rate by 25 basis points. This paper examines the appropriate monetary policy response to a natural disaster such as Hurricane Katrina.

Our findings suggest that, in most circumstances, the monetary authority should *increase* its nominal interest rate target after a natural disaster that temporarily reduces productivity and destroys some capital stock. When monetary policy is conducted using a Taylor style rule, the higher inflation effect dominates the lower output effect such that the endogenous policy response to a disaster is a rise in the nominal interest rate. We then apply Woodford's (2002) findings on optimal monetary policy to show that the optimal response to a disaster depends on the sources of nominal rigidities. Any direct easing after a disaster, nonetheless, is dominated by the need to tighten policy in response to higher inflation and to accommodate the increase in the real interest rate. Thus, the optimal monetary policy response to a natural disaster entails an increase in the nominal interest rate.

The reaction of monetary policy to any recurring shock should be evaluated in terms of systematic responses to infrequent events, not as discretionary responses to random shocks. Individuals observe policy actions and form expectations about similar future events. These expectations must be endogenized within economic models in order to provide robust policy analysis. The findings from our disaster-scenario framework show that a rigorous model-based approach to policy analysis sometimes generates prescriptions that are at odds with the prevailing public opinion expressed in the popular press.

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APPENDIX A: Model Details

This appendix outlines the detailed equations of our dynamic stochastic general equilibrium (DSGE) model with both sticky prices and sticky wages. Our model is similar in structure to that in Gavin, Keen, and Pakko (2009), except that it includes a disaster shock. The calibrations needed to convert the price and wage stickiness into flexible specifications and the parameterization of the monetary policy rule are discussed in the text of the paper. Calibrated values for the remaining parameters are presented in Table 1. Once the system of equations is calibrated, the model is solved for its steady state parameter values; the model is linearized around that steady state; and the rational expectations solution is calculated using the methodology of King and Watson (1998, 2002).

Households**:** Households supply differentiated labor services to the firms in a monopolistically competitive labor market. Total aggregate labor hours, n_t, is calculated as a Dixit and Stiglitz (1977) continuum of labor hours, $n_{t,h}$, supplied by each household, $h \in [0,1]$:

$$n_t = \left[\int_0^1 (n_{h,t})^{\varepsilon_w/(\varepsilon_w - 1)} dh \right]^{(\varepsilon_w - 1)/\varepsilon_w},$$

where $-\varepsilon_w$ is the wage price elasticity of demand for household h's labor services. Firms' demand for household h's labor services are calculated by minimizing labor costs subject to the equation of aggregate labor hours:

$$n_{h,t} = \left(\frac{W_{h,t}}{W_t} \right)^{-\varepsilon_w} n_t,$$

where $W_{h,t}$ is the nominal wage rate of household h, and W_t is interpreted as the aggregate nominal wage rate:

$$W_t = \left[\int_0^1 (W_{h,t})^{(1-\varepsilon_w)} dh \right]^{1/(1-\varepsilon_w)}.$$

Households are infinitely lived agents who participate in state contingent securities markets. That assumption enables households to be homogenous with respect to consumption, investment, capital, money, and bonds. Household h values consumption, c_t, and real money balances, (M_t/P_t), but dislikes labor. Those preferences are summarized by the following expected utility function:

$$E_t \sum_{i=0}^{\infty} \beta^i \left(\ln(c_{t+i}^*) - \chi \frac{n_{h,t+i}^{1+\sigma_1}}{1+\sigma_1} \right),$$

where

$$c_t^* = \left((c_t)^{(\sigma_2-1)/\sigma_2} + b\left(\frac{M_t}{P_t} \right)^{(\sigma_2-1)/\sigma_2} \right)^{\sigma_2/(\sigma_2-1)},$$

E_t is the conditional expectation at time t, and β is the discount factor.

Households own the capital stock, k_t, and rent it to the firms. In each period, household h selects a level of investment, i_t, such that:

$$k'_{t+1} = \phi(i_t / k_t)k_t + (1-\delta)k_t,$$

where k'_{t+1} is amount capital carried into period $t+1$, $\phi(\cdot)$ represents a Hayashi (1982) form of capital adjustment costs and δ is the depreciation rate. The capital adjustment costs are the resources lost in the conversion of investment to capital, $i_t - \phi(i_i / k_t)k_t$, and are an increasing and convex function of the steady state investment-to-capital ratio such that $\phi(\cdot) > 0$ and $\phi''(\cdot) < 0$. A disaster, if it strikes, occurs at the beginning of period t before production begins. The non-destroyed capital, k_t, that is available for use in production is

$$k_t = k'_t - \kappa(\hat{D}_{t+1}).$$

Household h begins a period with an initial stock of nominal money balances, M_{t-1}, and receives a payment, $R_{t-1}B_{t-1}$, from its nominal bond holdings, B_{t-1}, where R_t is the gross nominal interest rate. During the period, household h receives labor income, $W_{h,t}n_{h,t}$, rental income from capital, $P_tq_tk_t$, dividends from the firms, D_t, a lump-sum transfer from the monetary authority, T_t, and a payment from the state contingent securities markets, $A_{h,t}$, where q_t is the real rental rate of capital. Those funds then are used to finance consumption and investment purchases and end-of-the-period bond, B_t, and money, M_t, holdings. The budget constraint for household h is represented as follows:

$$B_t + P_t(c_t + i_t) + M_t = W_{h,t}n_{h,t} + P_t q_t k_t + D_t + R_{t-1}B_{t-1} + T_t + M_{t-1} + A_{h,t}.$$

Finally, household h chooses a level of c_t, i_t, k_t, B_t, and M_t that maximizes its expected utility subject to its capital accumulation and budget constraint equations.

Household h negotiates a wage contract that can remain in place for an unknown number of periods. The opportunity to renegotiate a wage contract follows a Calvo (1983) model of random adjustment. That is, η_w is the probability that household h can set a new nominal wage, W^*_t, and $(1 - \eta_w)$ is the probability that its nominal wage can only increase by the steady state inflation rate, π. When a wage adjustment opportunity occurs, household h selects a nominal wage, W^*_t, which maximizes its utility given the firms' demand for its labor:

$$W_t^* = \left[\left(\frac{\chi \varepsilon_w}{\varepsilon_w - 1} \right) \frac{E_t \left[\sum_{i=0}^{\infty} \beta^i (1-\eta_w)^i \left(W_{t+i}\pi^{-i} \right)^{\varepsilon_w (1+\sigma_1)} \left(n_{t+i} \right)^{1+\sigma_1} \right]}{E_t \left[\sum_{i=0}^{\infty} \beta^i (1-\eta_w)^i \left(P_{t+i}\pi^{-i} \right)^{-1} \left(W_{t+i}\pi^{-i} \right)^{\varepsilon_w} n_{t+i} \left(c^*_{t+i} \right)^{(1-\sigma_2)/\sigma_2} \left(c_{t+i} \right)^{-1/\sigma_2} \right]} \right]^{\frac{1}{\varepsilon_w \sigma_1 + 1}},$$

where $(1 - \eta_w)^i$ is the probability that another wage adjustment opportunity will not take place in the next i periods. Finally, a value η_w equal to 1 implies that the nominal wage is perfectly flexible.

Firms**:** Firms, which are owned by the households, produce differentiated goods in a monopolistically competitive market. Firm *f* hires labor, $n_{f,t}$, and rents capital, $k_{f,t}$, from the households to produce its output, $y_{f,t}$, according to a Cobb-Douglas production function:

$$y_{f,t} = (k_{f,t})^{\alpha} (n_{f,t})^{(1-\alpha)},$$

where $0 \leq \alpha \leq 1$. Firm *f* then chooses the combination of labor and capital that minimizes its production costs, $w_t n_{f,t} + q_t k_{f,t}$, given its production function. Solving firm *f*'s cost minimization problem yields the following factor demand equations:

$$q_t = \psi_t \alpha (n_{f,t} / k_{f,t})^{(1-\alpha)},$$

$$W_t / P_t = \psi_t (1-\alpha)(k_{f,t} / n_{f,t})^{\alpha},$$

where ψ_t is the Lagrange multiplier on the cost minimization problem and is interpreted as the real marginal cost of producing an additional unit of output. The marginal cost, ψ_t, is identical for all firms because every firm pays the same rental rates for capital and labor.

Aggregate output, y_t, is a Dixit and Stiglitz (1977) continuum of differentiated products:

$$y_t = \left[\int_0^1 (y_{f,t})^{\varepsilon_p / (\varepsilon_p - 1)} df \right]^{(\varepsilon_p - 1)/\varepsilon_p},$$

where $-\varepsilon_p$ is the price elasticity of demand for good *f*. Cost minimization by households yields the demand equation for firm *f*'s good:

$$y_{f,t} = \left(\frac{P_{f,t}}{P_t} \right)^{-\varepsilon_p} y_t,$$

where $P_{f,t}$ is the price charged by firm *f* and P_t is a nonlinear price index:

$$P_t = \left[\int_0^1 (P_{f,t})^{(1-\varepsilon_p)} df \right]^{1/(1-\varepsilon_p)}.$$

Each period, firm *f* also may have an opportunity to select a new price, $P_{f,t}$, for its product,

$y_{f,t}$. Firm price adjustment opportunities follow a Calvo (1983) model of random adjustment. That is, the probability a new price, P^*_t, can be set is η_p, and the probability the price only can adjust by the steady state inflation rate, π, is $(1 - \eta_p)$. A price adjusting firm selects a price, P^*_t, that maximizes the discount value of its expected current and future profits subject to its factor demand and product demand equations:

$$P_t^* = \left(\frac{\varepsilon_p}{\varepsilon_p - 1}\right) \frac{E_t\left[\sum_{i=0}^{\infty} \beta^i \lambda_{t+i} \pi^i (1-\eta_p)^i \left(P_{t+i}\pi^{-i}\right)^{1+\varepsilon_p} \psi_{t+i} y_{t+i}\right]}{E_t\left[\sum_{i=0}^{\infty} \beta^i \lambda_{t+i} \pi^i (1-\eta_p)^i \left(P_{t+i}\pi^{-i}\right)^{\varepsilon_p} y_{t+i}\right]},$$

where $\beta^i\lambda_{t+i}\pi^i$ is the households' real value in period t of an additional unit of profits in period $t+i$, and $(1 - \eta_p)^i$ is the probability that the firm will not have another price adjusting opportunity in the next i periods. Finally, prices are completely flexible in this specification when η_p equals 1.

***The Monetary Authority*:** The monetary authority utilizes a generalized Taylor (1993) rule:

$$\ln(R_t / R) = \theta_\pi \ln(\pi_t / \pi) + \theta_W \ln(\Delta W_t / \Delta W) + \theta_y \ln(y_t / y) + \theta_D \ln(D_t / D) + \varepsilon_{R,t},$$

where R_t is the nominal interest rate, π_t is the actual gross inflation rate, ΔW_t is the gross nominal wage growth rate, D_t is the disaster shock variable, and $\varepsilon_{R,t}$ is a transitory monetary policy shock. Finally, ΔW equals π in the steady state because the model do not include any endogenous growth.

APPENDIX B: Log-Linear Approximation of the Disaster Shock

In order to map the regime-shifting framework onto the canonical difference-equation structure of the model, a log-linearized version of the Markov-switching process is expressed in the following form[14]:

$$\hat{D}_{t+1} = \rho_D \hat{D}_t + \varepsilon_{Dt+1}. \tag{B1}$$

It is convenient to define the baseline steady state as the unconditional expected value of the disaster shock:

$$\ln(\overline{D}) = \frac{1-p_{22}}{2-p_{11}-p_{22}}\ln(D^1) + \frac{1-p_{11}}{2-p_{11}-p_{22}}\ln(D^2). \tag{B2}$$

The composite expressions weighting the two values of D_t in (B2) are the ergodic probabilities of being in each of the two states.

When D_t is in state 1, its logarithmic deviation from the baseline steady state is

$$\hat{D}^1 \equiv \ln(D^1) - \ln(\overline{D}) = \frac{1-p_{11}}{2-p_{11}-p_{22}}[\ln(D^1) - \ln(D^2)]; \tag{B3}$$

and when D_t is in state 2, it is

$$\hat{D}^2 \equiv \ln(D^2) - \ln(\overline{D}) = \frac{1-p_{22}}{2-p_{11}-p_{22}}[\ln(D^2) - \ln(D^1)]. \tag{B4}$$

A useful property of a two-state Markov-switching process is that the conditional probabilities implicit in the expectation term in (B1) can be represented as a first-order autoregressive process. Using (B3) and (B4) and the probability transition matrix, it is straightforward to show that the autoregressive coefficient defined as $E_t(\hat{D}_{t+1} \mid \hat{D}_t)/\hat{D}_t$ is independent of the present state and is

[14] See Hamilton (1994, p. 684) for a detailed description of the AR(1) representation of the two-state Markov process. This procedure of linearizing a two-state Markov process also is used in Pakko (2005).

equal to $p_{11} + p_{22} - 1$.[15] For the linearly approximated simulations, this expression defines the value for ρ_D.[16] The sequence of disturbances placed into the model is calculated as

$$\varepsilon_{Dt} = \hat{D}_t - E_{t-1}(\hat{D}_t) = \hat{D}_t - (1 - p_{11} - p_{22})\hat{D}_{t-1}. \tag{B5}$$

[15] The expression $p_{11} + p_{22} - 1$ defines the stable eigenvalue of the probability transition matrix, P.

[16] Given our assumed values for the elements of the probability transition matrix, the implied autocorrelation coefficient equals zero in this application.

Table 1: Parameter Calibrations

Parameter	**Symbol**	**Value**
Depreciation rate	δ	0.025
Discount factor	β	0.99
Leisure utility parameter	σ_1	0.33
Consumption utility parameter	σ_2	0.5
Capital's share of output	α	0.33
Steady state gross quarterly inflation rate	π	1.005
Steady state labor supply	n	0.3
Price elasticity of demand	ε_p	6.0
Wage elasticity of demand	ε_w	6.0
Average capital adjustment costs parameter	$\phi(\cdot)$	i/k
Marginal capital adjustment costs parameter	$\phi'(\cdot)$	1.0
Elasticity of the i/k-ratio with respect to Tobin's q	$\chi = \left[(i/k)\phi''(\cdot)/\phi'(\cdot)\right]^{-1}$	-0.2

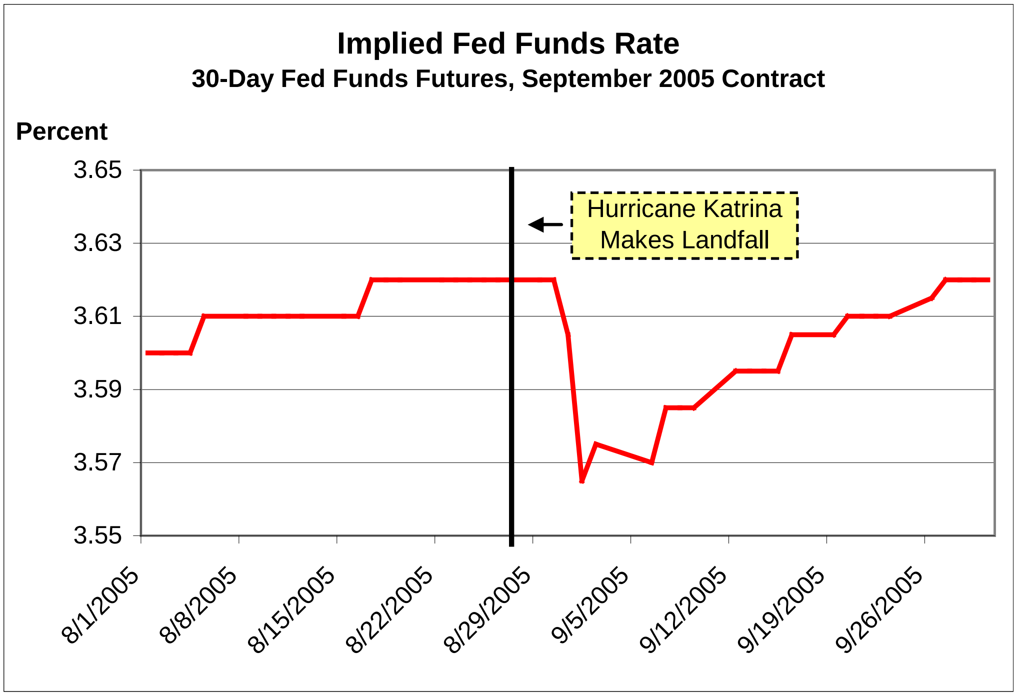
Table 2: The Contemporaneous Impact of a Disaster Shock (Percent)

Flexible Model	**y**	**π (a.r.)**	**R (a.r)**
Full Disaster Shock	-0.41	0.67	0.80
Capital Only (ζ = 0)	-0.10	0.14	0.15
Technology Only (κ = 0)	-0.30	0.53	0.65

Sticky Price Model	**y**	**π (a.r.)**	**R (a.r)**
Full Disaster Shock	-0.16	0.25	0.30
Capital Only (ζ = 0)	-0.09	0.13	0.14
Technology Only (κ = 0)	-0.07	0.12	0.15

Sticky Price and Wage Model	**y**	**π (a.r.)**	**R (a.r)**
Full Disaster Shock	-0.18	0.29	0.35
Capital Only (ζ = 0)	-0.13	0.20	0.23
Technology Only (κ = 0)	-0.05	0.10	0.12

Figure 1: Reaction of Fed Funds Futures



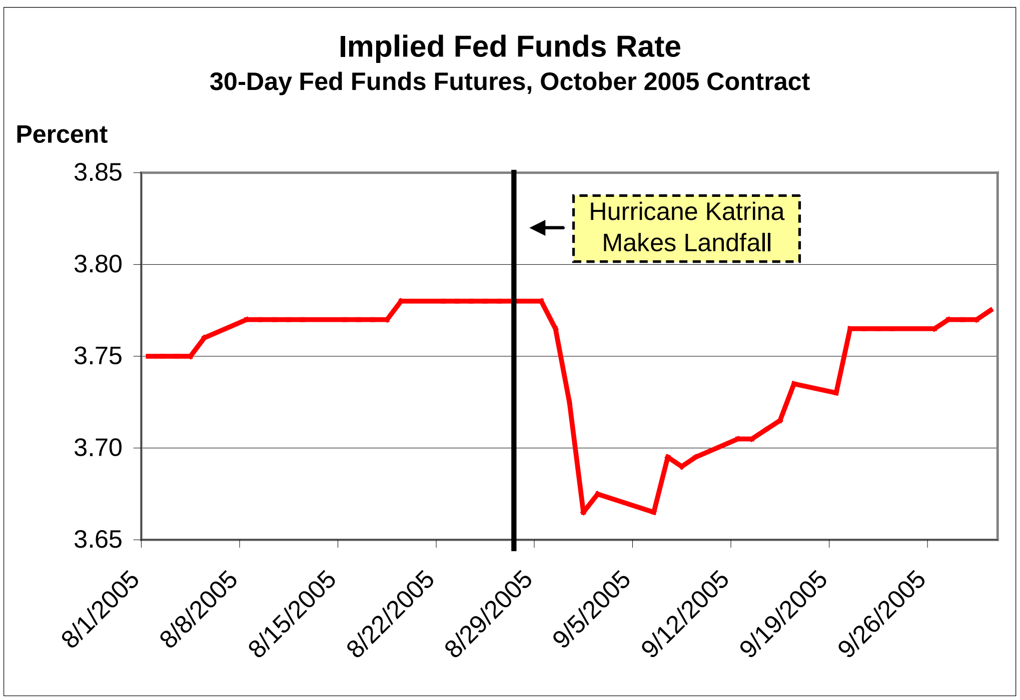


Figure 2: Taylor Rule Response

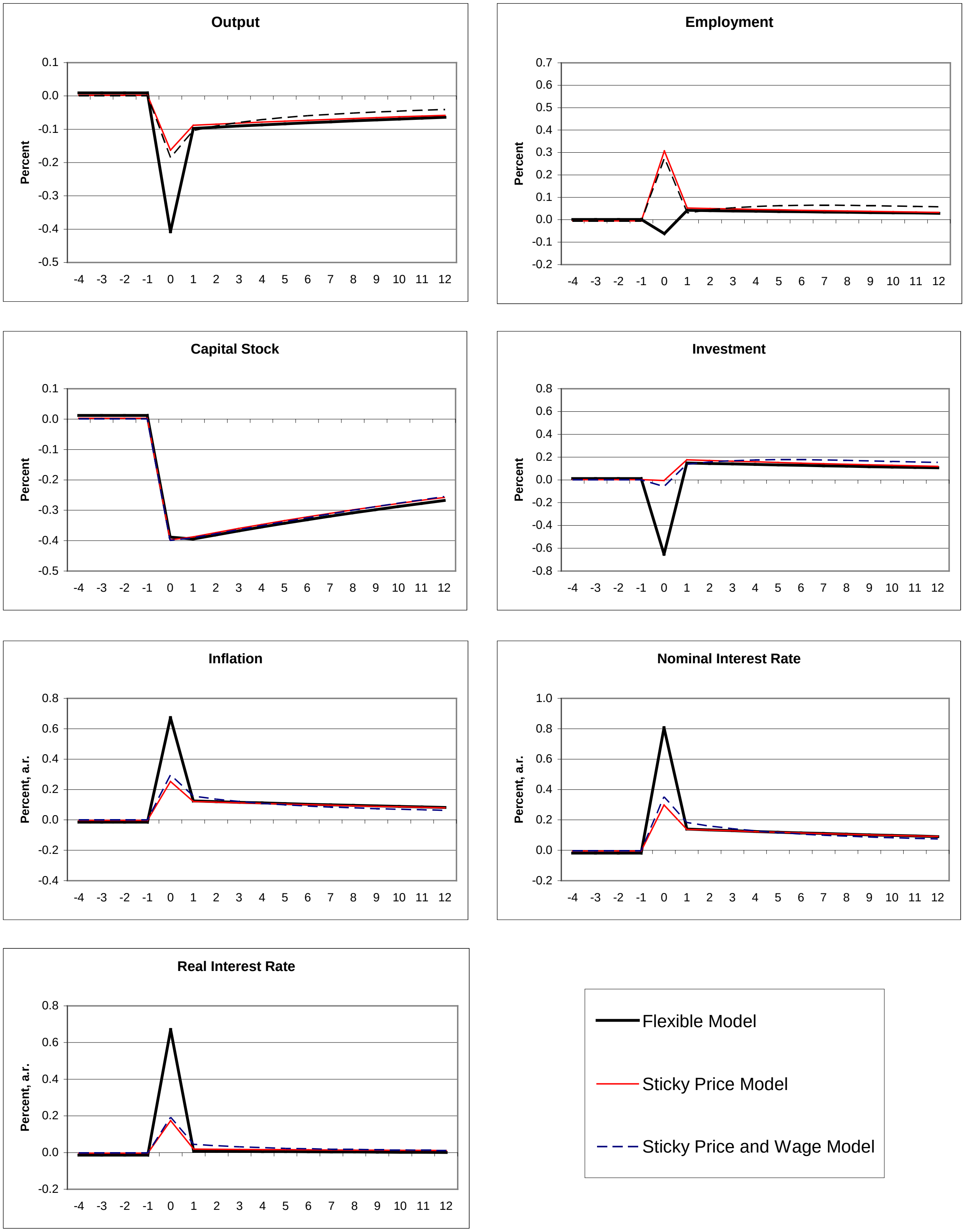


Figure 3: Fully Credible Price and Wage Inflation Control

Panel A: Optimal Control for Sticky Prices | **Panel B: Optimal Control for Sticky Wages** | **Panel C: Combination Policy**

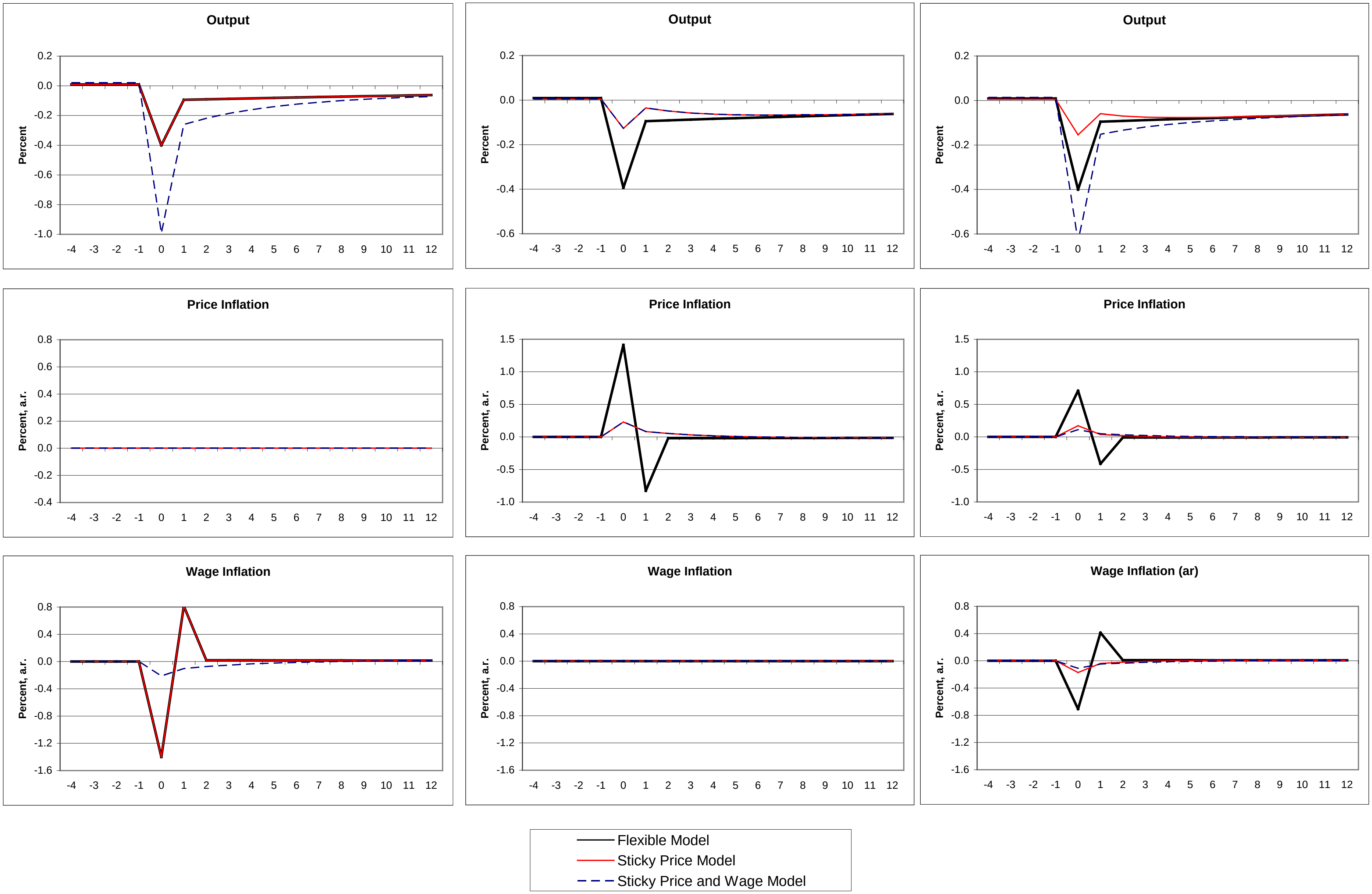
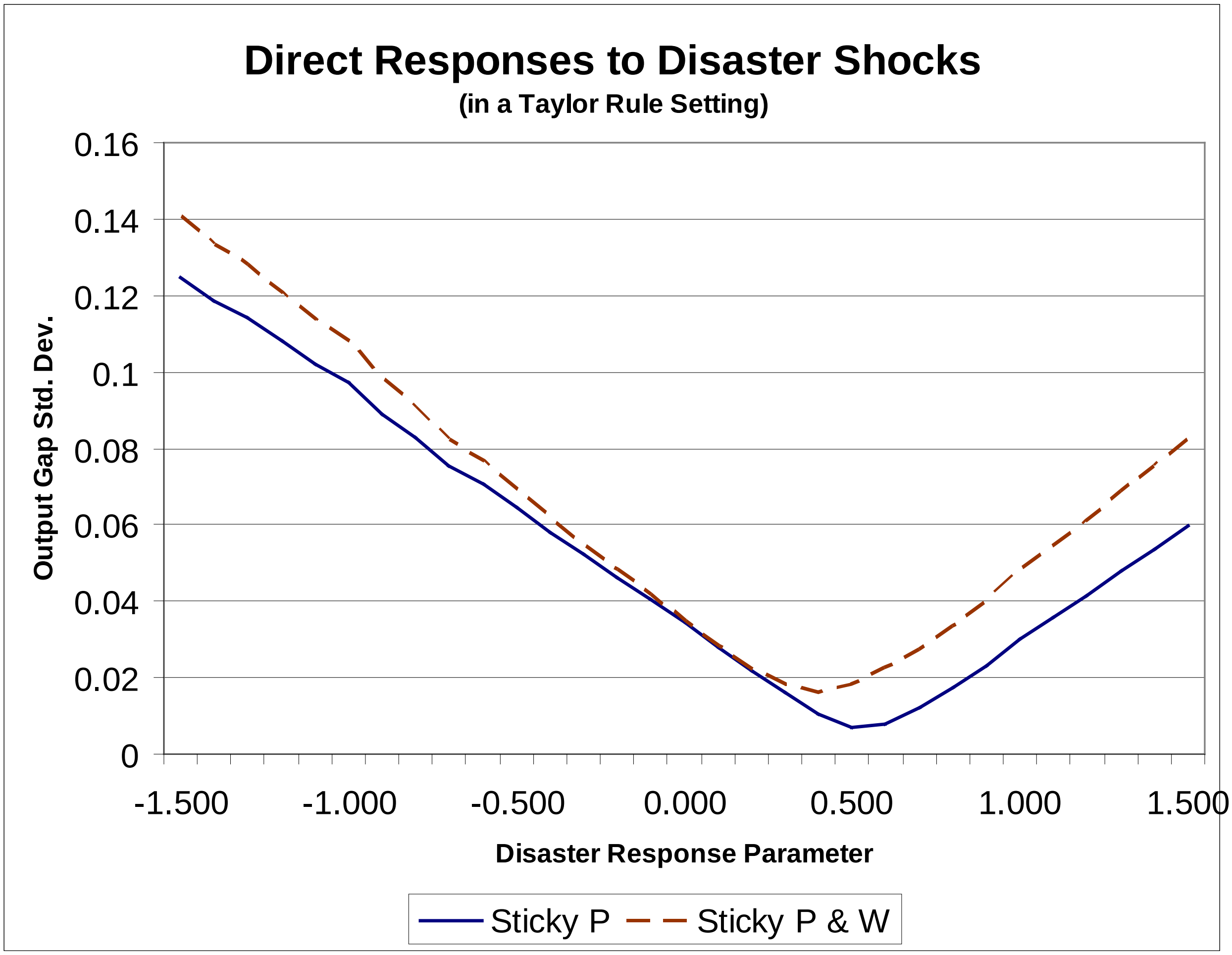
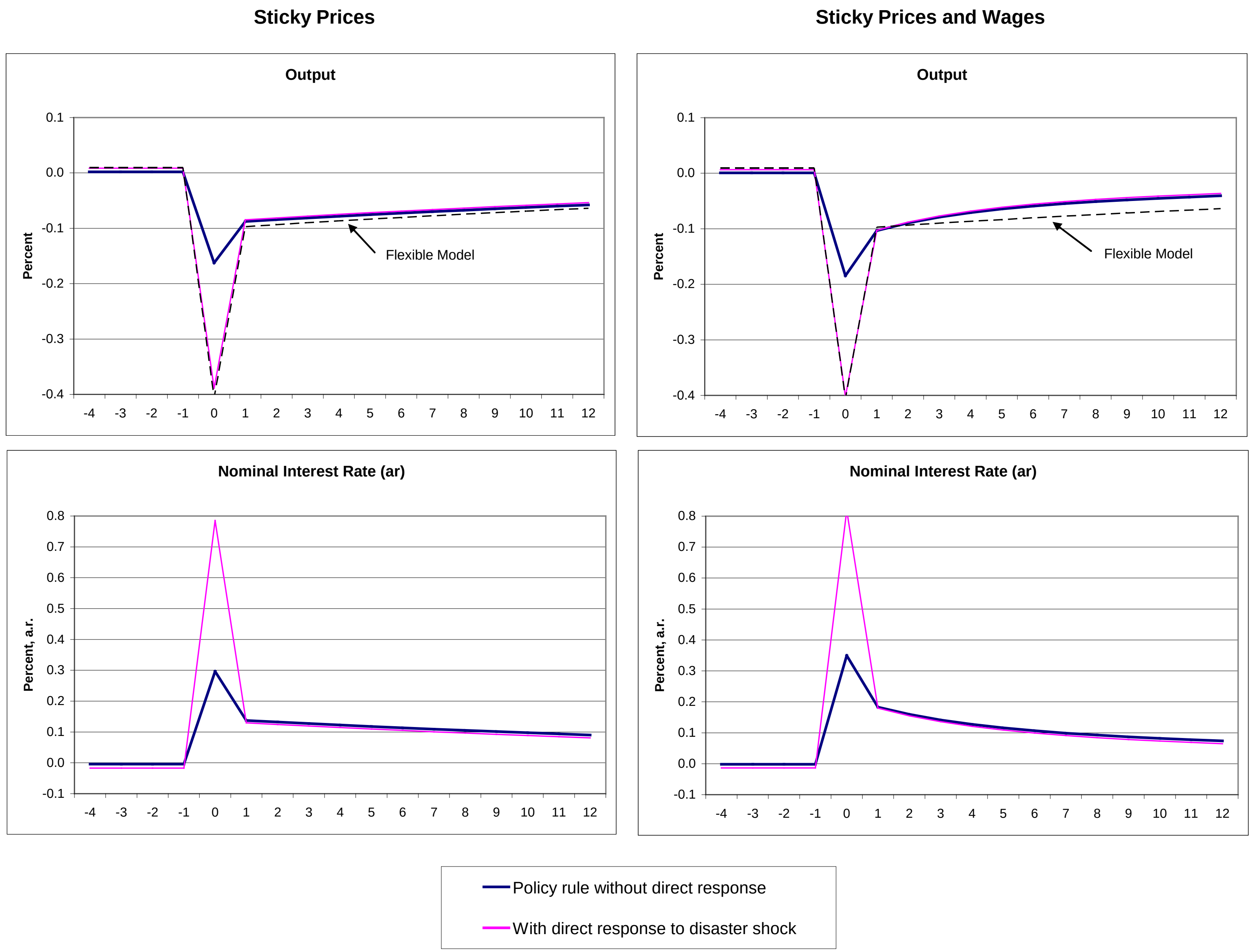


Figure 4:



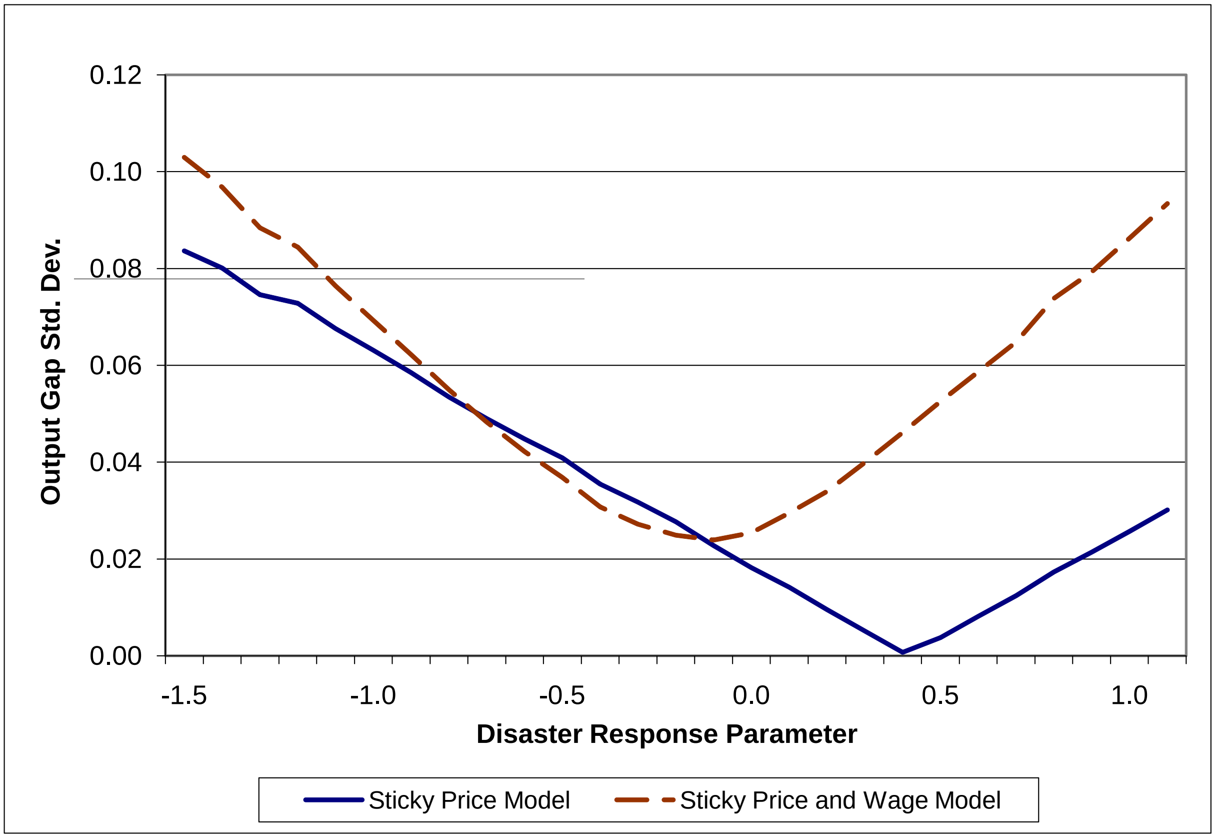
* Parameter values: $\theta_\pi = 1.5$, $\theta_y = 0.125$

Figure 5: Taylor Rule with Direct Responses to Disaster Shock



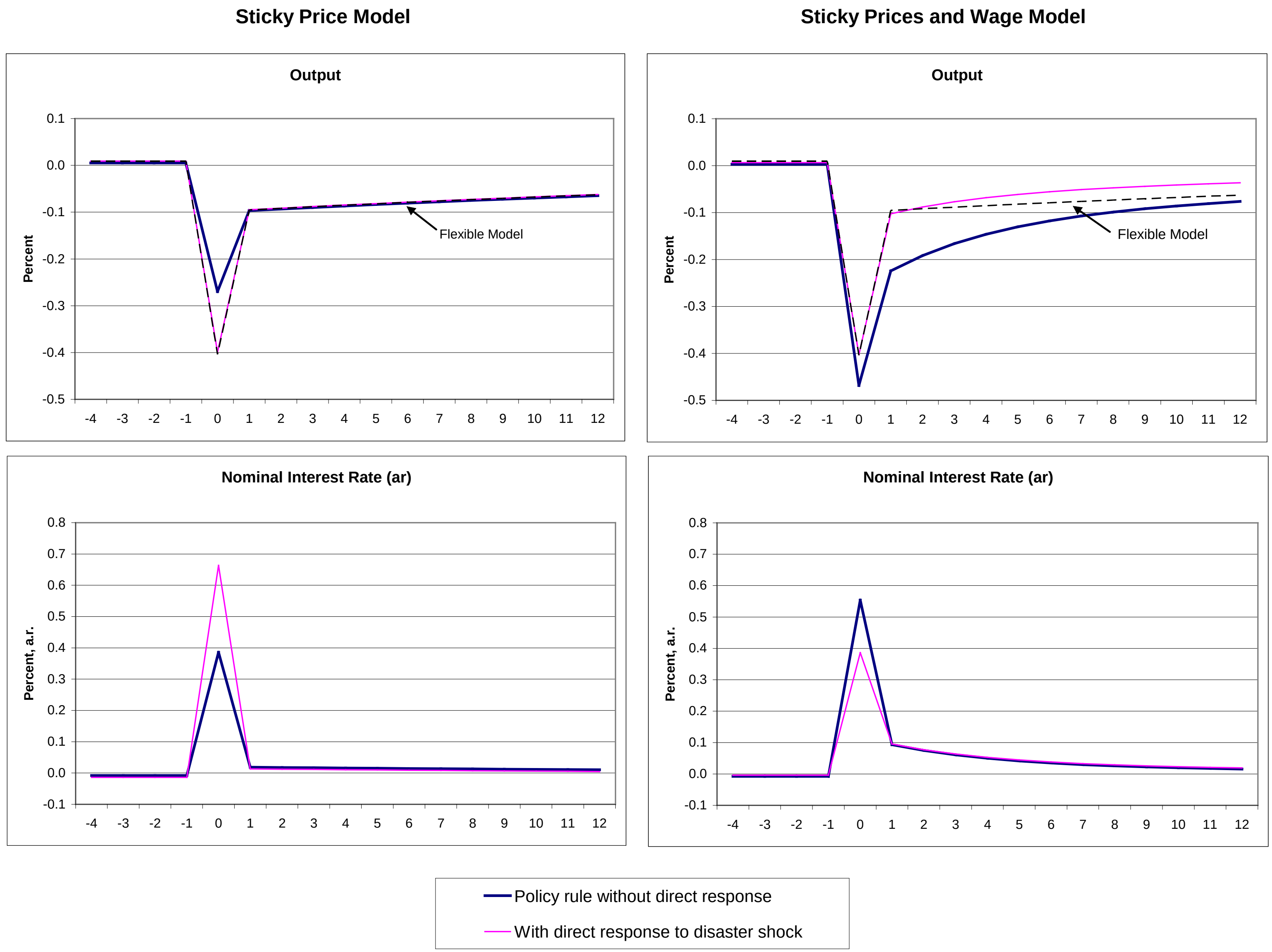
* Parameter values: $\theta_\pi = 1.5$, $\theta_y = 0.125$

Figure 6:
Direct Responses to Disaster Shocks
(With enhanced reaction to inflation)



* Parameter values: $\theta_{\pi} = 5.0$, $\theta_{y} = 0$

Figure 7: Enhanced Response to Inflation with Direct Responses to Disaster Shock



* Parameter values: $\theta_\pi = 5.0$, $\theta_y = 0$